Hydroclimatic Reconstruction of the Arbuckle–Simpson Aquifer using Tree Rings

Final Report Submitted to

Oklahoma Water Resources Board

By

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August 2009

Executive Summary

The annual growth rings in some climate-sensitive trees, such as post oaks, mimic the year-to-year pattern of hydroclimatic variability. Thus, during good years (i.e. favorable moisture and temperature conditions), the trees put on wide growth rings and during stressful years (below average precipitation and temperatures conditions) the trees put on narrow rings. Consequently, a statistical model that relates instrumental hydroclimatic time series (e.g. seasonal precipitation or streamflow) and tree-ring width indices for a particular location permits us to derive proxy hydroclimatic estimates for the period prior to the beginning of instrumental records for as long as the tree-ring index extends. Such long-term series are necessary in order to help scientists and policy makers place contemporary hydroclimatic dynamics in their proper historical perspective. Additionally, population growths, increased competition over, for example, available water resources, and uncertainty over the future pattern of climatic variability have combined to complicate water resources planning. To address these issues with confidence, scientists and policy makers need data on relevant variables that is much longer than the length of instrumental records available at most locations. Tree rings are especially useful in this regard because the data is annually resolved and precisely calendar-dated.

It is important to emphasize that tree-ring analysis, essentially, is a backward looking process. That is, it cannot be used to make predictive statements about the future. Its principal benefit or application is to generate proxy records that provide information on past events at time frames that predate instrumental records. These longer series may yield, for example, information on extreme events that occur so infrequently that they do not show up at all in the instrumental records or if they do, in insufficient realizations to permit meaningful analysis. In simplest terms, tree ring analysis allows scientists and stakeholders to answer questions like, ‘have we accounted for the worst drought (flood) that could be expected during the useful life span of this project?’ and ‘what is the long-term trend (in the climatic sense) of the variable (rainfall or streamflow) on which this project is based?’ This report contributes to answering those questions for the Arbuckle-Simpson aquifer study.

This study developed a 229-year long (1775-2004) Post Oak (*Quercus stellata*) tree-ring chronology from living trees for the Arbuckle-Simpson aquifer in south central Oklahoma. The chronology agrees very strongly (r=0.553, N=219, p<0.00001) with an existing chronology for the study area that extends from 1700-1995. Combining the two chronologies results in a new 304-year chronology from 1700-2004. This chronology was calibrated against instrumental monthly precipitation and streamflow, for the Arbuckle-Simpson aquifer area. Prior to calibration, the hydroclimatic series were tested for stationarity to ensure that the statistical model developed would be applicable over the entire range of the tree-ring index. The streamflow series proved to be non-stationary and required log-transformation. Only the results for precipitation and stream flow are presented here. Correlation functions analysis was used to determine the specific months and seasons of the year to which tree-ring growth corresponds. For precipitation, these are the late summer to early fall months of the previous year (August, September, October) and spring months of the current year (March to June). The significant months for streamflow are July to November of the previous year and June to August of the current year. For both precipitation and streamflow, the data for the appropriate months were combined and used to calibrate the tree-ring chronology. After verification using standard statistical techniques, the calibration model was used to reconstruct both variables back to 1700.

For precipitation, a simple linear regression model explained 47% of the variance in the ring-width index while a power model explained 40% of the streamflow variance.

A key objective of the study is to investigate drought risk in the study area. The drought of interest was specified *a priori* as the drought that occurs on average once in five years. For precipitation, this drought has total precipitation less than or equal to 22 inches during the reconstruction months and for streamflow the corresponding threshold is 1545 cfs. Using the above thresholds, the study shows that the droughts were most common during two periods; 1700-1770 and 1900-1960. The 1800s generally were a period of modest and infrequent droughts as has been the period from 1960 to present. In terms of drought magnitude, four of the most severe droughts occurred in the early to middle parts of the 1770s. It is unclear whether this reflects the fact that the tree-ring chronology used in the reconstruction has fewer samples in this range. More studies will be necessary to increase the sample depth towards the beginning of the chronology. The droughts of the 1950s also rank quite high in the precipitation series. The most severe droughts during the instrumental periods in the streamflow series differ somewhat from those identified in the precipitation records. The worst precipitation drought during the instrumental period occurred in 1910-1911 when precipitation totaled only 13.08 inches during the reconstruction months. Using the extended precipitation series (1700-2004), this drought has a chance of 1.6% of occurring in any one year. Similarly, the 1953 drought when 17.08 in of precipitation fell has 3.3% chance of occurring in any year. The worst drought from the streamflow records occurred in 1939 and has a 1.8% chance of occurring again in any year. The drought of 2000 ranked quite high and has a recurrence probability of 3.45%.

Droughts lasting two or more years occurred in about 18% of cases at the specified threshold. Hence, for the most part, the average drought with recurrence interval of 5 years in the Arbuckle-Simpson aquifer can be expected to last a single year.

Overall, the 300-year time series of precipitation and streamflow appears stable. There is little evidence that droughts are becoming more frequent or more severe. On the contrary, the last 40 years have experienced above average wet conditions resulting in infrequent and less severe droughts. This point is important for water resources planning because it suggests the lack of severe droughts during such long periods may lead to complacency or blunt learned adaptation behavior. It is important therefore to realize that more severe and frequent droughts than currently observed are more ‘normal’ for the region. Therefore, for worst case water resources planning, it may be advisable to derive drought thresholds from past periods that experienced more droughts than the last 40 years, which should be considered anomalously wet.

Table of Contents

List of Figures

List of Appendices

Tree Ring Chronology Development

Introduction

This is the final report of the study on Hydroclimatic Reconstruction of the Arbuckle-Simpson Aquifer Using Tree Rings. The study was conducted as a subcontract from the Oklahoma Water Resources Board to the University of Oklahoma in September 2004. The study presented in this report is part of the larger Arbuckle-Simpson Hydrology Study (http://www.owrb.ok.gov/studies/groundwater/arbuckle_simpson/arbuckle_study.php) mandated by Oklahoma Senate Bill 288 in May 2003. It describes the development of the tree-ring chronology, calibration, and verification as well as the precipitation and streamflow reconstruction. Finally, the reconstructed precipitation and streamflow series are utilized to investigate drought characteristics in the Arbuckle-Simpson aquifer.

For many applications, such as long-term water resources planning, instrumental (gauged) hydroclimatic records may not contain information about the full range of natural climatic variability possible (Meko et al, 2001; Woodhouse and Lukas, 2006). Because of the relatively short length of these records (typically 90 years or shorter) multiyear or multidecadal events may not be realized in sufficient numbers to permit definitive determination of the pattern of low frequency variability. The result can be over ambitious, unrealistic or, less commonly, over conservative estimates of water resources availability. By far the most widely cited example illustrating the deficiency of short instrumental records for long-term water resources development is the Colorado River Compact of 1922, which allocated the water supplied by the Colorado River among the states of California, Arizona, Colorado, Utah, Nevada, and New Mexico. The compact assumed an average annual flow of 16.2 million acre-feet for the river based on 14 years of measured flow records (1906-1919) at the Lees Ferry gauging site. Subsequently, Stockton and Jacoby (1976) using tree rings reconstructed the streamflow of the Colorado River at the same site for 400 years and showed that the long-term mean annual streamflow was actually 13.5 million acre feet, significantly lower than the amount upon which the compact and allotment was based. It transpired that due purely to chance, the period upon which the compact was based was among the wettest in 400 years (see also Meko et al, 2001; Woodhouse and Lukas, 2006). The inability of the river to meet the allotted water amounts among compact members once the anomalously wet period ended, as well as the attendant litigations and squabbles, stand as important reminder of the need to base water resources development on data that is as long as possible. Since that famous study, tree rings have been used extensively and with great success to reconstruct droughts and streamflow for various parts of the world (Meko and Graybill, 1995; Cook et al., 1999; Woodhouse, 2000; 2001;2006 Jain et al., 2002).

Here in the USA, water resources managers in the southwestern states in particular have made great strides in incorporating tree-ring based hydroclimatic reconstructions in the decision support system for major water resources development projects. In May 2005, a workshop titled Developing Hydroclimatic Reconstructions for Decision Support in the Colorado River Basin brought together 24 scientists and 26 water resources managers, policy makers and planners (http://wwa.colorado.edu/products/forecasts_and_outlooks/intermountain_west_climate_summary/articles/june_feature.pdf). Two factors account for this convergence of interest in the southwestern states. The first is the presence of a thriving and world-famous community of tree-ring experts in the region, led by the Laboratory for Tree Ring Research at the University of

Arizona in Tucson (http://www.ltrr.arizona.edu/). The second is the climate history and experience of the region, beginning with the over allocation of the waters of the Colorado River as described above, increasing demand, as well as episodic but persistent droughts of uncertain recurrence intervals.

The above dynamics are not unique to the southwestern states. Even in those regions that are not traditional drought hot spots, it can be expected that knowledge concerning the long-term pattern of climatic variability will become more critical as uncertainty concerning the frequency and magnitude of future climatic events, such as droughts and floods, combine with increased anthropogenic demand for water to complicate water resources planning. Additionally, competition among stakeholder groups and their sometimes diametrically opposed water needs and time scales may also raise new questions that instrumental records alone cannot resolve satisfactorily. These considerations underlie a need for incorporating hydroclimatic data series that are as long as possible in water resources development projects.

Study Objectives

The specific objectives of this study are to:

(i) Develop a 200-300 year reconstruction of precipitation and streamflow for the Arbuckle-Simpson aquifer using tree rings.

(ii) Utilize the reconstructed series to analyze drought characteristics, including frequency, duration, and intensity in the Arbuckle-Simpson aquifer. Of special interest are occurrences of drought events whose duration or frequency exceeds those of the worst droughts in the instrumental time series.

Basic Principle of Tree Rings

Trees grow in response to a wide range of environmental conditions including temperature, precipitation, and ecological dynamics among many other factors (see Frits, 1976). As a result, the pattern of variations in tree-ring width from one year to the next is closely related to the year-to-year variability of the factor (or factors) to which the tree is most responsive. Frequently, the most important climatic factors tend to be precipitation and temperature. Thus, during years of stressful climatic conditions, such as below average precipitation or cold conditions, trees put on narrow rings. Conversely, tree rings are wider than average when conditions are more favorable than normal. Knowledge concerning this basic principle has been traced to the early eighteenth century when "..several authors commented on the narrowness of tree rings dating from the severe winter of 1708-1709" (Bradley, 1999, p.397). In the English-speaking world, A.E. Douglass is generally considered the "father of tree-ring" studies. An astronomer by training, A.E. Douglass needed a long climate record to test his hypothesis of a connection between sunspot and climate variability. Such records did not exist in the early decades of the 20th century in the arid southwestern United States where Douglass worked. He recognized however that variation in the widths of annual tree rings might provide a proxy record of rainfall variability. His efforts to derive such proxy records (Douglass, 1914, 1919) uncovered the basic principles that became the foundations for modern tree-ring analysis or dendrochronology.

Not all tree species form annual rings. Tree-rings form in response to induced cambial dormancy during cold winter months (a temperature stress) or dry periods (moisture stress). Thus, those trees in which cambial activity continues throughout the year, such as evergreens, never develop annual rings. Similarly, trees growing in locations where climatic variables do not impose serious constraints on their physiological processes also do not develop rings or they have rings that are relatively uniform from year to year. Such rings are described as ‘complacent’ and are of limited utility for dendrochronological studies. The most desirable types of trees are those whose rings are ‘sensitive’ or ‘responsive’ to climatic conditions i.e. the ring widths vary from year to year in response to climatic variability. As a general rule of thumb, sensitive trees are deciduous trees that grow in rocky outcrops in hilly terrain, without access to a reservoir of water or moisture, such that a climatic stress is reflected in the size of the ring that the tree puts on for that year or season.

Study area and sample collection

The detailed descriptions of the physical setting, geology, hydroclimatic, and social aspects of the Arbuckle-Simpson aquifer (Figure 1) appear in several publications of the Oklahoma Water Resources Board and therefore are not repeated here (see http://www.owrb.ok.gov/studies/reports/reports.php). The aquifer is located within Oklahoma Climate Division 8 (hereinafter OKCD8), which includes several precipitation gauging sites that date to the first decade of the 20th century (http://lwf.ncdc.noaa.gov/oa/climate/climatedata.html). The annual and normalized precipitation for all gauging sites in OKCD8 appears in Figure 2. The figure shows that the top five years experiencing the most severe standardized negative precipitation departure from the long-term mean (1895-2007) are, in order of decreasing severity, 1963, 1910, 1896, 1901, and 1956. It would be interesting to see how this ranking of precipitation anomalies compares with anecdotal or stakeholder perceptions of drought severity. Conversely, the top five wettest years during the instrumental period are (in descending order) 1957, 1990, 1945, 1923, and 1908. In terms of duration, the longest period of below average precipitation occurred between 1909 and 1918 interrupted only by the above average precipitation in 1915. There were only two years of above average rainfall in the intervals between 1930 and 1939 (1932, 1935). Similarly the period from 1951 and 1958 also had only two years of above average rainfall (1953, 1957). The 13-year wet period from 1984 to 1997 is unprecedented since the beginning of precipitation measurements in the study area. Only one year during that period (1988) experienced below average rainfall. Other wet periods of note occurred in 1919 – 1929 (three deficit years) and 1905-1908. Figure 3 shows the total annual streamflow for Blue River (gaged near the town of Blue) as well as the streamflow time series (measured at various times throughout the year) for Byrds Mill Spring near Fittstown. It is important to note that the streamflow data for Byrds Mill Spring (Figure 3) is incorrect because it does not include the portion of flow that is diverted to Ada. This diversion occurs through a 36-inch pipe with an intake point located directly at the spring enclosure, whereas the flow measurements plotted in Figure 3 occur further downstream. Consequently, the 'true' flow of the Spring must include both the creek flow and the diverted amounts. Unfortunately, records of the amount of water diverted through the pipe go back only to 1989 although the City of Ada has been diverting water from the spring since 1911. For this reason, the tree-ring index was not calibrated against Byrds Mill Spring data. Both the precipitation time series and, especially, the Byrds Mill flow series, show a period of wetter than normal conditions that began around 1980 and persisted into the mid 1990s. However, it is unclear how often such wet - or corresponding dry - periods occur because the gauged data are relatively short. Thus, the Arbuckle-Simpson aquifer presents an excellent opportunity for applying tree-ring based reconstructions in order to gain a wider picture of the range of hydroclimatic variability.

The species used for this study is Post Oak (*Quercus stellata,* Appendix 1), which has been shown to be sensitive to climatic variability throughout most of its range in the USA including Texas, Oklahoma and Arkansas (Stahle and Cleveland, 1988; Stahle et al, 2000; ITRDB, http://frames.nbii.gov/metadata/websites/International_Tree-Ring_Data_Bank_(ITRDB).html). A total of 107 trees were cored primarily from three sites within and around the Arbuckle-Simpson aquifer. These samples were collected between August - December 2004 and February - March 2005. Samples were collected using Suunto increment borers at stressful sites, e.g. near hill tops and rocky terrain. Consistent with standard practice for minimizing random effects or noise on the tree-ring pattern, a minimum of two cores were taken for each tree wherever possible. Additionally, trees newly cleared for an access road near the western end of the aquifer (southwestern part of the Arbuckle Anticline) provided a unique opportunity to collect whole stem discs using a chain saw. Such discs are much easier to study because it is possible to follow a ring around the circumference of the tree, significantly increasing confidence in ring identification. Table 1 lists the areas where samples were collected along with brief characteristics at each site.

Table 1. Major sampling sites within the Arbuckle-Simpson aquifer area. Samples collected from sites but not yet analyzed are not listed.

Site Name	**Lat Long**	**Number of samples collected**		**Dates of Sample collection**
		Cores	Discs	
Ada	34:47:25 N 96:38:06 W	10		Aug 2004
Pontotoc Ridge	34:30:20 N 96:37:28 W	50		August/December, 2004
Hennepin	34:28:51 N 97:18:58 W	40	17	December 2004, March, 2005

Sample Preparation and Analysis

Sample preparation and analysis followed standard procedures consisting of the following steps:

(i). Core mounting and preparation (principally sanding) and ring counting to determine the age of each sample or core.

(ii). Visual crossdating using skeleton plots and development of calendar-dated site chronology.

(iii). Ring width measurements.

(iv). Verification of visual crossdates and chronology using computer software (COFECHA).

(v). Development of detrended and standardized chronology using ARSTAN, industry standard statistical software.

(vi). Analysis of correlation functions to determine which months or seasons of the year contribute to tree growth. Subsequent reconstruction pertains only to the months or seasons identified in this step.

(vii). Development of a statistical model describing the relationship between the tree-ring index and precipitation or streamflow.

(viii). Calibration (split sample) verification to test how well the model reproduces the actual measurements.

(ix). Reconstruction and extension of time series back in time if the statistical model passes all applicable tests in step (viii) above.

These steps are described briefly below.

Sample preparation and ring counts

The samples collected were taken to the tree-ring laboratory at the University of Oklahoma and prepared following standard procedures. First, the cores were mounted using Elmers' wood glue and strings to stabilize them for preparation. To expose the rings, samples were sanded with progressively finer sanding paper beginning with 100 grit through 180, 320, to 400 grits per square inch. The whole stem discs were clamped to a work bench and sanded using a rotary sander, also with progressively finer sanding paper. Next, the rings in each individual core or disc were identified and counted using a Leica S6D trinocular microscope. A ring count was accepted as valid only if it was verified by an independent counter. That is, two people had to independently arrive at the same ring count without ambiguity before it was accepted for further analysis. The longest ring series among the samples included in this study is 229 years. This permits us to develop a chronology from 1776-2004. The series stops in 2004 because the samples collected in 2005 were taken in March, prior to the onset of growth for that year. Figure 4 shows the age-frequency distribution of samples for which ring counts have been verified.

Visual crossdating

Visual crossdating was achieved using skeleton plots. This procedure uses a 2mm-ruled graph paper where one vertical line on the graph represents one ring on a sample. Each ring is assigned an inverse value on a scale of 1-10 based on its width (as determined visually) relative to the neighboring rings. Thus, narrow rings, indicative of drought or stressful conditions, are assigned a value close to 10 and rings only slightly narrower than normal score close to zero. Average or normal rings receive no score at all while wider than normal rings are marked with the symbol 'B' for big. By visually comparing the skeleton plots for all samples, the pattern of narrow and wide rings should align perfectly. Failure of the ring patterns to match is usually an indication that some rings may have been omitted or misidentified. In the present case, the process was facilitated greatly by the fact that the last ring for all samples was known precisely. Finally, when all the samples were matched against one another, a master chronology for the Arbuckle-Simpson aquifer was produced by averaging (again visually) the scores for each ring.

Ring width measurement

The ring widths were measured using a Leica S8APO Trinocular microscope and a Velmex measuring system (Figure 5). The setup consists of an Acu-Rite stage recorder platform which moves the sample being measured. To reduce eye stress, a video camera (Micro image video systems) affixed to the third eye piece of the trinocular scope transfers the image to a Toshiba TV monitor. The rings are aligned with cross hairs on the TV screen and the stage recorder is advanced to the start of the next ring. The ring width (in hundredths of a millimeter) appears on a Quick Check display monitor. A tab-2 printer button transfers the measurement to a computer connected to the measuring system. Software on the computer, J2X measure, widely used for ring width measurements, captures the ring width in the desired format.

Statistical verification of visual crossdating

The computer software COFECHA was used to verify the visual crossdate and help identify problem segments. Written by Richard L. Holmes in 1982, COFECHA is a well-tested and widely used software for data quality control and statistical verification of crossdating. Using a suite of statistical methods, it identifies portions of a crossdated series that may have errors due to dating or measurement.

To enhance the characteristics that facilitate crossdating, low frequency variance and persistence are removed by applying respectively, cubic smoothing spline and autoregressive modeling.
In this study, a 32-year spline was applied. Then the series were log-transformed to weight proportional differences equally and each transformed series tested against the master dating series segment by segment using a suitable overlap, in this study, 40 year segments overlapped by 20 years.

COFECHA identifies five types of possible errors or flags that aid verification and quality control. A segment is assigned an 'A' flag if its correlation with the master is less than a specified significance threshold. The second type of flag, a 'B' flag, is triggered when the series shows a higher correlation against the master at a point other than that at which it was crossdated visually (i.e. from the skeleton plots). That is, the program takes each series as crossdated visually and calculates a Pearson correlation coefficient against the master series for overlapping 20 year periods. Then the series is shifted forward one year at a time up to 10 years and also backwards from its original position one year at a time up to 10 years to see if it correlates higher at a different location. A 'C' flag indicates that the year-to-year change in ring widths for a particular series is much larger than the mean year-to-year change for other series. A 'D' flag denotes a missing ring and an 'E' flag signifies that a ring width is a statistical outlier from the mean of all rings for that year. Not all flags are fatal or require immediate action. 'B' and 'D' flags are the most serious and indicate that a sample has been misdated. If many samples are available, an especially troublesome segment can be omitted from the analysis without loss of accuracy. For this study, 31 samples satisfied all criteria and were combined to produce the

Arbuckle-Simpson chronology. Additional samples will be added on to this chronology as they become available. Thus, the chronology produced dates from 1776 to 2004.

