Arkansas Water Resources Center

LONG-TERM RECONSTRUCTION AND ANALYSIS OF WHITE RIVER STREAMFLOW

Research Project Technical Completion Report

Project G-1409-02

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ABSTRACT

LONG-TERM RECONSTRUCTION AND ANALYSIS OF WHITE RIVER STREAMFLOW

A 281-year reconstruction of White River annual runoff at Clarendon, Arkansas, was developed from a regional average of nine Oklahoma, Missouri, and Arkansas tree-ring chronologies (six post oak, *Quercus stellata*, and three baldcypress, *Taxodium distichum*). Inhomogeneity of the gaged series was detected with both double mass analysis (using state average total annual Arkansas precipitation) and regression (using the regional tree-ring average). Simple regression calibrated the homogeneous runoff data with the average ring width data from 1930 to 1980. Comparing the reconstruction with independent data verified the regression model. Variance of the reconstruction increases significantly during the 20th century, a change that may be caused by climatic shifts or by anthropogenic disturbances in the watershed. Years of surplus and deficit runoff are non-randomly distributed in both gaged and reconstructed series. This non-randomness appears to be caused by a significant tendency for inter-annual persistence of runoff extremes, which may provide a basis for improvement of probabilistic forecasts of White River runoff.

Malcolm K. Cleaveland, David W. Stahle and John G. Hehr

Completion Report to the U.S. Department of the Interior, Geological Survey, Reston, VA, June, 1988.

Keywords -- Climate/Planning/Dendrochronology/Stochastic Hydrology/Paleohydrology/Time Series Analysis/Rainfall-Runoff Processes/Rivers/Drought/White River/Arkansas/Missouri

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INTRODUCTION

The demand for high quality surface and groundwater supplies by agricultural, industrial and municipal interests has increased nationwide, in some cases exceeding existing supplies [U. S. Water Resources Council, 1978]. The Southcentral United States is experiencing rapid growth in population and water demand, and available supplies may soon become inadequate in or near the arid southern Plains or in areas of intensively irrigated agriculture such as the Grand Prairie of eastern Arkansas [U. S. Water Resources Council, 1978; Bryant et al., 1985] Surface water supplies in the Southcentral United States are subject to substantial interannual variability due to natural fluctuations in climate. In fact, the Arkansas-White-Red and the Texas-Gulf water resource regions [U. S. Water Resources Council, 1978] have been identified as having two of the three most variable runoff regimes in the 19 subdivisions of the continental United States [Stockton and Boggess, 1979]

Arkansas is particularly well endowed with high quality surface water resources, and proposals for interbasin transfers both within and from Arkansas have generated controversy. Consideration is being given to the transfer of surface water from the White River to augment dwindling groundwater supplies in the Grand Prairie of eastern Arkansas [U.S. Army Corps of Engineers, n.d.], where water-intensive rice and soybean production make a significant contribution to the state economy [Arkansas Agricultural Statistics Service, 1988]. The possible transfer of "surplus" water from Arkansas to supplement supplies in Texas has also been investigated [U. S. Army Corps of Engineers, 1982] and the Dallas-

Ft. Worth water supply system will extend eastward to Lamar County, only 80 km from Arkansas (Dallas Water Utilities, 1986).

Apart from the many economic and environmental questions concerning possible interbasin transfers of surplus water, there is uncertainty about the long-term availability of surplus flow regimes in Arkansas. The probable discontinuous nature of surplus flows would impose serious planning and design constraints on the possible use of this water resource component. Because the gaged runoff data is limited to the past century in Arkansas, a thorough investigation of the history and dependability of surplus flows is probably not possible solely on the basis of the historic record [Rodríguez-Iturbe, 1969]

A. Purpose and Objectives

Proxy tree-ring data are often wel correlated with hydrometeorological variables such as precipitation and temperature, and can therefore be useful for developing long-term estimates of specific hydrological variables such as runoff. Tree-ring data are particularly suited to the analysis of drought or low flow characteristics because moisture stress is a fundamental growth-limiting factor which can be faithfully reproduced in properly selected ring width data. During years of abundant precipitation, multiple factors such as temperature, competition, or soil fertility may limit growth in individual trees, usually creating greater standard errors in the ring width indices derived for those years [Fritts, 1976]. For this reason tree-ring reconstructions of very wet years usually involve greater error and should be interpreted cautiously [e.g., Blasing et al., 1988].