Development of standardized and residual chronology

The verified crossdated series produced by COFECHA were next submitted as input to the software ARSTAN, also industry standard for chronology development. Written by Dr. Edward R. Cook (1985) at the Tree-Ring Laboratory, Lamont-Doherty Earth Observatory, the program detrends and indexes each series then applies a robust estimation of the mean value to remove the effects of ecological dynamics. Principal component analysis is applied to the common interval to separate different signals contained in the time series. Two chronologies result from this process; a standard chronology without autoregressive modeling and a residual chronology with autoregressive modeling applied.

Based on the samples collected for this study, the ARSTAN chronology extends from 1776-2004. However, Dr. David Stahle of the University of Arkansas previously produced a Post Oak chronology for samples collected near Lake of the Arbuckles (within the study area) that extends from 1700 to 1995. The residual chronologies produced by Stahle and this study agree strongly on several statistical criteria ($r=0.553$ $N=219$, $p<0.00001$) (Figure 6). The T test for difference of means and analysis of variance suggests the two series are statistically identical. Consequently, the chronologies were combined (by simple averaging) resulting in one chronology that extends from 1700 to 2004.

Correlation Function Analysis

Although an annual tree ring represents the cumulative growth of the tree during the year, rarely does a tree grow continuously throughout the year (such trees would in fact not be very useful for tree- ring analysis). In general, growth occurs predominantly in a few critical months, such as spring or fall depending on the species and location. Additionally, climatic conditions during the previous-year growing season (T_{-1}) may also influence growth during the current-year growing season (T_0). It is important therefore to identify the specific months or periods of the year to which tree ring growth responds. This is achieved by computing "a sequence of coefficients between the tree-ring chronology and the monthly climatic variables, which are ordered in time from year T_{-1} to T_0 (Biondi and Waikul, 2004, p. 302). Two types of coefficients (also called functions) are commonly calculated. The first are "correlation functions", which are the coefficients derived from univariate estimates of Pearson's product moment correlation. The second, "response functions" are the coefficients obtained from multivariate estimates from a principal component regression model (Biondi and Waikul, 2004; Briffa and Cook, 1990).

In this study, the software program DENDROCLIM2002 (Biondi and Waikul, 2004), was used to calculate the correlation functions. Developed in Microsoft Foundation Classes with visual C^{++}, the program uses bootstrapped confidence intervals to estimate the significance of the correlation functions, significantly reducing the risk of false significance. Additionally, recognizing that the climate-tree growth relationship may change over time, DENDROCLIM2002 tests the stability of calibration models by computing the relationship for multiple periods and minimizing for bias.

The calibration process attempts to match the response of a tree as indicated by its ring width against the climatic variable for the corresponding year. In this study, the variables investigated include monthly precipitation and streamflow. The following paragraphs describe the climatic data sets used for calibration.

Climatic Data

Monthly precipitation data averaged for all gauging stations in OKCD8 for the period 1895-2007 were obtained from the National climatic data Center (NCDC; http://lwf.ncdc.noaa.gov/oa/climate/climatedata.html; Appendix 2). This data set is widely used by the climate research community and information regarding its quality control can be found on at the above webpage. Consequently, no further quality control was performed on this data for this study. The monthly streamflow data was obtained from (http://waterdata.usgs.gov/nwis/sw). Again, quality control information on this data set exists in various publications of the NCDC and USGS.

The monthly data for all four variables was supplied as input to DENDROCLIM2002. The time interval for the analysis was set at 22 months, i.e. the last 10 months of the previous year's growing season and 12 months during the current year's growing season. For each variable, the months identified as statistically significant (α=0.05), that is those that contribute the most to tree growth were combined (i.e. totaled) and used for calibration and reconstruction. Thus, the proxy estimates derived refer only to the specific months identified from the above procedure and not for the entire year. Table 2 lists the months used for calibration.

It is necessary to test the precipitation data for stationarity prior to its being used for calibration, because non-stationary time series require different procedures from stationary ones. Figure 7 shows the plot of the total rainfall for the months identified from correlations functions as and the corresponding cumulative probability plot for the same time series. The cumulative probability plot suggests time series may be non-stationary, indicated by the break in the fitted line. To test for this possibility, the time series was segmented into two at the point indicated by the probability plot and the cumulative probabilities of the two segments were again calculated and superimposed on the same graph (Figure 8). The two curves align, suggesting that probability estimates derived from them would be statistically similar. Under conditions of non-stationarity the values would be expected to be statistically significantly different. Investigating further the possibility of non-stationarity, the Shapiro_Wilks test for normality was applied to the time series. The test yields a W-Statistic of 0.979 (P = 0.082), indicating normality at the 0.05 confidence level.

Table 2. The months identified from correlation function analysis as statistically significant (α=0.05) in determining tree growth based on bootstrapped confidence intervals. The months are labeled numerically. Thus, July appears as 7, August is 8 etc. These are the months used for calibration for each of the variable listed in the table.

	Months Used for Calibration and Reconstruction																	
	Previous Year (T_{-1})						Current Year (T_0)											
Variables	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Precipitation		X	X	X			X		X	X	X	X						
Streamflow	X	X	X	X	X							X	X	X				

Calibration

Table 2 shows the months that are significantly correlated with precipitation based on the results of correlation functions as computed by Dendroclim. These are the months used for calibration and reconstruction. Thus, for precipitation, the monthly totals for August, September, and

October of the previous year as well as the January, March, April, May, and June precipitation for the current year were summed, producing a new precipitation time series, which then was calibrated against the residual Tree Ring Index (TRI). Using a scatterplot, several statistical models describing the relationship were explored including linear regression, power, exponential, and polynomial equations. Model suitability was evaluated in terms of the percentage variance explained and randomness of residuals produced from fitting the test model. A simple linear regression model was chosen for calibration (Fig. 9). The model yields a strongly significant Pearson correlation coefficient (r) between the TRI and the precipitation series of 0.685 (N=90, P<0.00001). The adjusted explained variance is 0.47, in other words, 47% of the observed variation in the TRI can be explained by variations in precipitation for the selected months. Figure 9 shows that the spread of the scatter points around the regression model is much tighter in the lower end, i.e. narrow rings, than in the upper rings. This point has implications for reconstruction if this model is used; it suggests that years of low precipitation will have lower variance than wet years. Other investigators (e.g. Woodhouse et al, 2006) have also reported similar observation.

Verification

Precipitation

A split sample calibration and verification procedure was adopted in order to test how well the selected model estimates precipitation based on TRI. The precipitation time series was divided into two approximately equal periods: 1914-1960; 1961-2004 and the relations between the two variables in each time period was established (Figure 10). Then, the relationship developed for the first time period (1914-1960) was used to estimate the precipitation for the second time period (1961-2004) and vice-versa. The estimated precipitation was then compared with the actual (instrumentally measured) precipitation for that time period using simple regression analysis (Figure 1) and analysis of the residuals. For the first time period, the Pearson correlation coefficient (r) between estimated and measured precipitation is 0.69 (R^2 = 0.47, N = 46, P < 0.00001) and for the second, r = 0.70 (R^2 = 0.49, N = 44, P<0.00001). Consistent with the observation made earlier, note that Figure 11 shows the model fits high precipitation events less tightly than the low events.

In addition to the correlation coefficients, the residuals (Figure 12) from the predicted precipitation for all three periods (1914-2004, 1914-1960, 1961-2004) were analyzed for runs and evidence of systematic bias. A runs test performed on the regression residuals for both series showed no systematic bias or persistence. These results suggest the relationship between predictor and predicant is robust and has not changed within the calibration period. It was decided therefore to use the entire series relationship for reconstruction (Figure 13). The reconstruction equation used is thus:

$$\hat{y} = 29.674x - 1.356 \quad (1)$$

Where $\hat{y}$ is estimated precipitation and *x* is the value of TRI for corresponding year.

Streamflow

The streamflow data was handled in a similar manner. In this case, the cumulative probability plot (Figure 14) suggests the data is non-linear and this result was confirmed using the Shapiro-Wilk test for normality (W-Statistic = 0.878; P < 0.001). Thus, the streamflow data was log-transformed (Figure 15) and the new series was again tested for normality. The new W-Statistic is 0.985 (P = 0.602) suggesting the $\log_{10}$ transformed series can be considered normal. Therefore, for the remainder of this report, values of the streamflow data referred to were obtained from the log-transformed series. Figure 16 shows the calibration process and equations for the streamflow. Split sample verification was again carried out as described previously. The reconstruction, using the entire period of data is

$$\hat{y} = 3.4035x^{0.3794} \qquad (2)$$

Table 3 lists the calibration equations and time intervals used as well as their explained variance.

Table 3. The calibration models and variance explained of the variables investigated

Variable	Time Period	Calibrating Model	% Variance Explained
Precipitation	1914-2004	29.674x-1.3506	46.0%
Streamflow	1938-2004	$3.4035x^{0.3794}$	40.2%

The results of Table 3 are consistent with known physical dynamics. For example, it is well known that the relationship between precipitation and streamflow is non linear. In the Arbuckle-Simpson aquifer, the situation is complicated further by the fact that the Blue River receives significant spring flow. Thus, the tree rings, which respond to precipitation, appear to be mirroring this non-linear relationship with streamflow even though the specific months used for calibration are not the same.

Figure 17 presents the Arbuckle-Simpson Tree Ring Index and reconstructed precipitation for the fall of previous year and Spring of current year from 1700-1913. The entire series, including the measured precipitation data extends to 2004. Superimposed on the precipitation time series plot is the 5-year running mean. Figure 18 shows the reconstruction of the streamflow time series also with the 5-year running mean superimposed. Appendix 3 lists all of the reconstructed precipitation and streamflow data.

In the following section, this reconstructed series is utilized to investigate drought and dry periods in the Arbuckle-Simpson aquifer.

Hydroclimatic Reconstruction

The first section of this report described in detail the development of the tree-ring chronology for the Arbuckle-Simpson aquifer as well as the use of that chronology for reconstructing the precipitation and streamflow time series for the aquifer back to 1700. This section of the report focuses on the use of the reconstructed data to investigate droughts and periods of water deficits in the Arbuckle-Simpson aquifer. First, it describes the overall pattern of the time series variability, then the basis of the approach used to define droughts. Finally, drought events are extracted from the time series and analyzed.

Analysis of the long-term temporal pattern of variability

The long-term average precipitation (1914-2004) for the reconstruction months is 28.06 in. Figure 19(a) shows the departure of the precipitation time series from this average. Superimposed also is the 10 year-moving average. The plot reveals the wetter than average conditions of the 1970s and 80s. While unprecedented in the instrumental record, wet episodes approaching comparable durations have occurred during the 1740s and 50s, 1810s and 30s, and 1920s. On the other hand, drier than average periods tend to follow (or precede) these wet periods. Thus, notable drier than average conditions persisted in 1860, 1880-1900, and 1960s. In general, it appears that the second half of the 19^{th} century was one of reduced precipitation pattern (Figure 19b). On the one hand, the period experienced many long drier than average conditions but the intensity or average deficit during each event was generally mild. In contrast, the 18^{th} Century events tended to be more 'spiked', i.e. above average wet or dry periods with greater intensity but comparatively shorter duration. It should be kept in mind that towards the beginning of the time series the number of tree cores used in the reconstruction diminishes and so the estimates may not be as robust as in the later parts of the series.

Figure 20 describes similar pattern for streamflow. Again, the moderate conditions during the second half of the 19^{th} Century are noteworthy. Unlike the precipitation series however, the dry conditions of the late 1990s appear much steeper, perhaps suggesting greater sensitivity. It is worth remembering also that the impacts of anthropogenic water withdrawals were not accounted for in the time series.

Establishing a Drought Threshold

Both the definition of drought as well as its analysis depend critically on the threshold value or level at which drought is recognized and extracted from the record (Figure 21, see also Dracup *et al*., 1980; Woo and Tarhule, 1994). The threshold controls every aspect of drought including the event frequency, drought duration, and drought magnitude. The above discussion broadly examined the precipitation and streamflow patterns relative to mean of the instrumental period. In reality, however, the statistical mean is not an appropriate threshold for use in defining drought. To demonstrate this, consider a perfectly random time series. The mean of such time series would perfectly segment the data in two with half the values above and half below. As a result, every other year would experience ‘drought’. Few activities will take hold in a location where drought is expected every other year. Therefore, the ‘true’ drought threshold must be a value lower than the series average. Determining this value is problematic first because of the nature of drought itself and second because of the lack of consensus regarding drought definition. A commonly used drought definition is that it is the deficiency of water with respect to a location, time, and activity for which it is normally adequate. The problems inherent in the above qualitative definition are obvious. For example, how much water is ‘normal’ for the location, time, and activity? Furthermore, what is the magnitude of departure from that normality and for how long should it persist to constitute drought? Researchers have tried to answer these questions using various indicators, including percentiles, recurrence intervals, standard deviation, and the parameters of some underlying probability distribution describing the process under investigation.

For this report, following consultations with the Oklahoma Water Resources Board, it was decided to use as threshold the 5-year recurrence interval because it abstracts droughts that closely match known drought events familiar to the public during the instrumental period. Additionally, there is some indication that the delineated droughts agree with anecdotal evidence from springs and groundwater measurements collected as part of the long-term hydrogeology study of the Chickasaw National Recreation Area (*see* Hansen and Cates, 1994). The 5-year threshold defines droughts that have a probability of occurrence in any given year of 0.2 or events whose inter-arrival time is, on average, 5 years. For precipitation, the 20^{th} percentile value is 22 inches and for streamflow, the 5-year annual flow is 1545 cfs.

Drought Occurrence and Frequency

Figure 22(a) shows the precipitation droughts with the 5-year recurrence intervals since 1700 in the Arbuckle-Simpson aquifer. A number of observations could be made with respect to Figure 22. Based on the 5-yr threshold, 57 drought events occurred in the Arbuckle-Simpson aquifer between 1700 and 2004, resulting in an average interval of 5.33 years between droughts events. The inter-event interval is a function of the *a priori* specification of the threshold. As may be expected, however, these events are not uniformly distributed throughout the time series. In general, droughts were relatively more common and severe during the 1700-1775 year time frame. As mentioned previously, note that a smaller density of tree samples were available during this period. Another period of relatively high frequent drought occurrence is the 1910-1960 time period. In contrast, most of the 1800s were either drought free or experienced only sporadic and mild drought. The period since 1970 also has experienced mild and infrequent drought events.

Drought Magnitude and Long-term Return Frequency

Figure 22 provides also information on drought magnitude. It shows that four of the most severe droughts occurred during the early to mid 1700s. The worst drought during the entire period was in 1707 when the precipitation deficit relative to the 5-year threshold reached 13.8 in. Other severe droughts occurred in 1855 and 1910-11. The 1910-1911 drought was the most severe (intense) during the period of instrumental record. Yet, with benefit of the reconstructed proxy series, we see that the severity of 1910-1911 event was equaled or exceeded four times between 1700 and 1910. Thus, we see that rainfall departure of this magnitude occurs about once in 60 years. Note that there has been no event of comparable severity since 1911 but the results above indicate such severity is not unusual and is therefore likely to occur again. Another drought that seems to resonate in people's consciousness in Oklahoma is the 1953 drought when only 17.08 inches of precipitation were received in the Arbuckle-Simpson aquifer during the reconstruction months. Such rainfall deficit has not been exceeded since 1953. Note however, that such deficit was exceeded twice (1910-1911) during the instrumental period and nine times during the reconstructed time series. In terms of probability therefore, there is a 3% chance that a drought of such magnitude or worse will occur in any given year. While relatively small, it is important to note that both of the above probabilities are higher than those obtained during the instrumental records alone (i.e. 0.9% and 2.65% respectively). Thus, the reconstructed time series permits allows us to estimate especially the probabilities of low frequency events with greater confidence than would be possible with shorter record length.

A similar plot for the reconstructed streamflow time series can be interpreted in the same manner (Figure 23). Here, the worse drought during the instrumental period occurred in 1939, followed by the 1956 drought and, interestingly, the 2000 event. Figure 24 shows the cumulative probabilities of the precipitation and streamflow series for the entire 300-year period. The figure indicates that the above droughts have, respectively, the following long-term probabilities of occurrence: 1.80%, 2.13%, and 3.45%. The differences between the most severe drought years identified from the streamflow and precipitation time series may indicate the non-linear nature of the relationship between the two variables. However, two other possibilities must be kept in mind. First, the months used in aggregating and reconstructing the two variables are different (see Table 2). Second, anthropogenic impacts, principally water withdrawals, which will affect streamflow values more directly than precipitation, were not accounted for.

Drought Duration

The selected precipitation threshold is equaled or exceeded 10 times by events lasting up to two consecutive years during the 300-year proxy record. Statistically therefore, one may expect such event to occur, on average, once in about 30 years. No droughts longer than two years were observed at this threshold. For streamflow, nine droughts of two-year durations occurred during the same period and one three year event between 1742 and 1744. However, owing to the manner in which the data are aggregated, i.e. specific months of the year as opposed to an actual calendar or water year total, the interpretation of drought duration must be conducted with care. It is possible that the droughts may have broken during the intervening months not included in the reconstruction. With that qualification, we can state that about 20% of the time, the drought that occurs about once every five years in the Arbuckle-Simpson aquifer will persist for multiple years. In general however, droughts lasting a single year are much more common for the threshold analyzed.

Summary and Conclusions

This study has produced a 304-year tree-ring chronology of the Arbuckle-Simpson aquifer to support decision-making on long-term water resources management and facilitate communication with stakeholders. The chronology developed specifically for this study is based on 31 living Post Oak samples and is 229-years (1775-2004). It agrees strongly with another Post Oak chronology in the study area produced by Dr. David Stahle at the University of Arkansas, Fayetteville, allowing us to combine the two by simple averaging to produce a new chronology with a greater number of samples that extends from 1700-2004.

Calibration and reconstruction were based on correlation function analysis. The results indicate that for precipitation, the months that most influence tree-ring width comprise precipitation in the fall of the previous year and the spring of current year. Based on a simple linear regression model, the average precipitation during these amounts explains 46% of the variation in ring width, which is statistically significant at $p < 0.00001$. Thus, the tree-ring indices (TRI) could be used with confidence to derive proxy estimates of the precipitation.

For streamflow, the months showing significant correlations with the residual tree-ring chronology are the summer to fall months of the previous year and summer months of the current year. These months explain 40% of the variability in tree-ring width, again statistically significant at $p < 0.0001$.

For many applications, the ideal situation would be to reconstruct the annual totals or averages of these variables. However, a reconstruction is possible only if there is a strong statistical basis and physically meaningful basis for doing so. These constraints limit the applicability of tree-ring based reconstructions. There is evidence also to suggest that most calibration models tend to have reduced variance in the low end i.e. dry years. The significance of this is that dry years can be reconstructed with greater accuracy than wet years.

Based on practical consideration, the magnitude of drought that occurs on average once in 5 years was used as the threshold for extracting droughts from the reconstructed series. For precipitation, this threshold numerically is 22 inches. It indicates that the first three fourths of the 18th Century had more frequent and severe droughts. Four of the most severe droughts during the entire period occurred during this time. It is unclear whether reduced sample depth plays a role in this pattern. The first half of the 20th Century also witnessed frequent droughts with moderate to severe droughts. The 1800s experienced the mildest and least frequent droughts. Also the last three decades have been relatively drought free. The reconstructed streamflow series shows generally similar pattern although the droughts of the last three decades rank among the most severe. This may be a function of the non-linear relationship between precipitation and streamflow or it might indicate anthropogenic impacts on the hydrologic system.

Multi-decadal droughts are rare to non-existent at this threshold. This finding is very significant because a key objective of this study is to provide the long-term climatic context against which to evaluate both contemporary droughts as well as the risk of multi-decadal drought. As emphasized throughout the report, however, drought characteristics are a function of the threshold used to define them. Thus, a different threshold will certainly yield drought events with different frequencies, durations, and intensities. On average, droughts lasting two years or longer occur about once every 20 years for both precipitation and streamflow. Yet, the interpretation of multiple year droughts must be done with care because of the manner in which the reconstructed data were aggregated. Thus, droughts lasting one year are much more common.