In this paper we use a network of moisture sensitive post oaks

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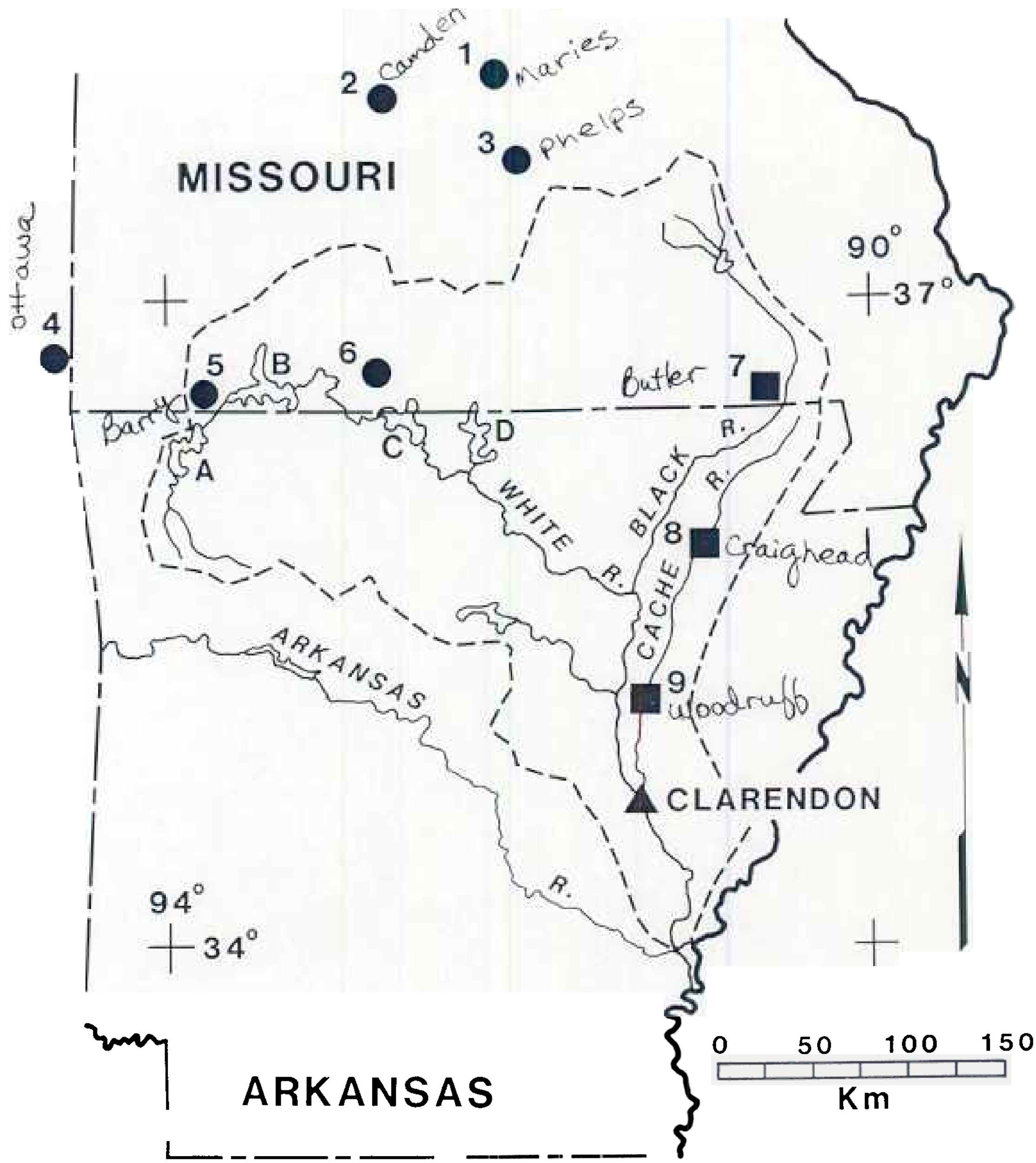

Figure 1. Locations of the tree-ring chronologies used in reconstruction of White River Basin annual runoff at Clarendon, Arkansas, (triangle). The six post oak chronologies (circles) are 1) Little Maries River, MO, 2) Hahatonka, MO, 3) Democrat Ridge, MO, 4) Neosho River, OK, 5) Roaring River, MO, 6) Clayton Ridge, MO, and the three baldcypress chronologies (squares) are 7) Allred Lake, MO, 8) Egypt, AR and 9) Black Swamp, AR. The four largest impoundments (that affect this study) in the White River Basin (dashed line) are (A) Beaver, (B) Table Rock (C) Bull Shoals and (D) Norfork.