Finally, the recurrence intervals of the most severe droughts observed during the instrumental period are relatively low. These findings suggest that while periods of variability have occurred in both the precipitation and streamflow time series, the Arbuckle-Simpson aquifer as a whole can be said to have experienced relatively stable hydroclimatic conditions during the past three decades. There does not appear to be evidence in support of increasing desiccation or wetness based on the tree-ring index. This conclusion must necessarily be qualified by the following constraints or possible complicating factors: (i) the effect of anthropogenic water withdrawals was not accounted for. However, factoring in water withdrawals will increase the streamflow amounts and therefore is not likely to increase drought severity; (ii) the droughts analyzed here are drought with expected recurrence interval of 5 years. Using a different, less stringent threshold may produce drought time series with different characteristics.

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Acknowledgments

This study was funded by a subcontract from the Oklahoma Water Resources Board. I thank Robert Fabian and Noel Osborn for the tremendous logistical support they provided. Rachel Turney conducted most of the fieldwork and laboratory analysis. Dr. David Stahle's Arbuckle tree-ring chronology was accessed from the International Tree Ring Database (http://www.ncdc.noaa.gov/paleo/treering.html), which is maintained by NOAA's Paleoclimate Program. Dr. Biondi provided his DENDROCLIM2002 program for free and is gratefully acknowledged. I am indebted to Prof. Peter Waylen of the University of Florida, Gainesville, for his advise on the statistical analysis. Finally, numerous landowners willingly allowed us access on their lands and very generously gave of their time in helping us locate suitable sampling points. Deserving special mention are Dr. Randall Ross, who offered his land and introduced us to many landowners, Jim Erwin of the Pontotoc Nature Preserve, Ms Laurie Williams, who gave us a great tour of her ranch and showed us trees we would never have located on our own; The Life Style Center, Steven Jolly of the Arbuckle Master Conservancy Center and most important of all Mike and Donna Warren. This study would not be possible without your assistance.

Diagrams

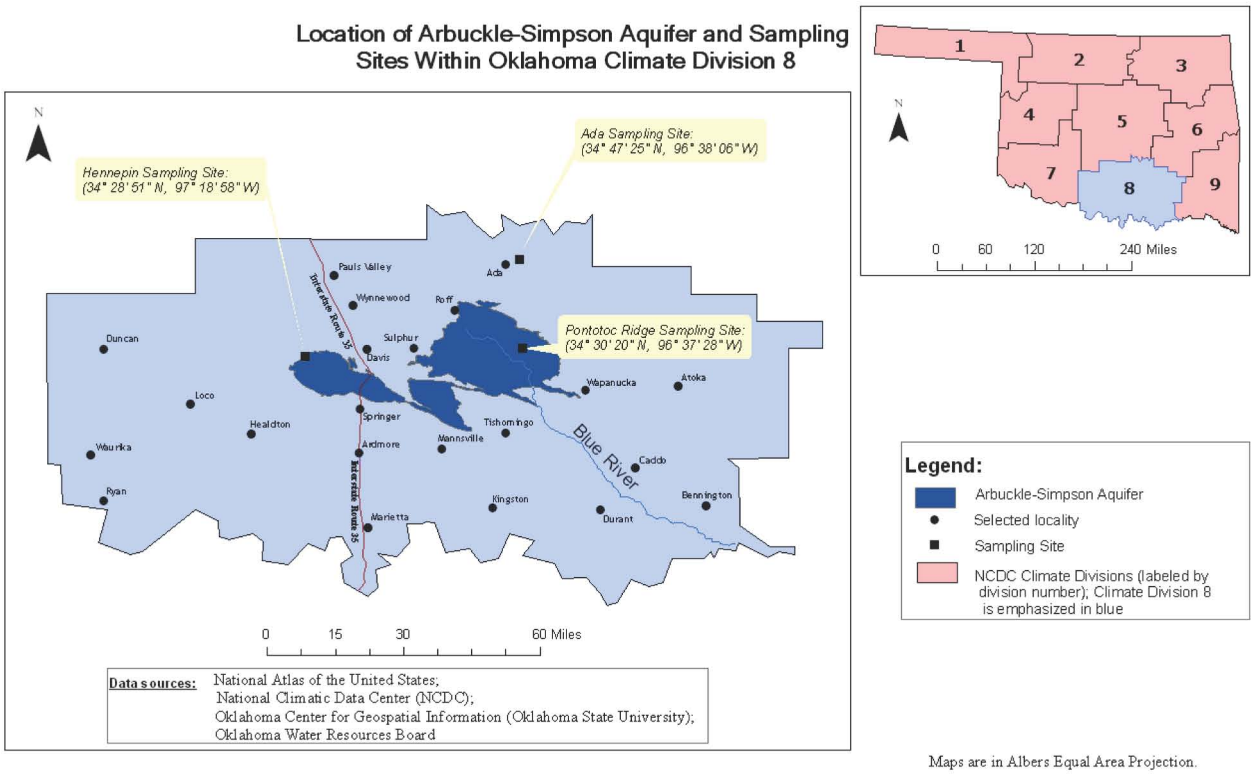


Figure 1. Location of the Arbuckle-Simpson Aquifer in Climate Division 8 in Southern Oklahoma.

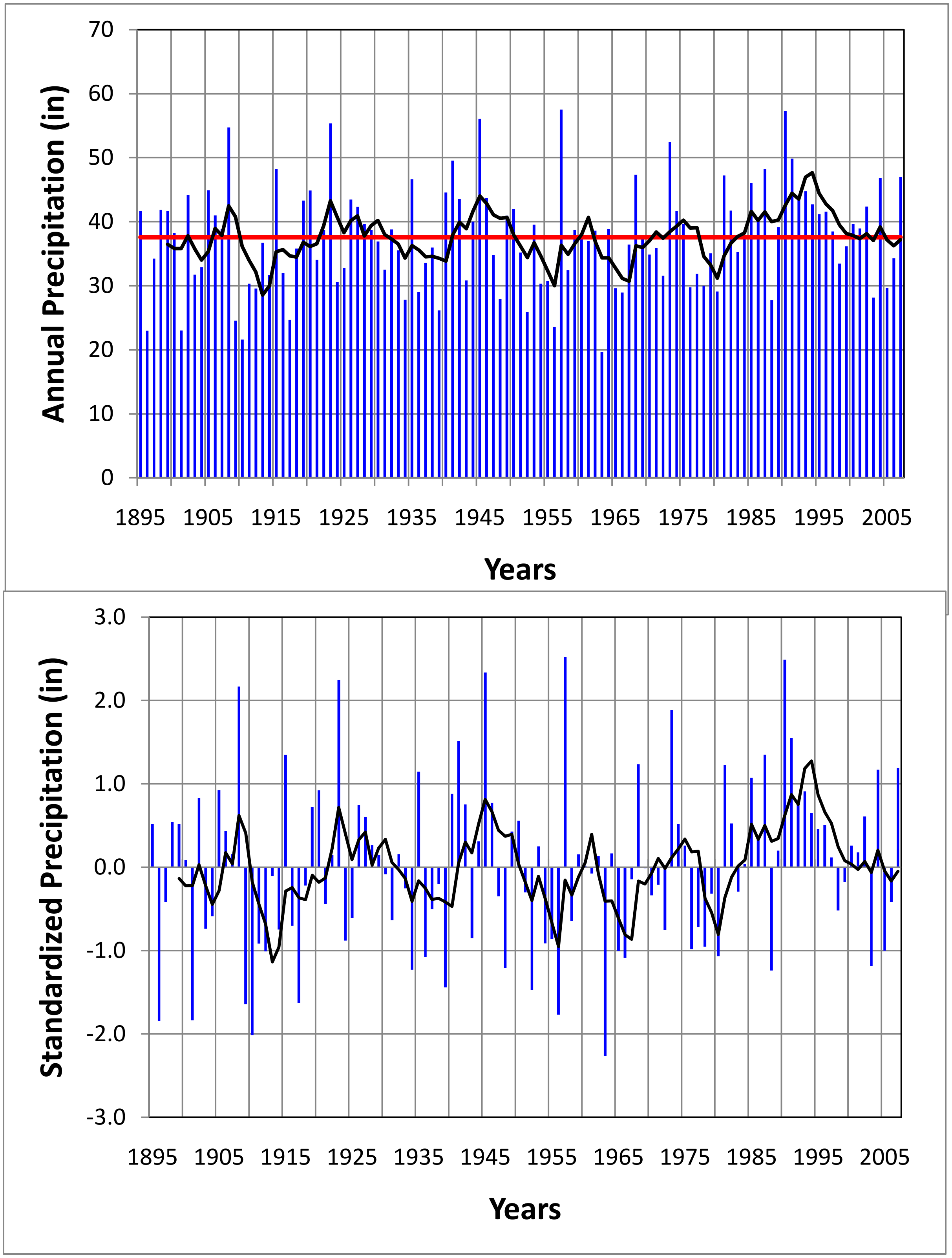
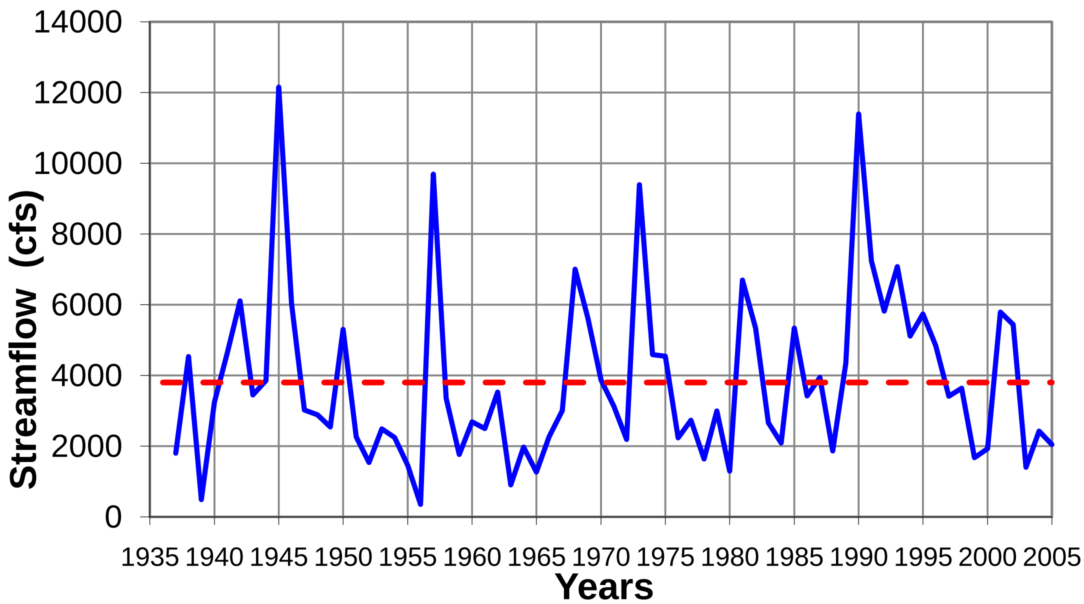


Figure 2. Top panel: Total annual precipitation for all gauging sites in OKCD8. The red line is the long-term (1895-2007) mean precipitation, black line is the 5-year moving average; Lower panel: the standardized annual precipitation index for OKCD8 normalized with respect to the long-term mean.



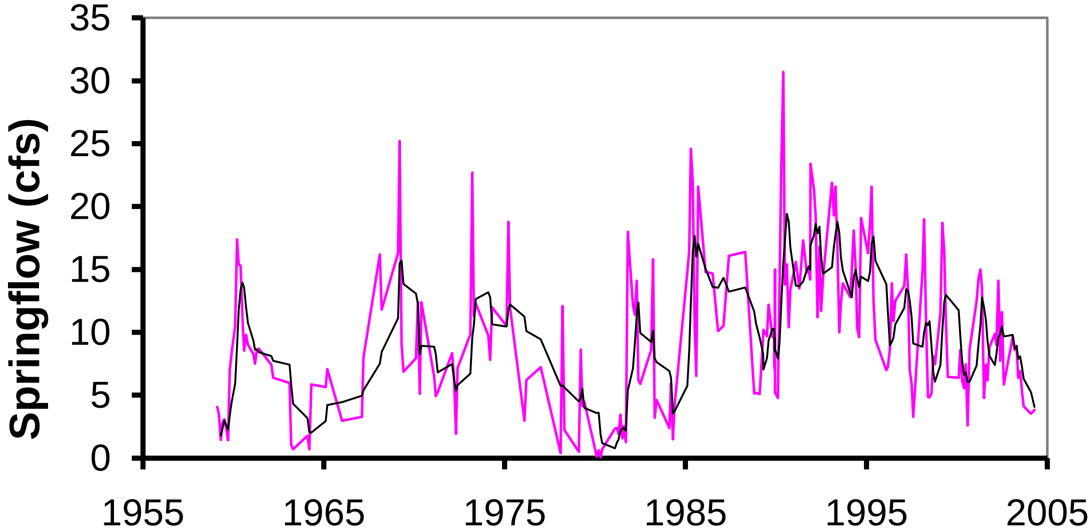


Figure 3. Top panel: Total annual streamflow of Blue River near Blue, Oklahoma (USGS 07332500). The red dashed line is the long-term average flow. Bottom panel: Annual flow of Byrds Mill Spring near Fittstown (USGS 07334200). The flow measurements were taken at irregular intervals. Amounts of water diverted through a 36-in. pipe to Ada upstream of the measurement points have not been factored into the plotted flow amounts.

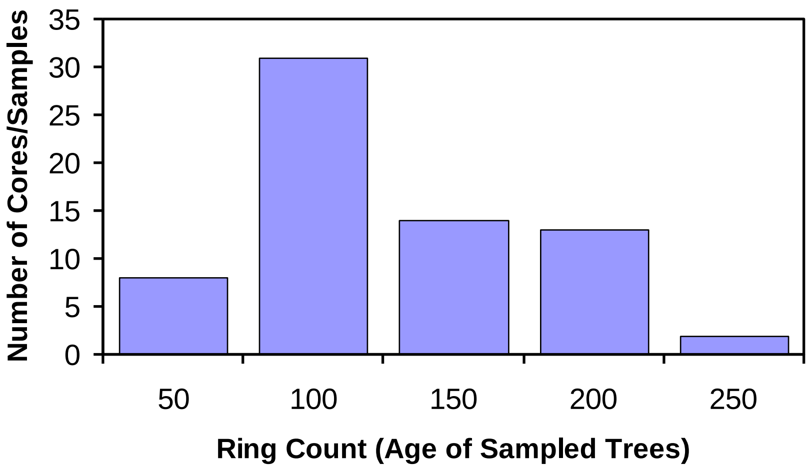


Figure 4. Frequency distribution of the number of samples in various age groups. The total number of cores is 68 from 31 individual trees. The samples come from all three sampling sites.

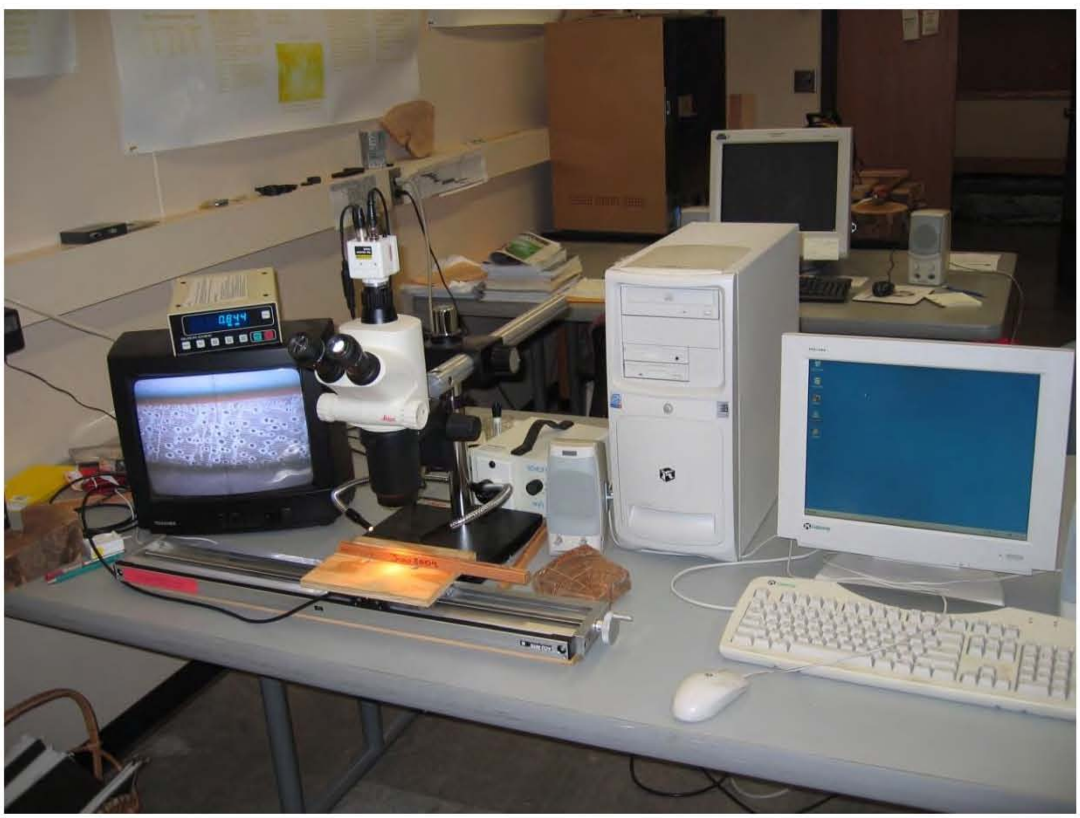


Figure 5. The Velmex ring width measurement system at the Laboratory for Tree Rings Research at the University of Oklahoma.

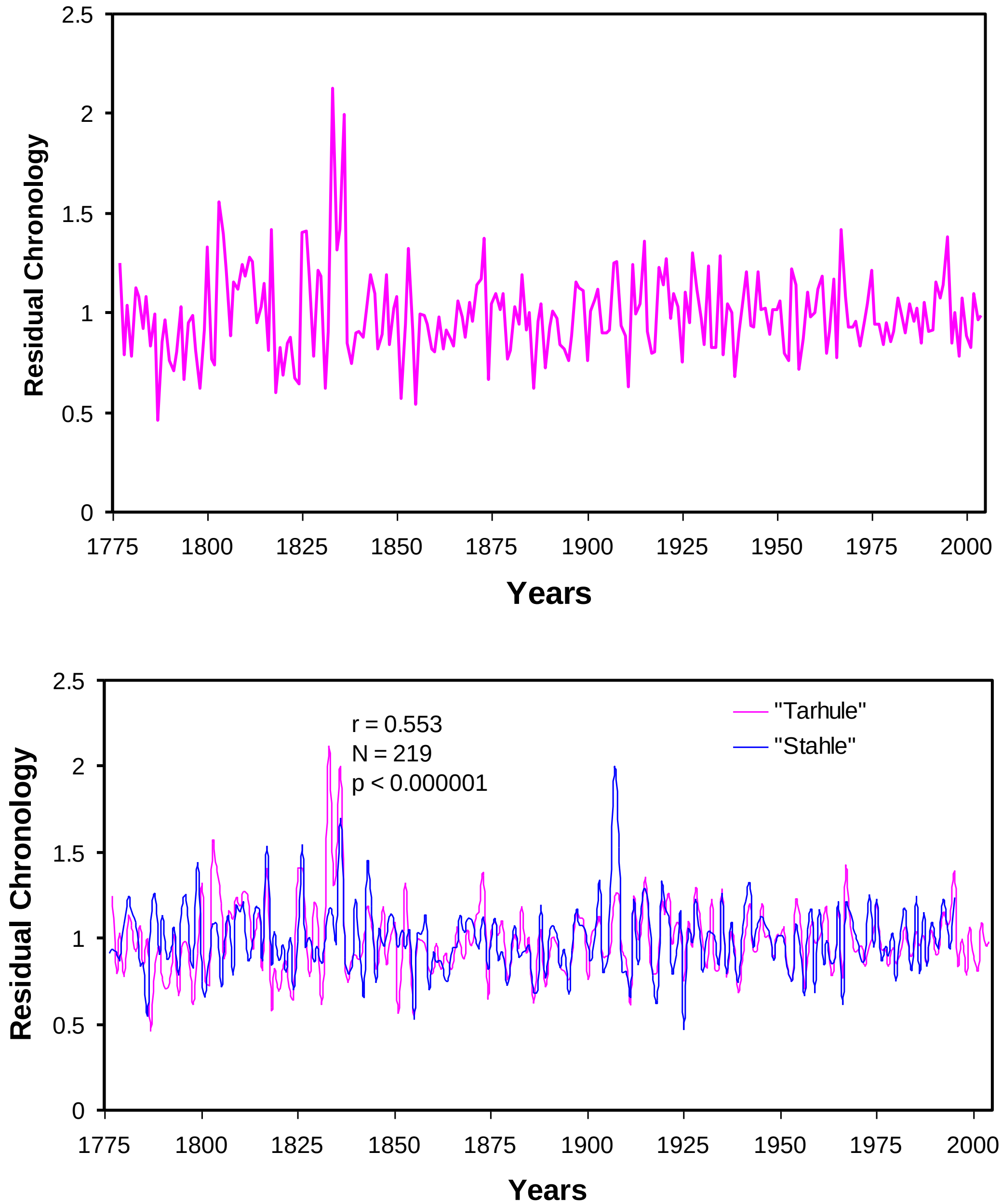
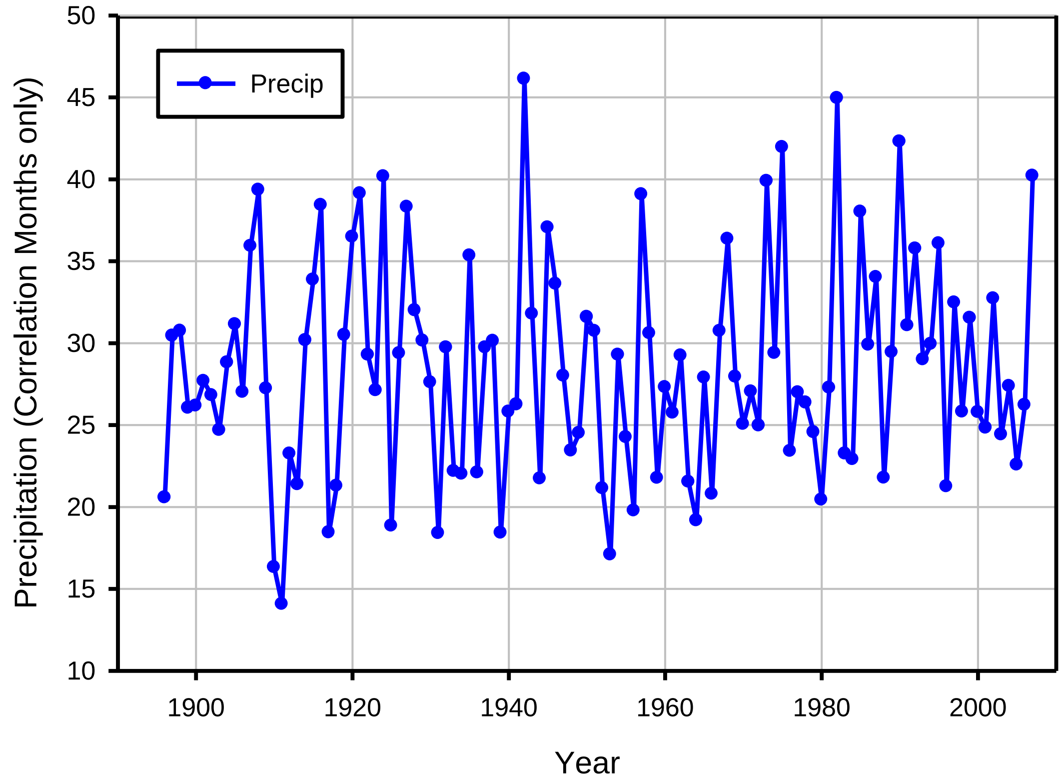


Figure 6. The Post Oak residual chronologies for the Arbuckle-Simpson aquifer produced in this study (top panel) and Dr. David Stahle of the University of Arkansas (lower panel). The two chronologies were averaged because of their strong statistical agreement.



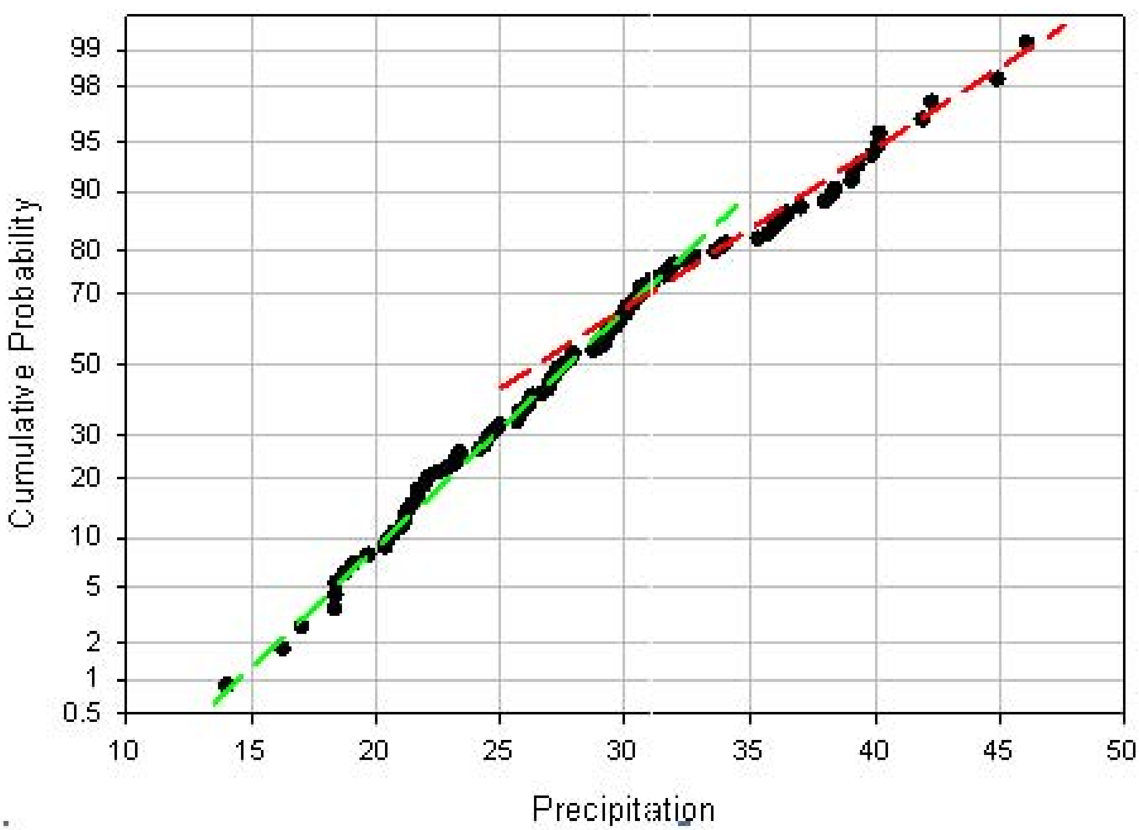


Figure 7. Upper panel: Plot of the total rainfall for the months to be used for calibration and reconstruction. Lower Panel: Cumulative probability plot of the precipitation time series shown in the upper panel

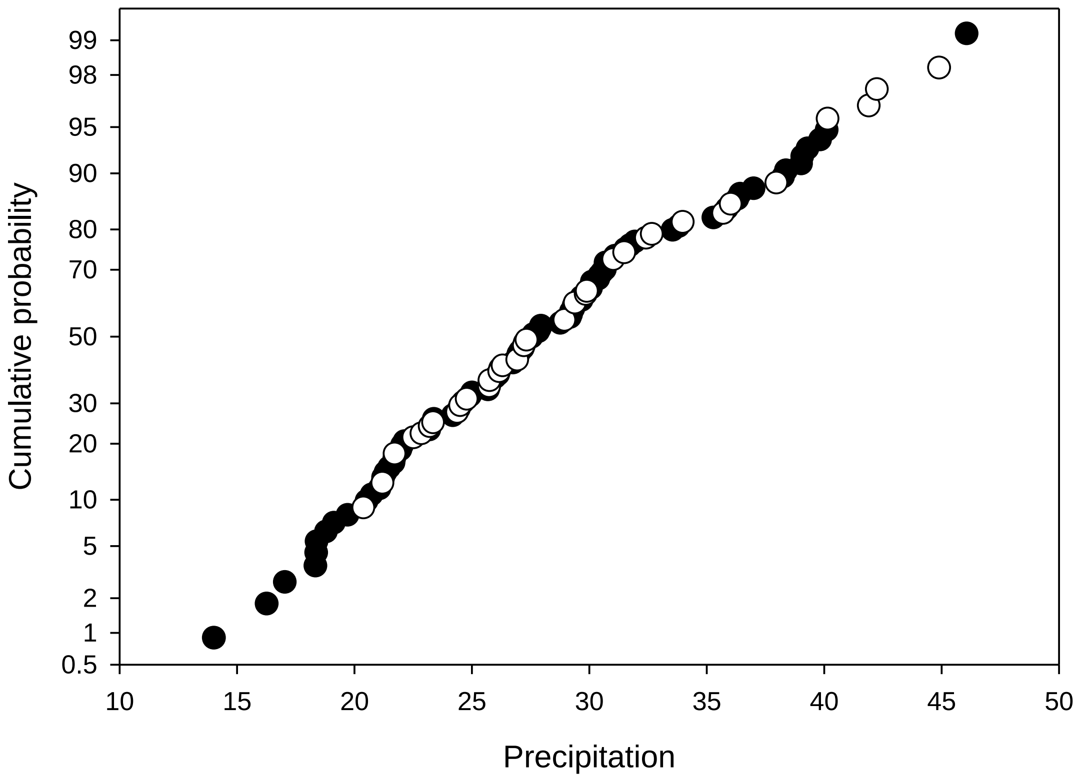


Figure 8. The cumulative probability plots of the two sub segments of the precipitation time series superimposed. The series was segmented in 1975. Black dots plot the probabilities of the first time period and white dots are the probabilities of the second time period.

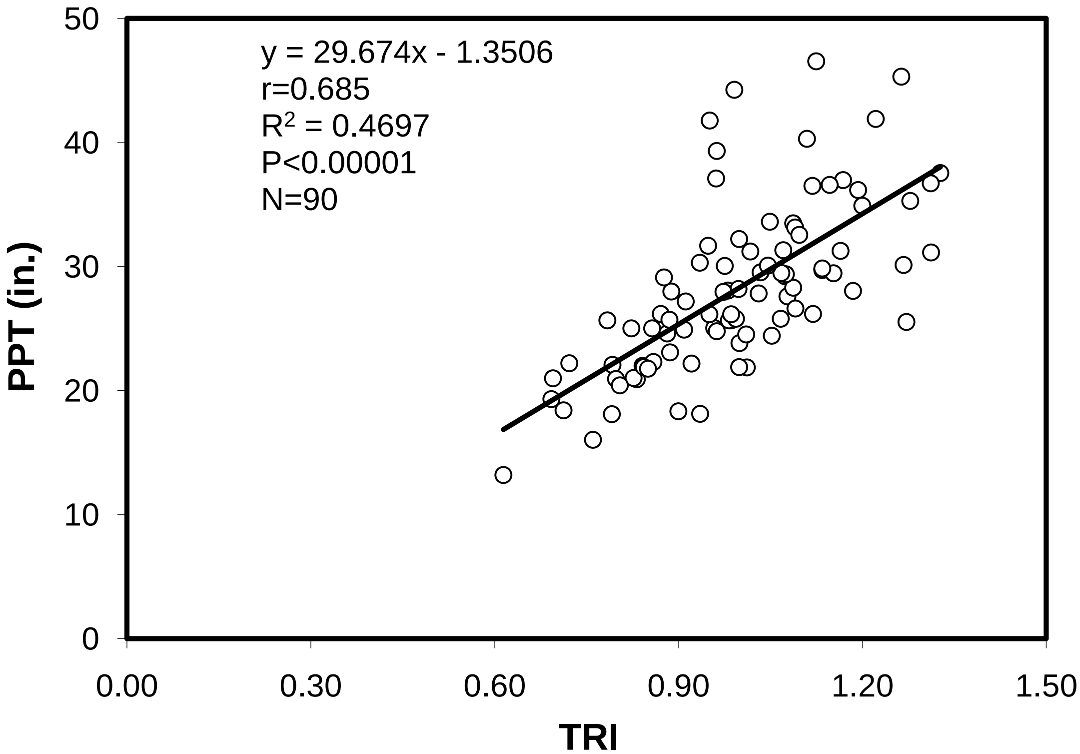
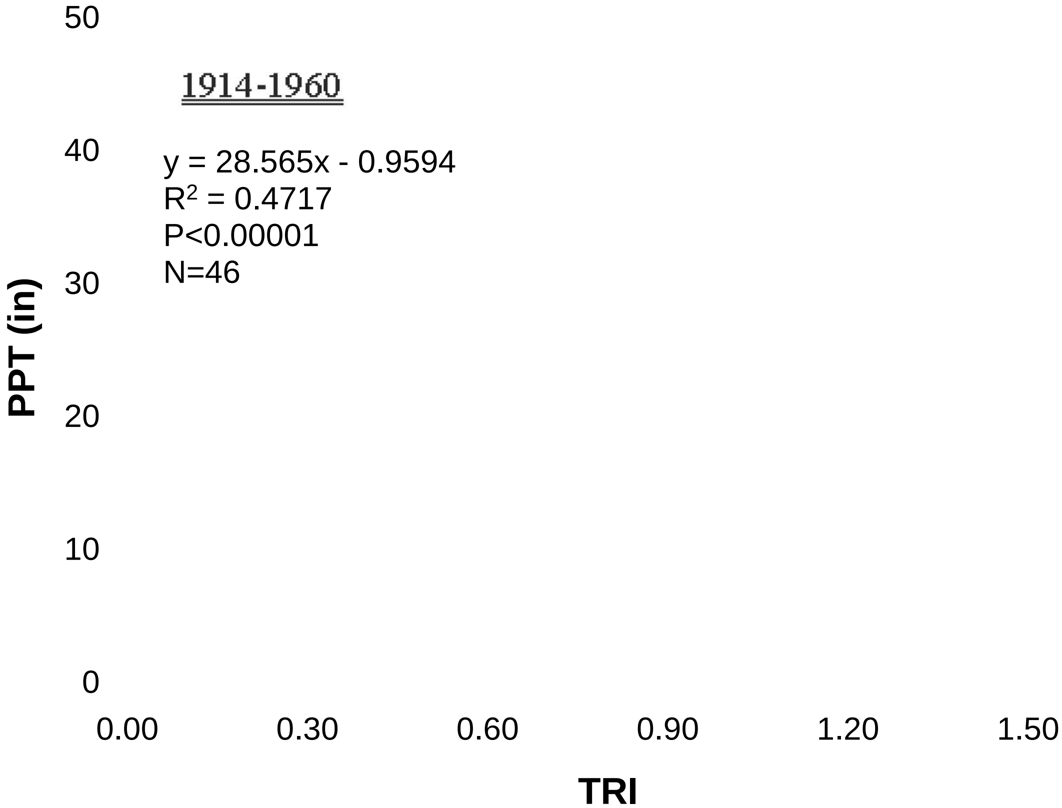


Figure 9. Relationship between total precipitation and tree-ring index.



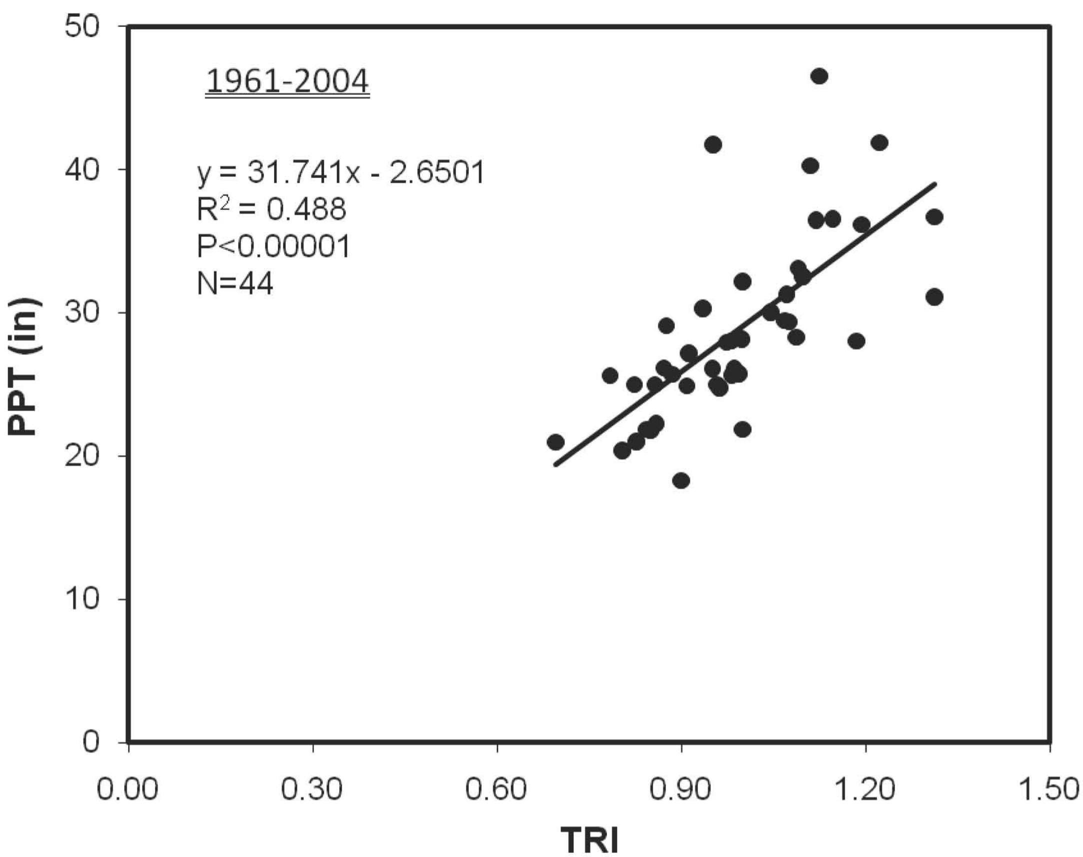


Figure 10. Calibration equation models for each of the two periods used for verification

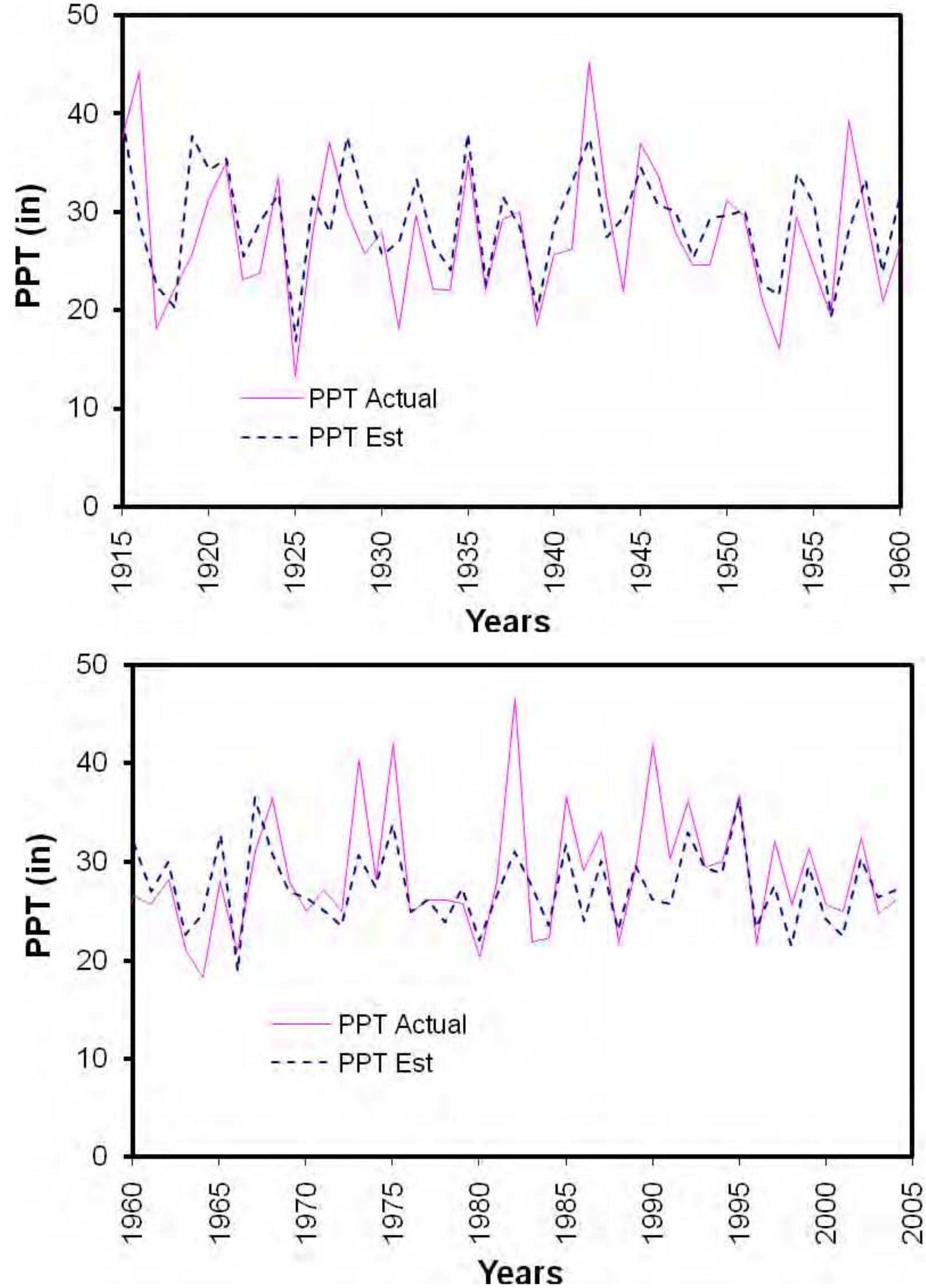


Figure 11. (a) Actual precipitation for 1915-1960 estimated using the calibration equation derived for 1961-2004. (b) Actual precipitation for 1961-2004 estimated from the calibration equation derived for 1915-1960.