Clarendon gage is far enough above the confluence of the Arkansas and Mississippi Rivers to be largely unaffected by fluvial damming from either river [U. S. Geological Survey, 1984]

Intensive logging of the upland oak-hickory and pine forests occurred during the early twentieth century. These logging operations and land clearing for agriculture may have affected the discharge, suspended sediments, or bed load of the White River, at least temporarily during the initial wave of clearing. Four large-scale impoundments for flood control, power generation, water supply, and recreation purposes were constructed in the basin from 1943 to 1980 [U. S. Geological Sur- 1984], and these projects have promoted both the economic develop- of the central Ozarks and agricultural productivity along the lower White River. The volume of high quality surface water stored in these reservoirs is certainly one of the most important resources in the Ozarks, but the present and future management of these supplies remain subject to a conflicting array of public and private pressures.

Related Research and Activities

Properly developed tree-ring chronologies are particulary well uited as surrogate runoff records because of great age (some species exceed 1000 years), absolute dating, annual to seasonal resolution, sensitivity of tree growth to climatic variables that also influence runoff, and the wide availability of tree-ring data in the specific drainage system of interest [Fritts, 1976; Stockton and Boggess, 1980]. A number of previous studies have employed surrogate or proxy data such as tree rings to extend relatively short streamflow records. The most important and wel known tree-ring reconstruction of runoff was for the Colorado River, reported by Stockton (1975). The reconstructed long-term mean annual runoff in the Colorado River was only about 13.5 maf between 1564 and 1962, some 2.0 maf year^{-1} less than the amount allocated in the Colorado River Compact of 1922 [Stockton and Jacoby, 1976] It appears that the Compact was based on gaging data from a period of sustained high flow unequaled in the last 450 years. These results provide a classic illustration of both the need to consult proxy data when confronted with short, potentially biased gaging records and the potential practical importance of tree-ring data.

Other hydrological applications of tree-ring data include a reconstruction of summer streamflow in the Occoquan River, Virginia, which indicated that critical low flows were more frequent in the reconstructed data prior to the period of instrumental records [Phipps, 1983]. Cook and Jacoby [1983] reconstructed summer low flows in the Potomac River, and for similar reasons concluded that the gaged discharge measurements for the Potomac are not entirely representative of the last 250 years. Jones et al. [1984] have demonstrated the hydrological application of tree-ring data in the British Isles, while Stockton and Fritts [1973] and Brinkmann [1987] have used tree-ring chronologies to reconstruct past lake levels

The use of proxy data to investigate long streamflow series in the Southcentral United States has been limited to early tree-ring studies by Hawley [1937] in Tennessee. No quantitative estimates of past runoff have been reported in the White River Basin, although Guyette [1981] has demonstrated significant correlation (r = 0.75) between growth of eastern red cedar (Juniperus virginiana) and June minimum discharge of the Gasconade, James, and Current rivers in southern Missouri vidual red cedar up to 700 years old have been reported from the Ozark Plateau [Guyette, 1981; Guyette et al., 1980], and hold great promise as long proxy hydrological series.

METHODS AND PROCEDURES

A. Gaging Data

We selected the U.S. Army Corps of Engineers (COE) gaging record at Clarendon for reconstruction because it is the longest in Arkansas it is believed to provide a reasonable integration of the surface water supply in the entire White River Basin, the gage has never been moved and homogeneity of the record does not appear to have been seriously affected by post-war reservoir development. Clarendon discharge was not available from 1921 to 1930, but a single rating table to convert gage height to discharge for those years was supplied by the Memphis District COE [S. A. Lehr, Jr., persona communication, 1987]. The rating table has the notation "Based on L.W. (low water) Measurements in 1917--High Water 1927"

Correlations between monthly, seasonalized, and annual mean daily discharge and the regional tree-ring chronologies [Stahle et al., 1985b] were used initially to determine which chronologies should be used and what fraction of the year might be most successfully reconstructed. Seasonal mean daily discharge for February through July produced the highest correlation ($r = 0.64$, $P < 0.001$, but annual mean daily discharge pa rg rt