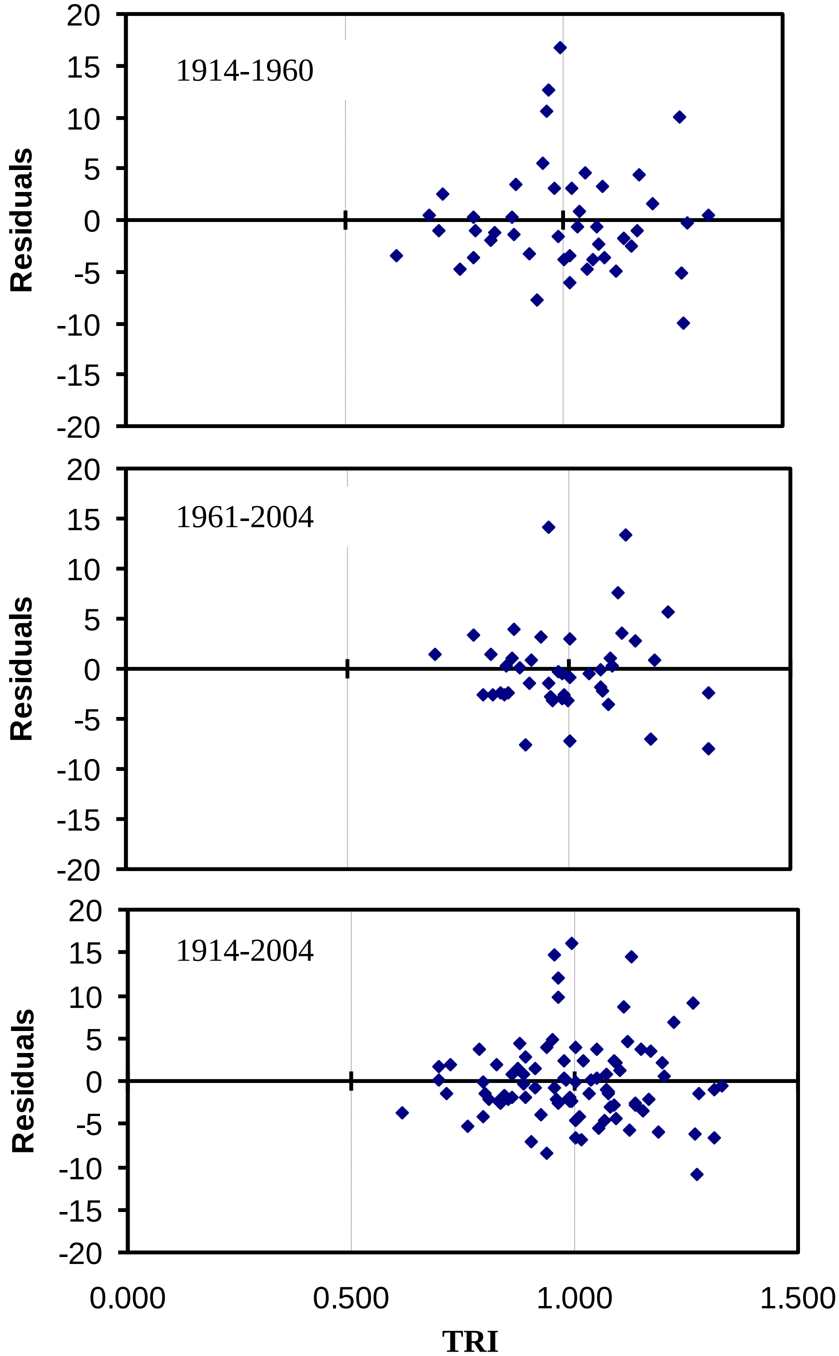


Figure 12. Plot of residuals for the precipitation calibration intervals. The top panel shows the residuals obtained from estimating precipitation for the period 1914-1960 using the calibration equation for the second time period. The middle panel is the residuals from estimating the precipitation for the second period using the calibration model for the first period. The bottom panel shows the residuals from the entire series using the calibration model for 1914-2004.

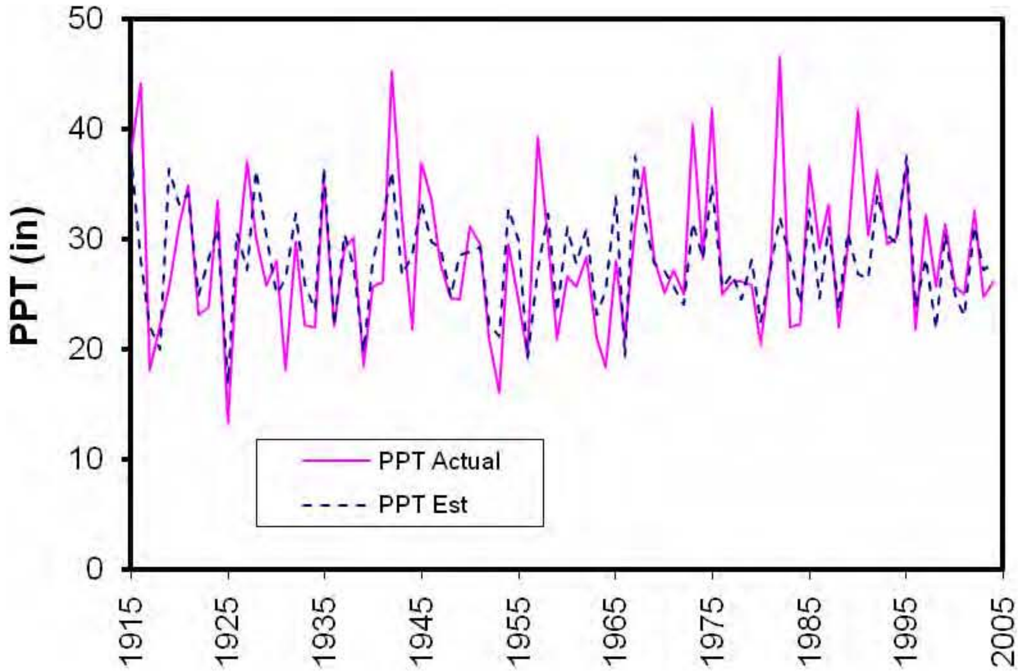


Figure 13. Estimated and actual precipitation for the entire series of precipitation.

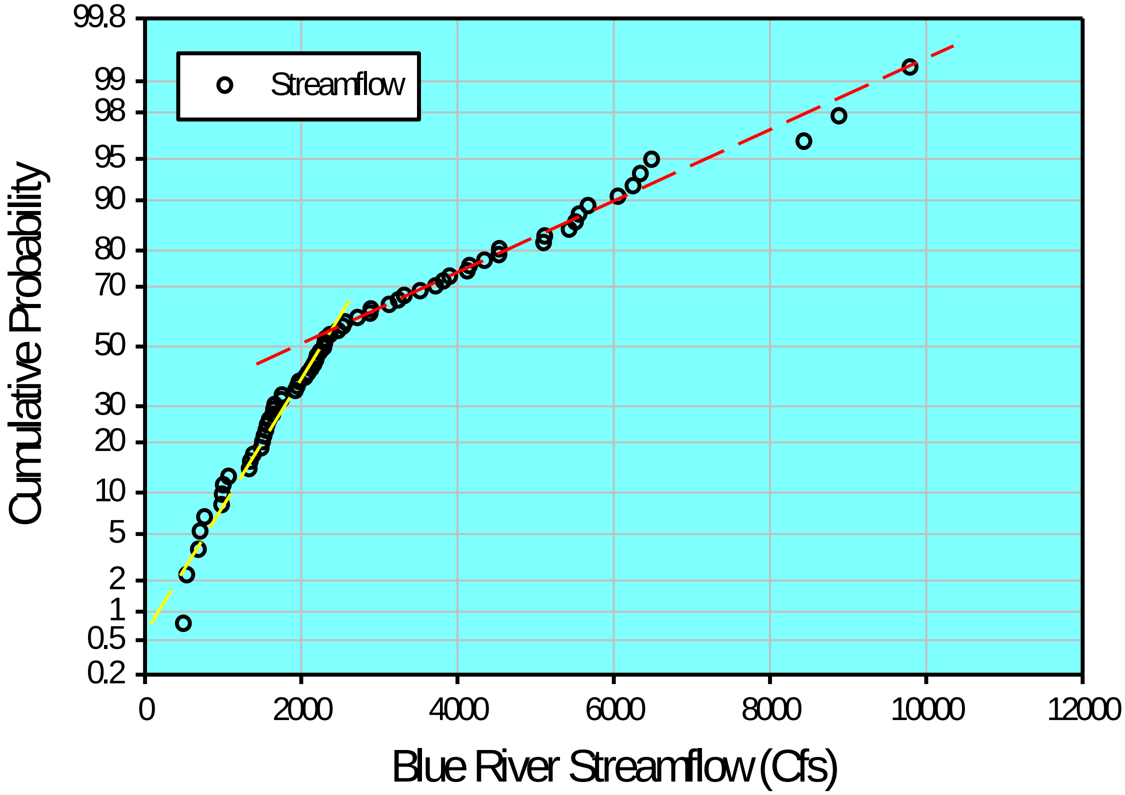


Figure 14. The cumulative probability plot of the streamflow data for the Blue River measured at the Blue gauging station.

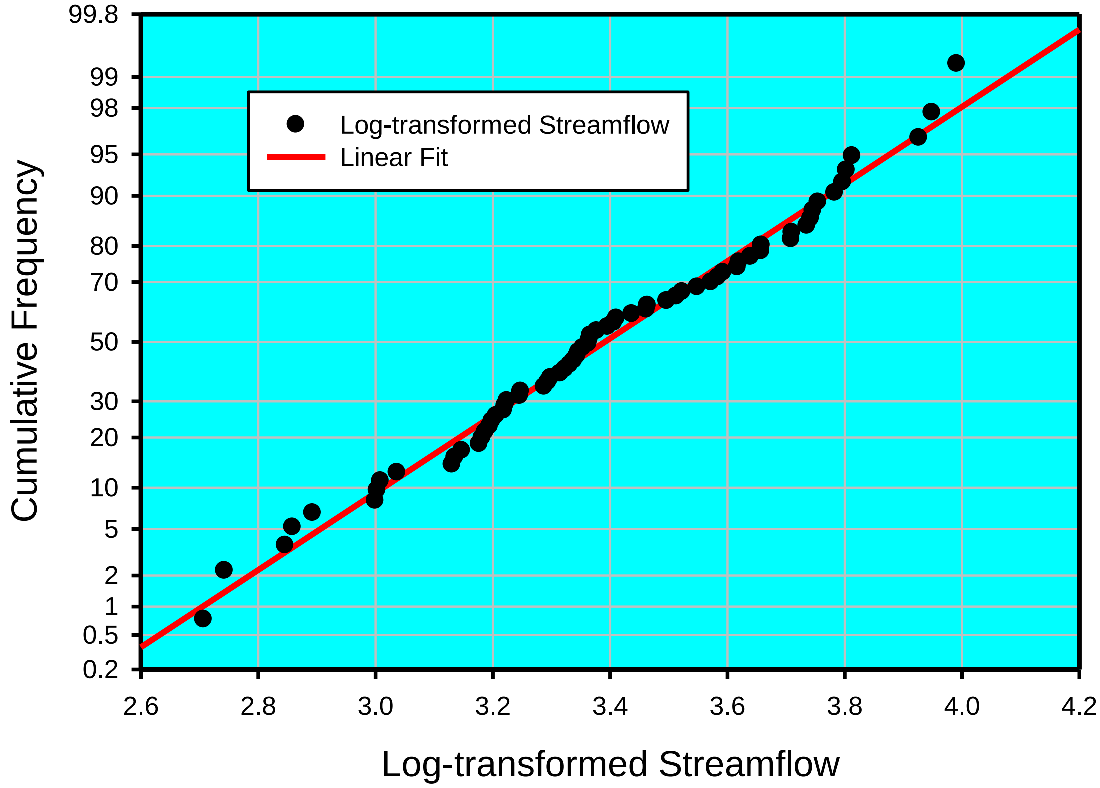


Figure 15. Cumulative probability plot of the log-transformed streamflow values for Blue River near Blue.

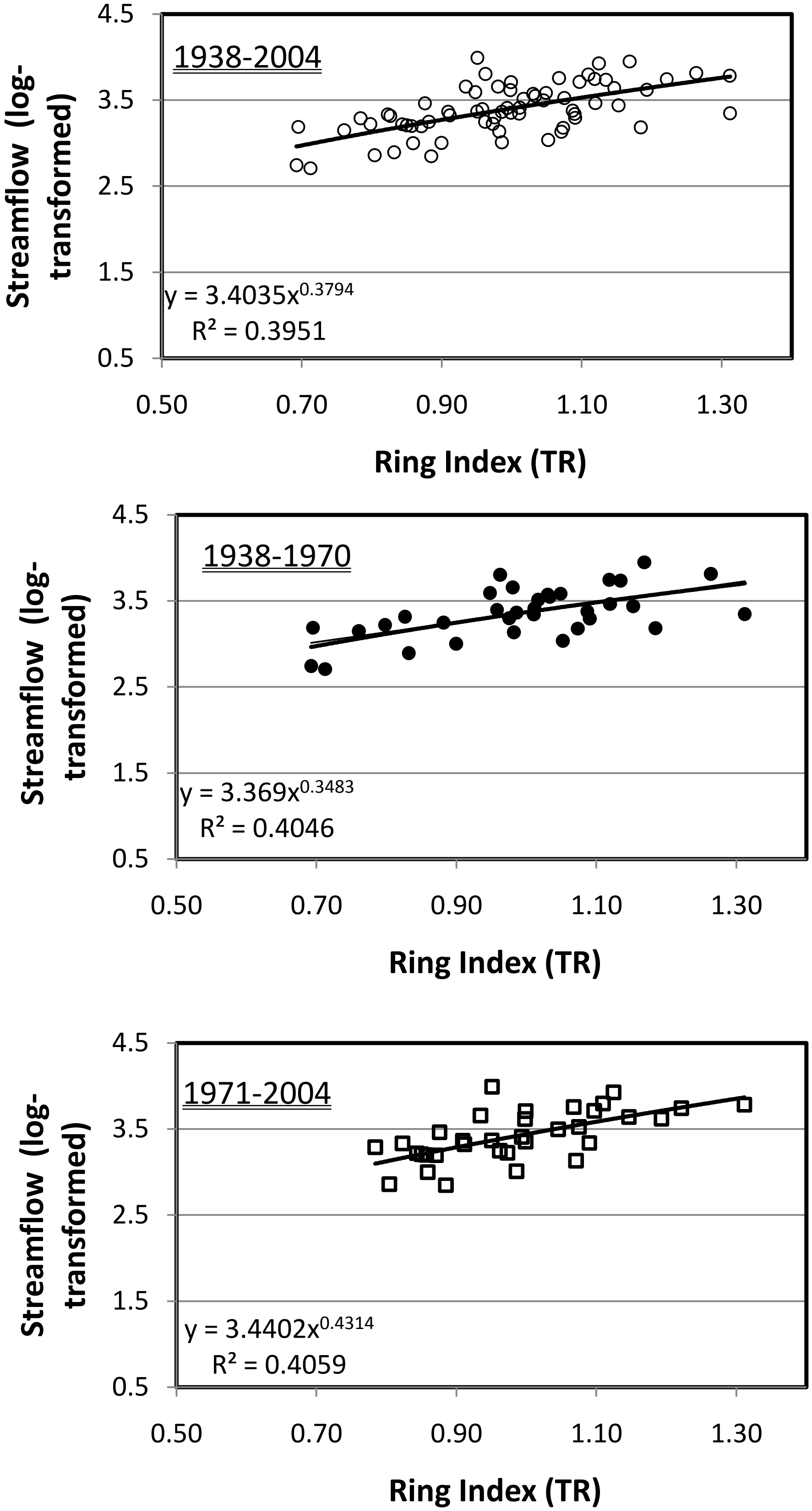
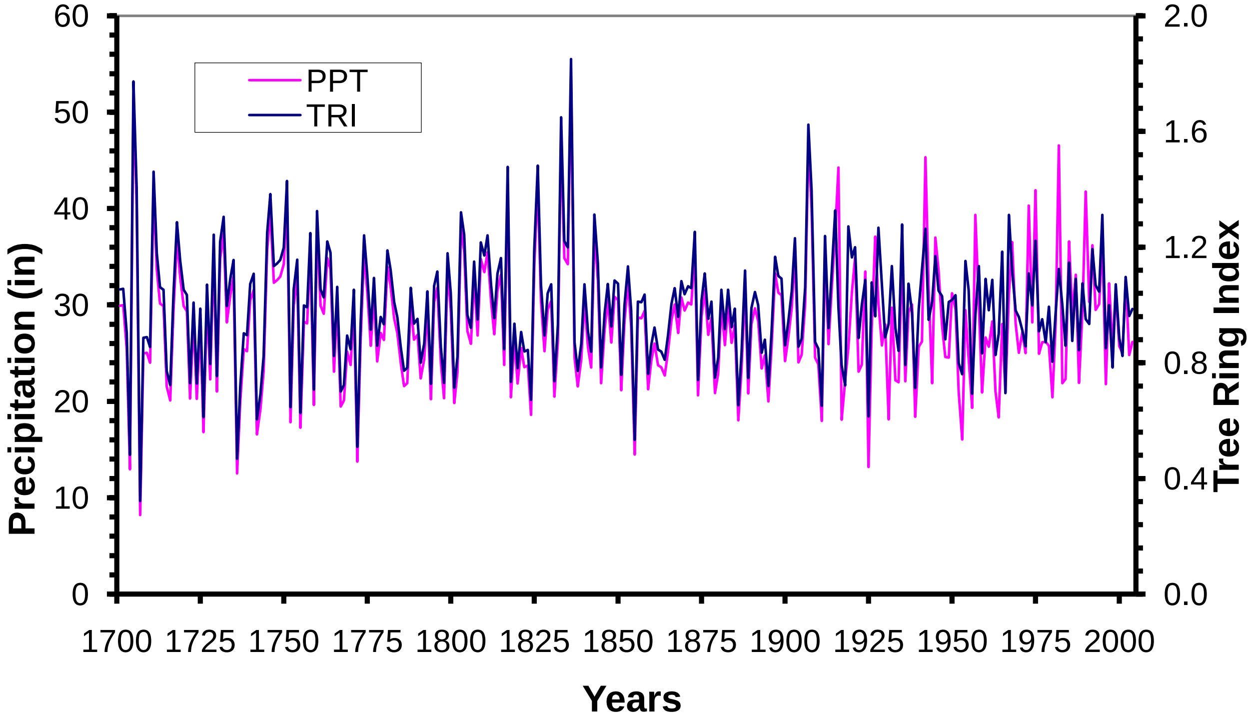


Figure 16. Calibration models for streamflow



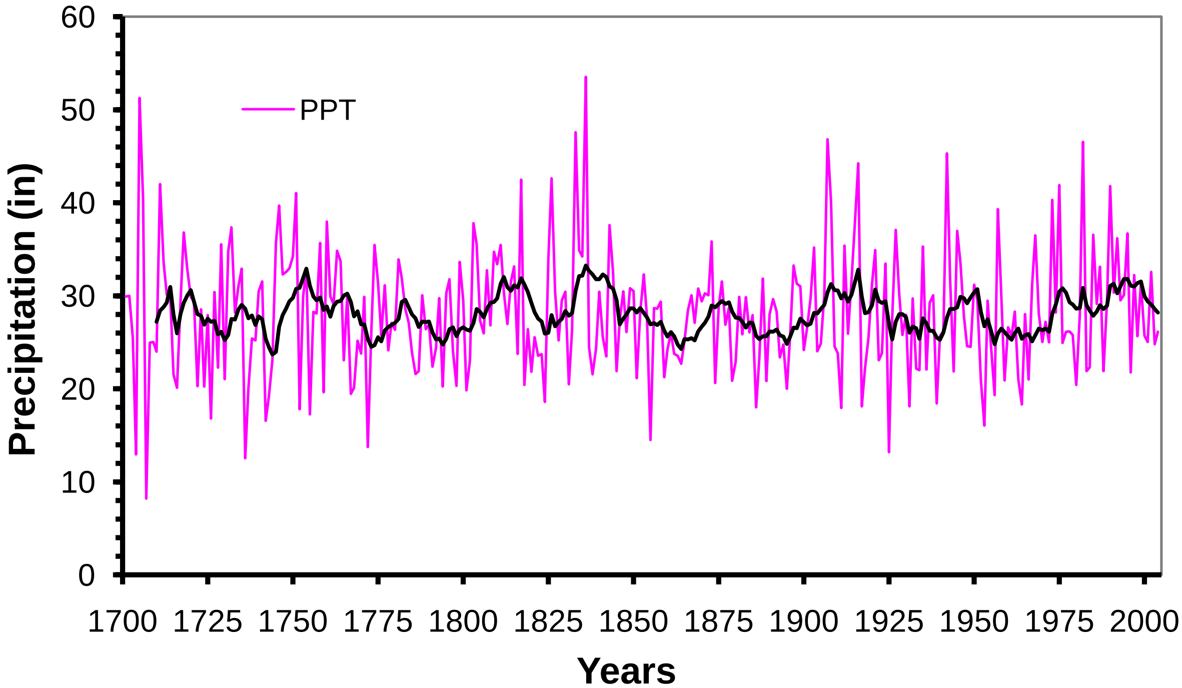


Figure 17. Top panel: The combined Arbuckle-Simpson aquifer tree-ring index (blue line, right axes) and precipitation (purple line, left axes) from 1700-2004. The data from 1913-2004 is the actual measured precipitation. Bottom panel: The precipitation time series with 5-year moving average superimposed.

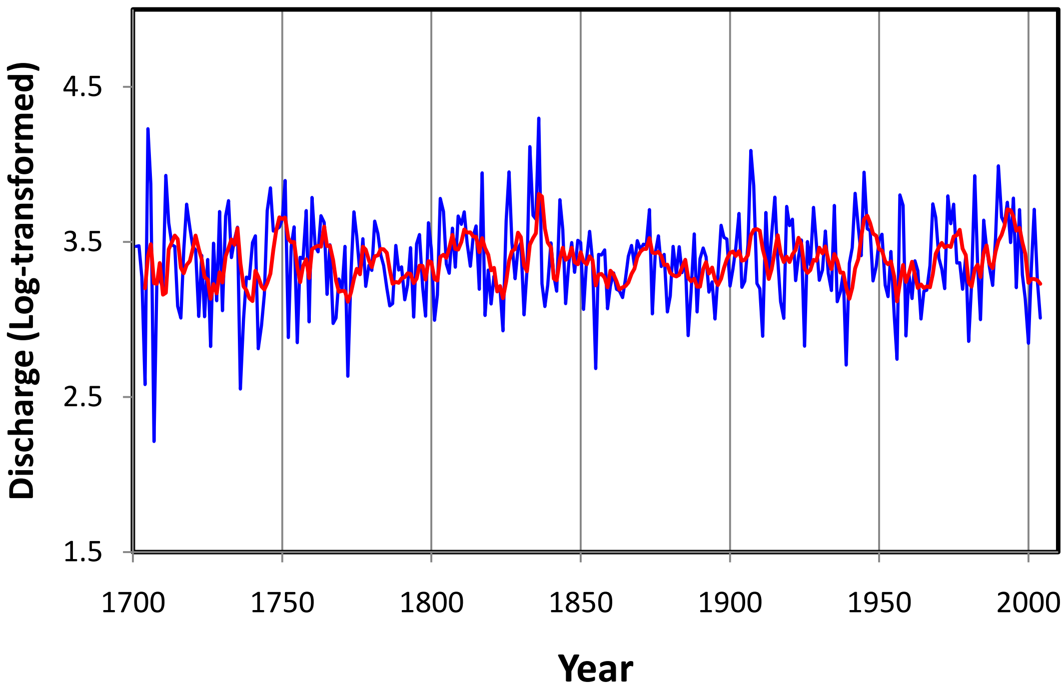
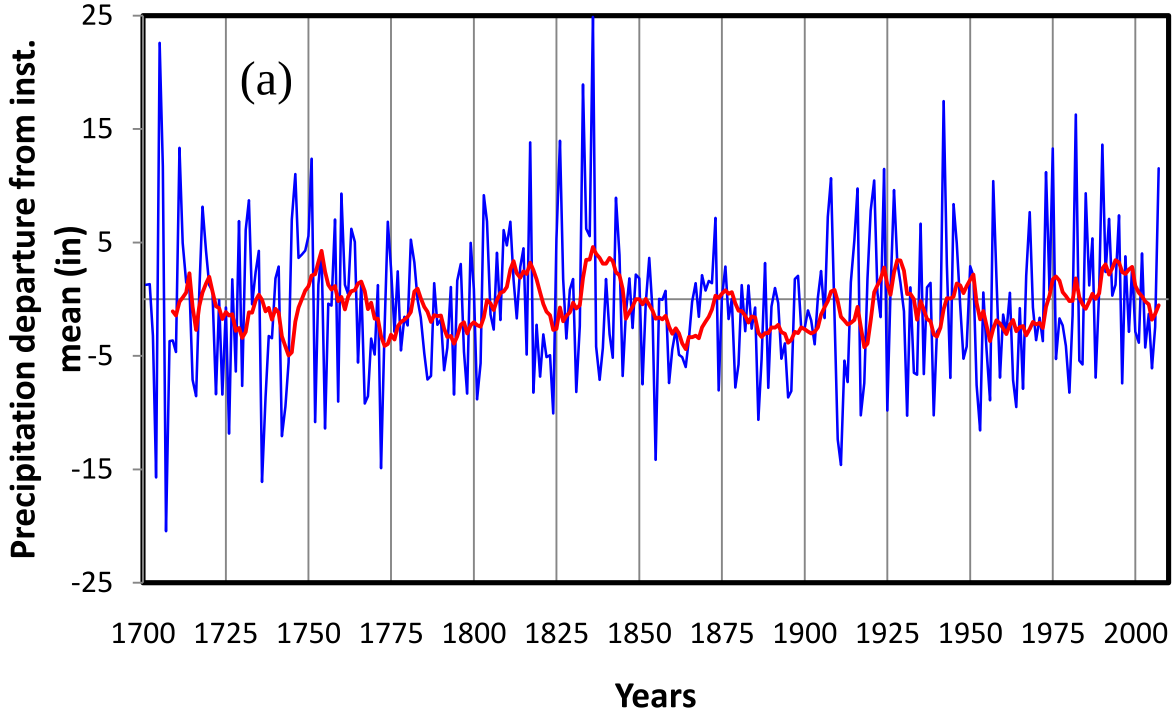


Figure 18. The reconstructed streamflow time series for the Arbuckle-Simpson Aquifer. Red line is the 5-year moving average.



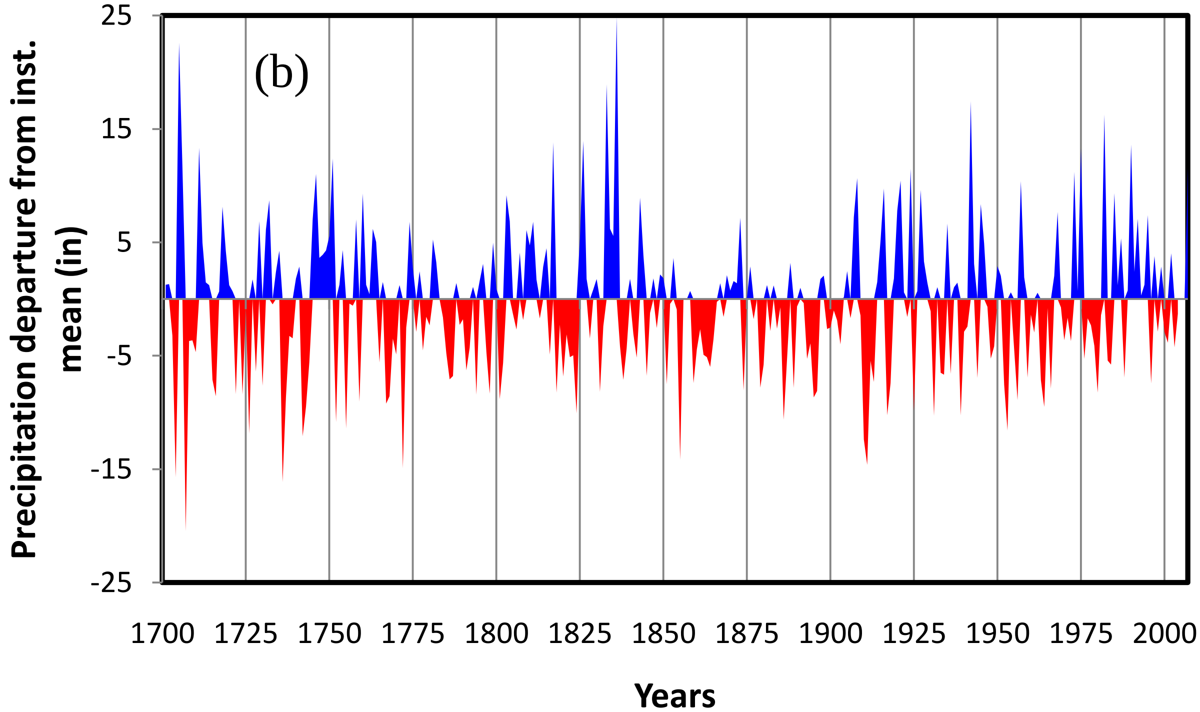
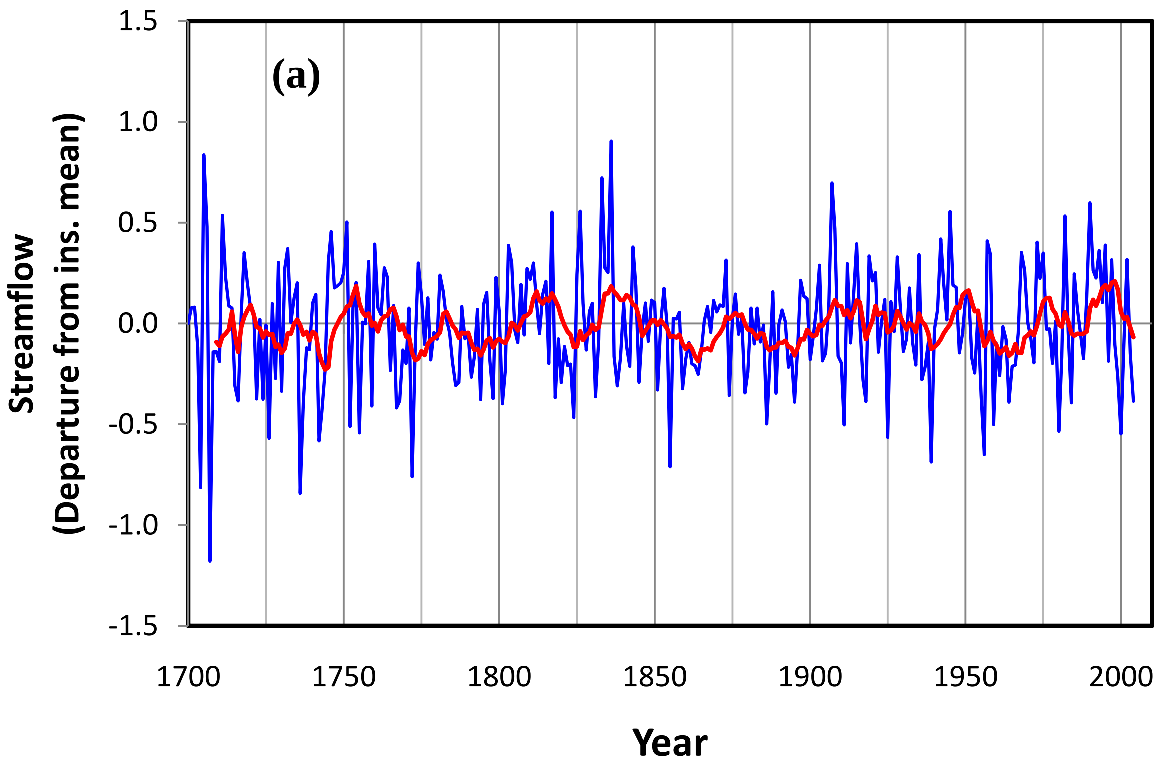


Figure 19 (a) Plot of the reconstructed precipitation showing the departure of the series from the mean precipitation during the instrumental period. Red line is the 10-year moving average.
(b) Same as in (a) but shown as an area plot to give an indication of drought duration.



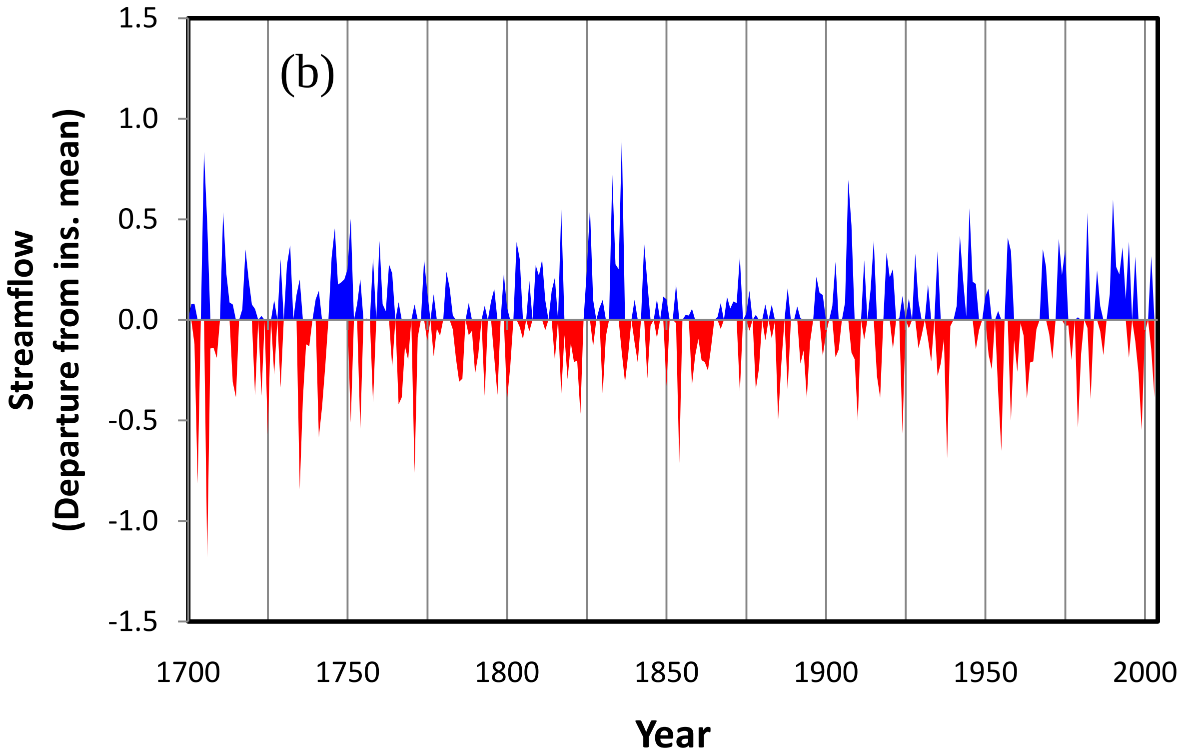


Figure 20(a) Plot of the reconstructed streamflow showing the departure of the series from the mean streamflow during the instrumental period. Red line is the 10-year moving average.
(b) Same as in (a) but shown as an area plot to give an indication of drought duration.

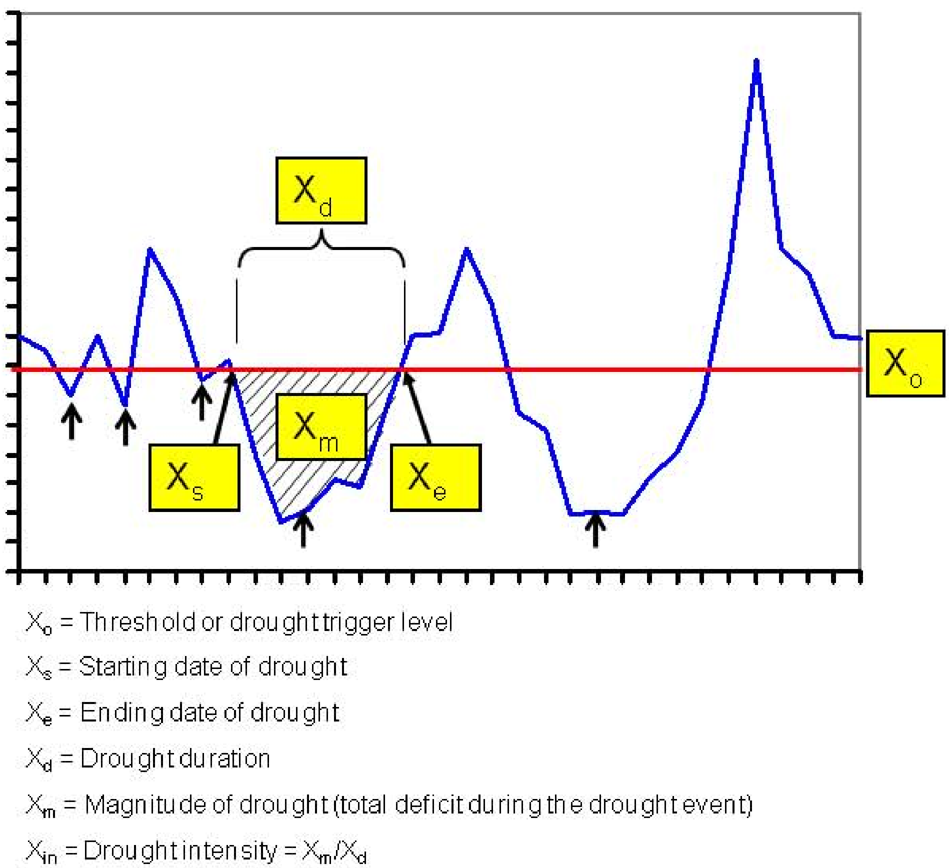


Figure 21 Drought concept and terminology

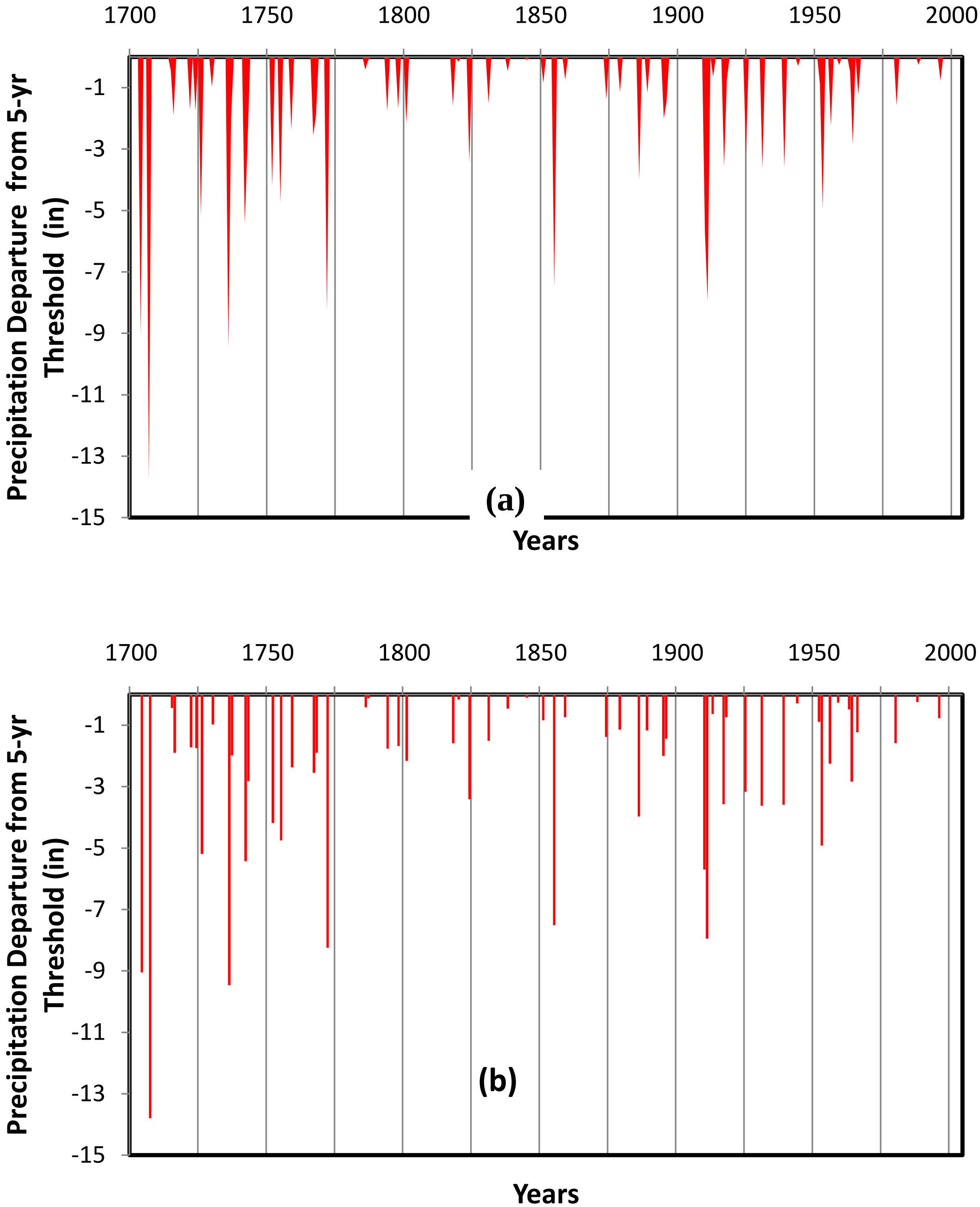


Figure 22. The 5-year drought series in the Arbuckle-Simpson aquifer based on reconstructed (1700-1914) and instrumental (1915-2004) precipitation.

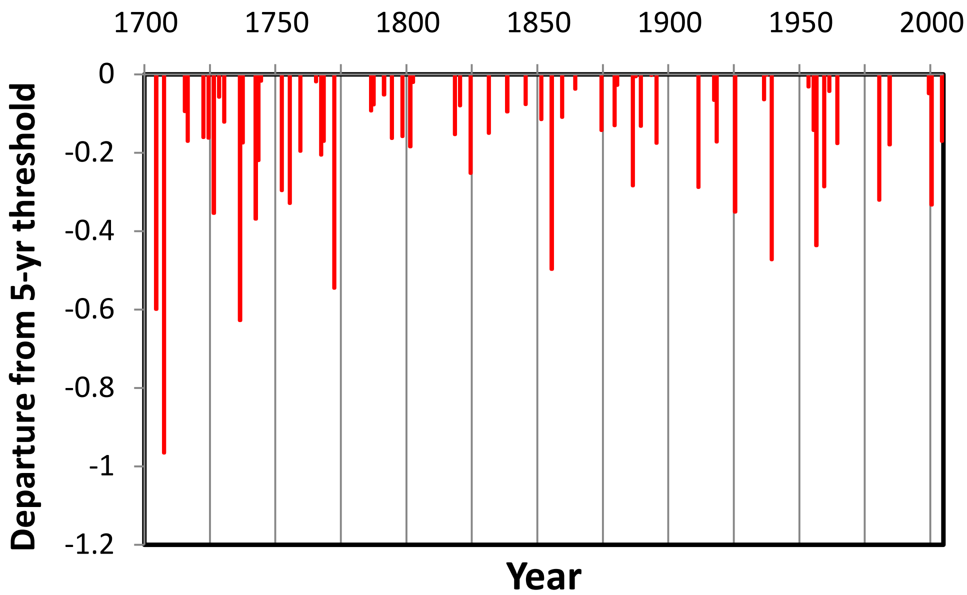


Figure 23. The 5-year drought series in the Arbuckle-Simpson aquifer based on reconstructed (1700-1914) and instrumental (1915-2004) streamflow.

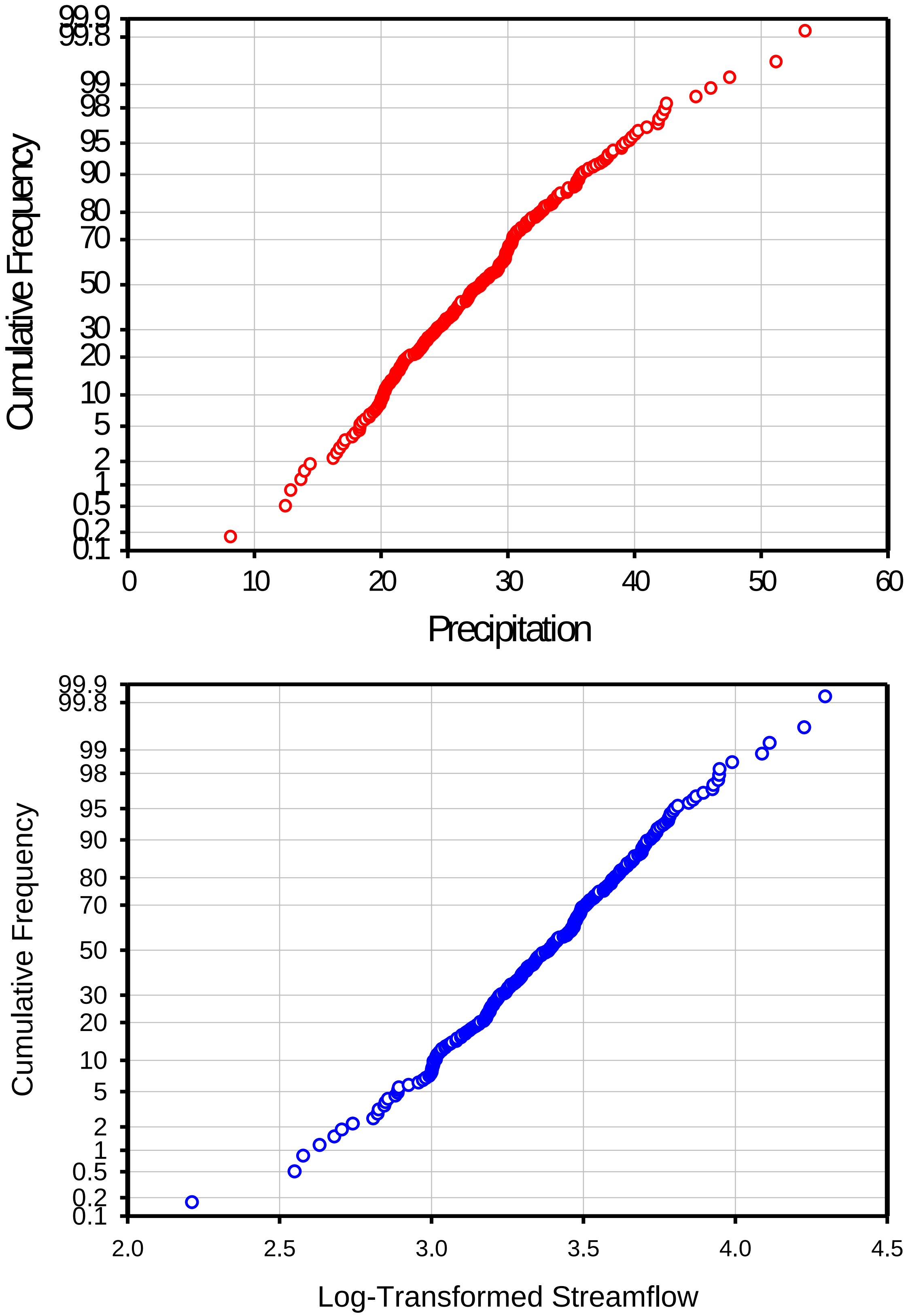


Figure 24. The cumulative probabilities of precipitation (upper panel) and streamflow (lower panel) for the entire reconstructed time period 1700-2004.

Appendix 1

Pictures of a Post Oak tree in the study area.

Appendix 2

The list of precipitation gauging stations in Oklahoma Climate Division 8 used in deriving average monthly precipitation series. The data and station list were obtained from the NCDC webpage (http://www.ncdc.noaa.gov/oa/climate/research/monitoring.html)

COOPID	STATION	County	LAT	LONG	Elevation (ft)	Data Period
340017	ADA	PONTOTOC	34:47	-96:41	1015	1914 to 2008
340147	ALLEN	PONTOTOC	34:54	-96:25	878	1997 to 2006
340292	ARDMORE	CARTER	34:10	-97:08	880	1914 to 2008
340296	ARDMORE INTERM FLD	CARTER	34:18	-97:09	866	1948 to 1961
340296	ARDMORE MUN AP	CARTER	34:18	-97:01	725	1962 to 1969
340391	ATOKA	ATOKA	34:24	-96:08	565	1926 to 2008
340394	ATOKA DAM	ATOKA	34:27	-96:04	595	1963 to 1999
340863	BLUE 1 W	BRYAN	34:00	-96:14	504	1947 to 1948
340917	BOKCHITO	BRYAN	34:01	-96:08	630	1992 to 2008
341437	CANEY 1 E	ATOKA	34:14	-96:13	531	2000 to 2008
341436	CANEY 1 NNE	ATOKA	34:14	-96:13	565	1944 to 1952
341648	CENTRAHOMA 2 ESE	COAL	34:36	-96:19	710	1947 to 2008
341745	CHICKASAW NRA	MURRAY	34:30	-96:59	1055	1978 to 2008
341954	COALGATE 1 WNW	COAL	34:33	-96:14	610	1936 to 1982
342011	COLEMAN	JOHNSTON	34:16	-96:25	770	2000 to 2008
342054	COMANCHE	STEPHENS	34:16	-96:14	1025	1952 to 2008
342354	DAISY 4 ENE	ATOKA	34:33	-95:41	755	1947 to 2008
342660	DUNCAN	STEPHENS	34:30	-97:58	1125	1936 to 2008
342665	DUNCAN 1 SSW	STEPHENS	34:29	-97:58	1132	1948 to 1951
342678	DURANT	BRYAN	34:00	-96:22	600	1914 to 2008
342872	ELMORE CITY 3 SW	GARVIN	34:39	-97:27	1020	1943 to 2008
343083	FARRIS 3 WNW	ATOKA	34:16	-95:55	510	1944 to 1995
343688	GRADY 2 E	JEFFERSON	34:01	-97:38	895	1992 to 2008
344001	HEALDTON	CARTER	34:13	-97:29	734	1914 to 2008
344003	HEALDTON OKC 29	CARTER	34:14	-97:29	902	1914 to 1914
344051	HENNEPIN	GARVIN	34:31	-97:21	942	1948 to 1951
344052	HENNEPIN 5 N	GARVIN	34:35	-97:21	970	1993 to 2008
344865	KINGSTON 5 SSE	MARSHALL	33:56	-96:41	684	1946 to 2008
345108	LEHIGH 4 SW	COAL	34:26	-96:16	695	1948 to 2008
345216	LINDSAY 2 W	GARVIN	34:50	-97:38	980	1938 to 2008
345247	LOCO	JEFFERSON	34:16	-97:37	1070	1984 to 2008
345468	MADILL	MARSHALL	34:06	-96:46	770	1936 to 2008
345563	MARIETTA 5SW	LOVE	33:53	-97:10	802	1937 to 2008
345581	MARLOW 1 WSW	STEPHENS	34:39	-97:59	1250	1914 to 2008
345713	MCGEE CREEK DAM	ATOKA	34:19	-95:52	672	1982 to 2008

346859	PAOLI 2 W	GARVIN	34:49	-97:17	931	1948 to 1951
346901	PARKER 1 S	COAL	34:43	-96:11	801	1959 to 1965
346926	PAULS VALLEY 4 WSW	GARVIN	34:44	-97:17	940	1914 to 2008
347214	PONTOTOC	JOHNSTON	34:30	-96:38	1025	1941 to 2008
347705	ROFF 2 WNW	PONTOTOC	34:38	-96:53	1255	1948 to 1951
348587	SULPHUR PLATT NAT'L PK	MURRAY	34:30	-96:58	991	1917 to 1978
348884	TISHOMINGO NATL WR	JOHNSTON	34:12	-96:39	642	1925 to 2008
349032	TUSSY	CARTER	34:30	-97:32	998	1993 to 2005
349395	WAURIKA	JEFFERSON	34:10	-98:00	912	1914 to 2008
349399	WAURIKA DAM	JEFFERSON	34:14	-98:03	991	1987 to 1997
349841	YUBA 2 W	BRYAN	33:49	-96:14	610	1947 to 1975

Appendix 3

The reconstructed precipitation (1701-1914) and Blue River flow (1701-1937). The streamflow data is log 10 transformed. The precipitation and streamflow values after those dates are the actual instrumental measurements.

Precipitation				Blue River		Precipitation				Blue River	
Year	TRI	PPT	PPT-5-y	Streamflow	Q-5-y	Year	TRI	PPT	PPT-5-y	Streamflow	Q-5-y
1700						1852	0.998	28.2	6.2	2513.44	968.44
1701	1.054	29.9	7.9	2965.47	1420.47	1853	1.134	32.3	10.3	3708.68	2163.68
1702	1.056	30.0	8.0	2982.58	1437.58	1854	0.981	27.7	5.7	2388.72	843.72
1703	0.903	25.4	3.4	1880.46	335.46	1855	0.534	14.5	-7.5	481.50	-1063.50
1704	0.482	13.0	-9.0	380.47	-1164.53	1856	1.012	28.7	6.7	2623.84	1078.84
1705	1.773	51.3	29.3	16961.69	15416.69	1857	1.010	28.6	6.6	2604.54	1059.54
1706	1.406	40.4	18.4	7468.15	5923.15	1858	1.036	29.4	7.4	2810.90	1265.90
1707	0.322	8.2	-13.8	163.74	-1381.26	1859	0.762	21.3	-0.7	1174.92	-370.08
1708	0.887	25.0	3.0	1787.02	242.02	1860	0.862	24.2	2.2	1648.34	103.34
1709	0.889	25.0	3.0	1798.50	253.50	1861	0.922	26.0	4.0	1996.34	451.34
1710	0.854	24.0	2.0	1605.78	60.78	1862	0.846	23.8	1.8	1564.08	19.08
1711	1.461	42.0	20.0	8511.65	6966.65	1863	0.839	23.5	1.5	1528.29	-16.71
1712	1.179	33.6	11.6	4196.76	2651.76	1864	0.810	22.7	0.7	1386.73	-158.27
1713	1.061	30.1	8.1	3025.69	1480.69	1865	0.893	25.1	3.1	1821.63	276.63
1714	1.053	29.9	7.9	2956.95	1411.95	1866	1.004	28.4	6.4	2558.67	1013.67
1715	0.772	21.6	-0.4	1216.83	-328.17	1867	1.059	30.1	8.1	3004.08	1459.08
1716	0.723	20.1	-1.9	1021.93	-523.07	1868	0.959	27.1	5.1	2234.63	689.63
1717	1.034	29.3	7.3	2798.65	1253.65	1869	1.083	30.8	8.8	3216.77	1671.77
1718	1.286	36.8	14.8	5550.22	4005.22	1870	1.037	29.4	7.4	2823.19	1278.19
1719	1.154	32.9	10.9	3922.60	2377.60	1871	1.065	30.3	8.3	3060.54	1515.54
1720	1.053	29.9	7.9	2956.95	1411.95	1872	1.059	30.1	8.1	3004.08	1459.08
1721	1.035	29.4	7.4	2806.81	1261.81	1873	1.253	35.8	13.8	5099.90	3554.90
1722	0.729	20.3	-1.7	1044.41	-500.59	1874	0.741	20.6	-1.4	1088.56	-456.44
1723	1.008	28.6	6.6	2593.01	1048.01	1875	1.016	28.8	6.8	2651.06	1106.06
1724	0.728	20.3	-1.7	1040.64	-504.36	1876	1.109	31.5	9.5	3460.56	1915.56
1725	0.987	27.9	5.9	2435.82	890.82	1877	0.952	26.9	4.9	2190.64	645.64
1726	0.612	16.8	-5.2	668.35	-876.65	1878	1.012	28.7	6.7	2623.84	1078.84
1727	1.070	30.4	8.4	3104.54	1559.54	1879	0.749	20.9	-1.1	1120.10	-424.90
1728	0.796	22.3	0.3	1322.14	-222.86	1880	0.817	22.9	0.9	1419.93	-125.07
1729	1.243	35.5	13.5	4969.44	3424.44	1881	1.053	29.9	7.9	2956.95	1411.95
1730	0.754	21.0	-1.0	1142.19	-402.81	1882	0.917	25.8	3.8	1962.23	417.23
1731	1.218	34.8	12.8	4655.05	3110.05	1883	1.052	29.9	7.9	2948.44	1403.44
1732	1.305	37.4	15.4	5823.75	4278.75	1884	0.924	26.1	4.1	2005.72	460.72

1733	0.996	28.2	6.2	2502.24	957.24	1885	0.987	27.9	5.9	2435.82	890.82
1734	1.092	31.1	9.1	3304.20	1759.20	1886	0.653	18.0	-4.0	785.90	-759.10
1735	1.155	32.9	10.9	3933.29	2388.29	1887	0.832	23.3	1.3	1493.14	-51.86
1736	0.468	12.5	-9.5	356.14	-1188.86	1888	1.119	31.9	9.9	3563.10	2018.10
1737	0.72	20.0	-2.0	1010.83	-534.17	1889	0.748	20.8	-1.2	1116.12	-428.88
1738	0.902	25.4	3.4	1874.51	329.51	1890	0.990	28.0	6.0	2454.13	909.13
1739	0.895	25.2	3.2	1833.28	288.28	1891	1.045	29.7	7.7	2889.45	1344.45
1740	1.073	30.5	8.5	3131.19	1586.19	1892	1.000	28.3	6.3	2528.45	983.45
1741	1.108	31.5	9.5	3455.73	1910.73	1893	0.834	23.4	1.4	1503.12	-41.88
1742	0.604	16.6	-5.4	647.05	-897.95	1894	0.880	24.8	2.8	1747.31	202.31
1743	0.692	19.2	-2.8	911.59	-633.41	1895	0.720	20.0	-2.0	1008.98	-536.02
1744	0.824	23.1	1.1	1453.74	-91.26	1896	0.909	20.56	-1.4	1916.47	371.47
1745	1.248	35.7	13.7	5034.33	3489.33	1897	1.167	30.43	8.4	4057.82	2512.82
1746	1.383	39.7	17.7	7064.01	5519.01	1898	1.100	30.73	8.7	3379.29	1834.29
1747	1.134	32.3	10.3	3713.79	2168.79	1899	1.091	26.03	4.0	3294.91	1749.91
1748	1.143	32.6	10.6	3806.62	2261.62	1900	0.861	26.16	4.2	1640.29	95.29
1749	1.156	33.0	11.0	3943.99	2398.99	1901	0.940	27.66	5.7	2107.95	562.95
1750	1.199	34.2	12.2	4427.00	2882.00	1902	1.047	26.79	4.8	2906.21	1361.21
1751	1.429	41.1	19.1	7890.98	6345.98	1903	1.231	24.67	2.7	4816.46	3271.46
1752	0.646	17.8	-4.2	764.81	-780.19	1904	0.856	28.8	6.8	1613.69	68.69
1753	1.054	29.9	7.9	2965.47	1420.47	1905	0.883	31.13	9.1	1764.24	219.24
1754	1.157	33.0	11.0	3954.72	2409.72	1906	1.061	26.99	5.0	3025.69	1480.69
1755	0.627	17.3	-4.7	709.70	-835.30	1907	1.624	35.9	13.9	12315.51	10770.51
1756	0.998	28.3	6.3	2517.19	972.19	1908	1.397	39.33	17.3	7299.00	5754.00
1757	0.992	28.1	6.1	2472.54	927.54	1909	0.873	27.21	5.2	1705.52	160.52
1758	1.248	35.7	13.7	5034.33	3489.33	1910	0.849	16.3	-5.7	1579.62	34.62
1759	0.707	19.6	-2.4	963.78	-581.22	1911	0.651	14.05	-8.0	778.32	-766.68
1760	1.325	38.0	16.0	6123.40	4578.40	1912	1.238	23.23	1.2	4905.23	3360.23
1761	1.054	29.9	7.9	2965.47	1420.47	1913	0.920	21.36	-0.6	1980.78	435.78
1762	1.026	29.1	7.1	2734.05	1189.05	1914	1.114	30.15	8.2	3513.97	1968.97
1763	1.22	34.9	12.9	4679.59	3134.59	1915	1.327	33.84	11.8	6154.04	4609.04
1764	1.181	33.7	11.7	4219.34	2674.34	1916	0.991	38.41	16.4	2465.16	920.16
1765	0.823	23.1	1.1	1448.87	-96.13	1917	0.791	18.43	-3.6	1299.64	-245.36
1766	1.062	30.2	8.2	3034.37	1489.37	1918	0.722	21.26	-0.7	1016.37	-528.63
1767	0.701	19.5	-2.5	942.64	-602.36	1919	1.272	30.47	8.5	5348.55	3803.55
1768	0.723	20.1	-1.9	1021.93	-523.07	1920	1.164	36.46	14.5	4030.49	2485.49
1769	0.894	25.2	3.2	1827.44	282.44	1921	1.200	39.11	17.1	4432.89	2887.89
1770	0.847	23.8	1.8	1569.24	24.24	1922	0.886	29.26	7.3	1781.31	236.31
1771	1.053	29.9	7.9	2956.95	1411.95	1923	1.000	27.09	5.1	2528.45	983.45
1772	0.509	13.8	-8.2	430.76	-1114.24	1924	1.087	40.15	18.2	3257.95	1712.95
1773	0.927	26.2	4.2	2027.74	482.74	1925	0.614	18.83	-3.2	673.76	-871.24
1774	1.241	35.5	13.5	4943.68	3398.68	1926	1.078	29.36	7.4	3171.50	1626.50
1775	1.103	31.4	9.4	3407.79	1862.79	1927	0.961	38.29	16.3	2251.73	706.73

1776	0.914	25.8	3.8	1946.88	401.88	1928	1.267	31.98	10.0	5287.18	3742.18
1777	1.094	31.1	9.1	3322.84	1777.84	1929	1.067	30.13	8.1	3073.69	1528.69
1778	0.859	24.1	2.1	1632.27	87.27	1930	0.888	27.58	5.6	1792.76	247.76
1779	0.959	27.1	5.1	2238.04	693.04	1931	0.935	18.38	-3.6	2078.79	533.79
1780	0.934	26.4	4.4	2069.14	524.14	1932	1.135	29.71	7.7	3718.90	2173.90
1781	1.189	33.9	11.9	4304.89	2759.89	1933	0.921	22.17	0.2	1990.10	445.10
1782	1.121	31.9	9.9	3582.90	2037.90	1934	0.841	22	0.0	1538.45	-6.55
1783	1.010	28.6	6.6	2608.39	1063.39	1935	1.278	35.32	13.3	5438.20	3893.20
1784	0.957	27.0	5.0	2224.42	679.42	1936	0.792	22.07	0.1	1304.11	-240.89
1785	0.851	23.9	1.9	1590.04	45.04	1937	1.074	29.71	7.7	1506.61	-38.39
1786	0.773	21.6	-0.4	1221.09	-323.91	1938	0.976	30.11	8.1	1990.67	445.67
1787	0.783	21.9	-0.1	1264.26	-280.74	1939	0.713	18.41	-3.6	509.33	-1035.67
1788	1.059	30.1	8.1	3008.39	1463.39	1940	0.986	25.79	3.8	2306.75	761.75
1789	0.935	26.4	4.4	2078.79	533.79	1941	1.120	26.24	4.2	2910.72	1365.72
1790	0.952	26.9	4.9	2187.28	642.28	1942	1.264	46.11	24.1	6501.30	4956.30
1791	0.800	22.4	0.4	1340.35	-204.65	1943	0.948	31.77	9.8	3917.42	2372.42
1792	0.867	24.4	2.4	1675.38	130.38	1944	1.012	21.71	-0.3	2576.32	1031.32
1793	1.048	29.7	7.7	2910.41	1365.41	1945	1.169	37.04	15.0	8892.01	7347.01
1794	0.728	20.2	-1.8	1038.75	-506.25	1946	1.049	33.59	11.6	3837.07	2292.07
1795	1.066	30.3	8.3	3069.30	1524.30	1947	1.031	27.98	6.0	3741.11	2196.11
1796	1.116	31.8	9.8	3533.56	1988.56	1948	0.882	23.42	1.4	1770.11	225.11
1797	0.855	24.0	2.0	1611.05	66.05	1949	1.011	24.49	2.5	2208.00	663.00
1798	0.731	20.3	-1.7	1050.09	-494.91	1950	1.017	31.57	9.6	3258.37	1713.37
1799	1.179	33.6	11.6	4196.76	2651.76	1951	1.034	30.72	8.7	3539.97	1994.97
1800	1.041	29.5	7.5	2856.17	1311.17	1952	0.798	21.11	-0.9	1663.41	118.41
1801	0.714	19.8	-2.2	988.90	-556.10	1953	0.761	17.08	-4.9	1406.05	-138.95
1802	0.822	23.0	1.0	1441.59	-103.41	1954	1.153	29.26	7.3	2741.57	1196.57
1803	1.320	37.8	15.8	6047.34	4502.34	1955	1.052	24.23	2.2	1088.93	-456.07
1804	1.243	35.5	13.5	4962.99	3417.99	1956	0.693	19.75	-2.3	553.35	-991.65
1805	0.966	27.3	5.3	2282.78	737.78	1957	0.963	39.06	17.1	6353.31	4808.31
1806	0.921	26.0	4.0	1990.10	445.10	1958	1.135	30.58	8.6	5445.03	3900.03
1807	1.150	32.8	10.8	3874.82	2329.82	1959	0.832	21.74	-0.3	781.63	-763.37
1808	0.950	26.8	4.8	2173.90	628.90	1960	1.091	27.29	5.3	1967.89	422.89
1809	1.217	34.7	12.7	4636.71	3091.71	1961	0.982	25.72	3.7	1367.73	-177.27
1810	1.171	33.4	11.4	4107.41	2562.41	1962	1.087	29.22	7.2	2387.81	842.81
1811	1.241	35.5	13.5	4943.68	3398.68	1963	0.827	21.52	-0.5	2065.38	520.38
1812	1.070	30.4	8.4	3100.12	1555.12	1964	0.900	19.16	-2.8	1006.93	-538.07
1813	0.954	27.0	5.0	2204.10	659.10	1965	1.185	27.87	5.9	1520.55	-24.45
1814	1.108	31.5	9.5	3450.92	1905.92	1966	0.695	20.77	-1.2	1541.70	-3.30
1815	1.163	33.1	11.1	4014.15	2469.15	1967	1.312	30.71	8.7	2223.31	678.31
1816	0.847	23.8	1.8	1566.66	21.66	1968	1.119	36.34	14.3	5571.86	4026.86
1817	1.477	42.5	20.5	8836.65	7291.65	1969	0.981	27.93	5.9	4549.88	3004.88
1818	0.734	20.4	-1.6	1061.52	-483.48	1970	0.958	25.04	3.0	2488.86	943.86

1819	0.936	26.4	4.4	2082.02	537.02	1971	0.912	27.02	5.0	2108.63	563.63
1820	0.782	21.8	-0.2	1257.71	-287.29	1972	0.857	24.96	3.0	1581.25	36.25
1821	0.907	25.5	3.5	1901.40	356.40	1973	1.110	39.87	17.9	6266.14	4721.14
1822	0.839	23.5	1.5	1528.29	-16.71	1974	0.998	29.37	7.4	4140.00	2595.00
1823	0.845	23.7	1.7	1556.35	11.35	1975	1.222	41.94	19.9	5533.50	3988.50
1824	0.672	18.6	-3.4	845.37	-699.63	1976	0.909	23.39	1.4	2317.39	772.39
1825	1.191	34.0	12.0	4333.72	2788.72	1977	0.951	26.97	5.0	2328.09	783.09
1826	1.482	42.6	20.6	8929.86	7384.86	1978	0.871	26.35	4.4	1566.75	21.75
1827	1.072	30.4	8.4	3117.84	1572.84	1979	0.994	24.54	2.5	2552.70	1007.70
1828	0.895	25.2	3.2	1830.36	285.36	1980	0.804	20.42	-1.6	722.77	-822.23
1829	1.040	29.5	7.5	2847.89	1302.89	1981	0.973	27.25	5.3	1678.80	133.80
1830	1.071	30.4	8.4	3113.41	1568.41	1982	1.125	44.93	22.9	8452.79	6907.79
1831	0.736	20.5	-1.5	1071.12	-473.88	1983	0.999	23.24	1.2	2259.44	714.44
1832	0.931	26.3	4.3	2053.14	508.14	1984	0.859	22.89	0.9	1000.00	-545.00
1833	1.650	47.6	25.6	13037.18	11492.18	1985	1.147	38	16.0	4365.16	2820.16
1834	1.221	34.9	12.9	4685.74	3140.74	1986	0.876	29.88	7.9	2904.02	1359.02
1835	1.199	34.2	12.2	4427.00	2882.00	1987	1.090	34.01	12.0	2177.71	632.71
1836	1.850	53.5	31.5	19871.95	18326.95	1988	0.844	21.75	-0.3	1655.77	110.77
1837	0.871	24.5	2.5	1697.26	152.26	1989	1.075	29.42	7.4	3334.26	1789.26
1838	0.772	21.5	-0.5	1214.71	-330.29	1990	0.951	42.28	20.3	9817.48	8272.48
1839	0.866	24.3	2.3	1669.94	124.94	1991	0.935	31.06	9.1	4549.88	3004.88
1840	1.072	30.4	8.4	3117.84	1572.84	1992	1.193	35.74	13.7	4168.69	2623.69
1841	0.908	25.6	3.6	1910.43	365.43	1993	1.068	28.98	7.0	5688.53	4143.53
1842	0.838	23.5	1.5	1520.70	-24.30	1994	1.046	29.93	7.9	3140.51	1595.51
1843	1.313	37.6	15.6	5934.69	4389.69	1995	1.312	36.06	14.1	6067.36	4522.36
1844	1.143	32.6	10.6	3801.42	2256.42	1996	0.850	21.23	-0.8	1606.94	61.94
1845	0.784	21.9	-0.1	1266.45	-278.55	1997	0.999	32.45	10.5	5116.82	3571.82
1846	0.971	27.4	5.4	2317.68	772.68	1998	0.784	25.79	3.8	1940.89	395.89
1847	1.073	30.5	8.5	3131.19	1586.19	1999	1.071	31.52	9.5	1352.07	-192.93
1848	0.926	26.1	4.1	2018.28	473.28	2000	0.885	25.77	3.8	703.07	-841.93
1849	1.085	30.8	8.8	3235.02	1690.02	2001	0.823	24.82	2.8	2147.83	602.83
1850	1.074	30.5	8.5	3135.65	1590.65	2002	1.097	32.7	10.7	5140.44	3595.44
1851	0.759	21.2	-0.8	1160.51	-384.49	2003	0.962	24.41	2.4	1766.04	221.04
						2004	0.986	27.36	5.4	1020.94	-524.06
						2005		22.55	0.6		
						2006		26.2	4.2		
						2007		40.19	18.2		

Appendix 4

Public perception of drought and flood occurrence as well s their impacts often may not align with the 'scientific' indicators of the event. Several reasons account for this, including the timing of these events. A drought (flood) that is mild in the statistical sense could have significant economic and social impact if it occurs at a critical point during, for example, the agricultural calendar such that it wipes off the years' harvests. Conversely, a deeply severe drought (flood) in the hydroclimatic sense may evoke no special feeling or memories if its social economic impacts were minimal for whatever reason. Thus, what people remember about droughts (floods) has as much to do about perception and social impacts as it does the degree of water deficit or surfeit. Frequently, the political context and non-climatic factors drive drought (flood) perception, public discourse, and memory.

Consequently, to get a comprehensive picture of drought and flood impacts in a region, it is often useful to consider not only the events as defined from the hydroclimatic records but also public perceptions and attitudes about droughts and floods in the region. For this report, we do this by analyzing newspaper accounts from the study area to glean public perceptions of the regions drought and flood history. We focus especially on the generally recognized drought years in the rainfall records. The goal is to show not what happened in the human sense but also aspects of the society that appeared especially vulnerable and the coping strategies that were adopted.

1939 drought

1939 was a good year for farmers in Bryan County. Although drought reduced the size of the crop that year, state farmers received 5 million dollars more money at the market than they did in 1938, according to the Department of Agriculture ('No byline,' Dec 29, 1939). In 1939, Bryan County cotton ginnings were on par with the year before, when 11,192 bales were ginned. By the end of October 1939, 10,960 bales were ginned in the county ('No byline,' Oct 27, 1939, pp.1).

Newspaper accounts seem to indicate varying levels of drought severity. Grain crops in Bryan County and SE Oklahoma were considerably smaller than normal for the winter season of 1938-1939 because of the dry weather (McCorkle, January 6, 1939). With few exceptions, fall moisture was inadequate for further crop growth. The slow rains that fell over Ada in the middle of November, 1939 were not seen as enough to break the drought ('No byline,' November 16, 1939). However, a water carnival marked the grand opening of Platt National Park at the beginning of June (Hill, May 28, 1939), which featured 'modern mineral water baths and plunges' (ad in *The Oklahoman* June 4, 1939). Additionally, residents of Sulphur 'swear by the sulphur water which shoots high in the air from 16 artesian wells…for visitors who don't like it there's plenty of clear water' (Hill, May 28, 1939).

The newspaper accounts contain no records of water rationing or other measures that would indicate water shortage during this year.

<u>1953 drought</u>

A severe drought that had been transpiring during this year that led to water restrictions in Hobart temporarily broke on April 5 when a strong storm cell led to tornado warnings from Davis to the Arkansas line near Muldrow, OK (Etheridge, April 6, 1953). On May 12, 1953, 3.15 inches of rain created a flash flood on Rock Creek near Sulphur. These rains covered the local football field with feet of water, trapping the high school's 'athlete instructor' in the equipment room resulting in his rescue by boat. Additionally, ten feet of water covered the local rodeo grounds (Etheridge, May 13, 1953). However, the drought continued. By June 11, there was no apparent crop damage in the wake of the drought ('No byline,' June 11, 1953). However, rain was needed soon to prevent damage to corn and to late-planted peanuts and cotton. The dry weather, however, was ideal for small grain crops such as wheat, oats, grain, and barley.

By July 11, 1953, many Bryan County farmers were creating more corn sillage than in any previous year in order to salvage some of the value of the burned and wilted corn and to ensure a feed supply for the livestock next winter; the sillage was projected to save livestock owners hundreds of dollars in feed during 1953 ('No byline,' July 12, 1953). The county [extension?] agent said that most of the corn had been severely damaged by the hot winds and drought during the previous thirty days. However, a July 13 article described a heavy rainstorm as an "all-day rain crop saver for Bryan County." A July 20 United Press International article (1953) said 'new rains pounded Oklahoma Monday, and the word 'drouth' [sic] was rapidly becoming history in many areas'. Presumably, Bryan County was included in this assessment because two major highways: U.S. 69 and U.S. 75, were closed because of water. Four inches of rain fell near Sulphur over a two-day period, causing the Washita River to reach bank-full stage near Davis ('No byline,' July 21, 1953).

1954 floods

Some major flood episodes were prevalent during 1954. In Durant, 1.87 inches of rain fell during the twenty-four hour period beginning at 7 AM on May 10, 1954 ('No byline,' May 12, 1954). This was followed by 1.18 inches of rain from 7 AM through 6 PM on Tuesday, May 11, 1954. By 6 PM on the 11th, the Blue River was at bank-full stage and still rising; other small creeks were also flooding. This storm also left unpaved roads impassable in Bryan County, and led farmers to delay planting peanuts and cotton. Sulphur saw 6.37 inches of rain from Saturday, May 8 through May 11. These storms flooded stock tanks but otherwise did not lead to flooding.

On June 7, 1954 high winds near Ada, Sulphur, and Ardmore uprooted trees and overturned trailers; these winds toppled a fifty-foot screen and a large sign in the Arbuckle open-air theater in Davis, causing $1500 in damage ('No byline,' June 8, 1954). In Sulphur, these winds were accompanied by a 'blinding rain' after 9 PM on that day, which lasted approximately one hour. A bus driver noticed a flash flood that covered US 77 under two feet of water near Davis.

The summer of 1955 saw some severe floods across the state. For instance, storms that occurred throughout Oklahoma on May 19, 1955 produced 10.16 inches of rain at Duncan and 11.75

inches on Comanche. (Neal and Taylor, May 20, 1955). On July 16, 1955, three inches of a 5.04 inch rain storm fell within an hour in Durant, which flooded around six downtown buildings ('No byline,' July 18, 1955).

1956 drought

Many considered this the worst drought to hit Oklahoma since the 1890s. This drought seemed to be one of the reasons for the interest of Ada, Sulphur, and Davis in constructing the Lake of the Arbuckles ('No byline,' July 8, 1956). During the summer of 1956, water usage caught up with water supply for the first time in Ada, causing Byrds Mill Spring to run 'lower than usual,' and leading the city to dig test wells south of the city in the South Canadian River ('No byline,' July 24, 1956). The city also restricted outdoor watering to two one-hour long periods three evenings per week. During the three weeks leading up to August 22, 1956, all outside water use had been restricted within the city limits (UPI, August 23, 1956). In September, a special election for the construction of a proposed reservoir on Clear Boggy Creek, south of the city, was held.

Ada was not the only city to enact some sort of watering restrictions in response to the drought. A *Durant Daily Democrat* article on June 14, 1956 mentioned the City of Ardmore's decision to enact watering restrictions (United Press International, June 14, 1956). Water use was restricted to domestic and commercial use; car washing and lawn watering were prohibited. No water could be used for a/c (air conditioning) unless it had re-circulating pump. The penalty for failing to adhere to the restrictions was 19 dollars per day and the cutoff of water. The city council's decision was preceded by notification that city only has 40-day supply of water.

Ardmore ordinarily got water from Mountain Lake reservoir in Arbuckles (north of Ardmore) and a city lake three miles NE of town. These reservoirs normally held a one-year supply amounting to one billion gallons. Mountain Lake was nearly bone dry, and City Lake had about 160 million gallons left. Neither lake has been full since April 1955. There are six lakes in 25-mile radius of Ardmore, but Ardmore had links to only two of them. The Councilmen voted to try to negotiate a contract for a 250 million gallon reservoir short distance from the city. Ardmore also considered constructing a 14-mi pipeline to Lake Murray, which would cost about $5,000. Ardmore rejected hiring a professional rainmaker, even though Lawton did. On Oct 6, local citizens were informed of the availability of a minimum supply of water due to the pumping of twelve feet of water from Ardmore Club Lake to City Lake ('No byline,' Oct 7, 1956).

On July 1, 1956, Pennington Creek, the main source of drinking water for Tishomingo, neared depletion ('No byline,' July 3, 1956). For the first time, water in the city's "Little Dam" was not running over the top; the creek was moving 'sluggishly' through a channel 1.5 foot deep by 6 feet wide. As a result, the Tishomingo City Council asked for the immediate (voluntary) curtailing of water use in that city, with plans for mandatory water restrictions if such actions proved unsuccessful. By July 8, the water supply situation in Tishomingo was 'critical' ('No byline,' July 9, 1956); Mayor Jack Parrish said the situation could worsen without residents' assistance. During the previous week (assuming the author meant between the 1^{st} and the 8^{th}), the water level in the city's dam fell below the adequate pumping level because of such heavy water use. The City Council therefore asked the local justice of the peace to inspect water use in each house and talk with residents about water use. As an emergency measure, the city sandbagged the turbine outlet of water through the dam to get the water to raise the water to pump level, which basically stopped the flow of Pennington Creek. In addition, the sewage disposal plant was emptying into a stream that was no longer flowing.

On August 21, 1956, the Caddo city council passed a resolution prohibiting the use of water lines to water livestock because of the fear of a water shortage, although one had not yet materialized ('No byline,' August 22, 1956).

Nevertheless, these restrictions appeared not to have hit Durant during this year. A *Durant Daily Democrat* article from July 24, 1956 mentioned that youngsters were washing cars as a fundraiser at the local Methodist church. In an article from August 8, Mayor Charles Fuller described his reaction to the voters rejecting a bond proposal to improve the city's water system: "we feel we have operated the department efficiently in not having to resort to water rationing in the face of this severe drouth [sic] and heat wave with the equipment we have."

However, on July 31, the drought in Durant moved from the serious to the critical stage. Farmers and ranchers were faced with a shortage of stockwater and grass in the western and southern portions of the county. Since most of the hay had been removed from the county because of the drought, a shortage was expected. Cotton and peanuts were severely damaged. The corn crop was expected to be the shortest in a number of years. On Friday, Oct 10, the USDA received a drought aid request from Bryan County ('No byline,' October 10, 1956).

On August 28, 1956, fear that the Blue River would not last as a viable water source for Durant inspired a USGS study on the topic, the results of which were released on August 30. The report said that the Blue River continued to be a viable water source, but that a new reservoir would not hurt matters (*Durant Daily Democrat* articles from August 22, August 30). At the end of September, engineers from the US Army Corp decided to reduce the power output from Dension dam for the next two months because of the very low levels of Lake Texoma. In the middle of October, congressmen Carl Albert (OK) and Sam Rayburn (TX) were trying to raise Lake Texoma to prevent repeated drought effects. The first general rain since June occurred in October. On Oct 21, 1956, the *Durant Daily Democrat* featured a full-page display titled "the rains came," showing pictures and captions of the drought which seemed to be disappearing. One picture featured the grading and smoothing of highway 70-E. This construction had been delayed due to the dry soil from the drought. On December 19, 1956, some municipalities between Pauls Valley and Lake Texoma received nearly 2.5 inches of rain ('No byline,' December 20, 1956).

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