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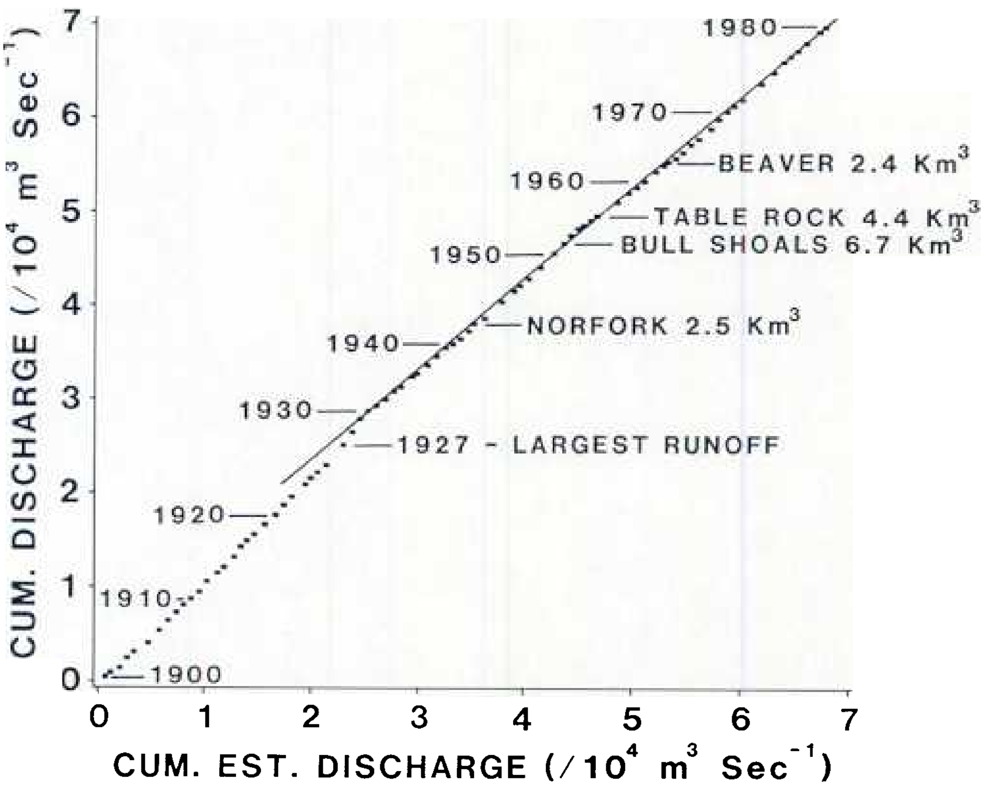

Figure 2. Double mass analysis of White River cumulative annual mean daily discharge at Clarendon, Arkansas, vs. cumulative estimated discharge (see text). Annotations on the graph show the years of largest discharge (gaged data) and major reservoir closures with impoundment capacity.

TABLE Calibration and verification statistics ($\underline{B}_0$ is the intercept and $\underline{B}_1$ is the slope of the regression model).

Calibration				Verification						
							Sign Test[d]		$\underline{t}$-Test[e]	
Period	R^2_{adj} [a]	$\underline{B}_0$	$\underline{B}_1$	Period	Correlation[b]	1st Difference[c] Correlation	Pos.	Neg.	Difference of Means	Reduction[f] of Error
1930-195	0.62***	-25.94	52.98	1952-1980	0.64***	0.60***	19[$]	10	.06ns[g]	+0.38
1952-1980	0.37***	-19.51	45.46	1930-1951	0.78***	0.80***	15[$]	7	.09ns[g]	+0.60
1930-1980	0.50***	-23.10	49.54	1900-1929	0.49**	0.48**	23**	7	0.91ns[g]	+0.08
1900-1929[h]	0.21**	3.54	24.94							

[a] Multiple correlation coefficient squared and adjusted for loss of degrees of freedom [Draper and Smith, 1980].
[b] Pearson correlation coefficient [Steel and Torrie, 1980].
[c] Pearson correlation coefficient [Steel and Torrie, 1980] between first differenced series.
[d] One-tailed sign test [Conover, 1980].
[e] Two-tailed paired observation test for the difference between means [Steel and Torrie, 1980]. Failure to reject H_o is the optimum result [Gordon, 1982].
[f] Reduction of error statistic [Fritts, 1976]. Any positive number is significant [Gordon and LeDuc, 1981].
[g] Not significant ($P > 0.05$).
[h] Regression statistics computed only for comparison of coefficients between periods (1900-1929 and 1930-1980).
$ $P \leq 0.10$
* $P \leq 0.05$
** $P \leq 0.01$
*** $P \leq 0.001$

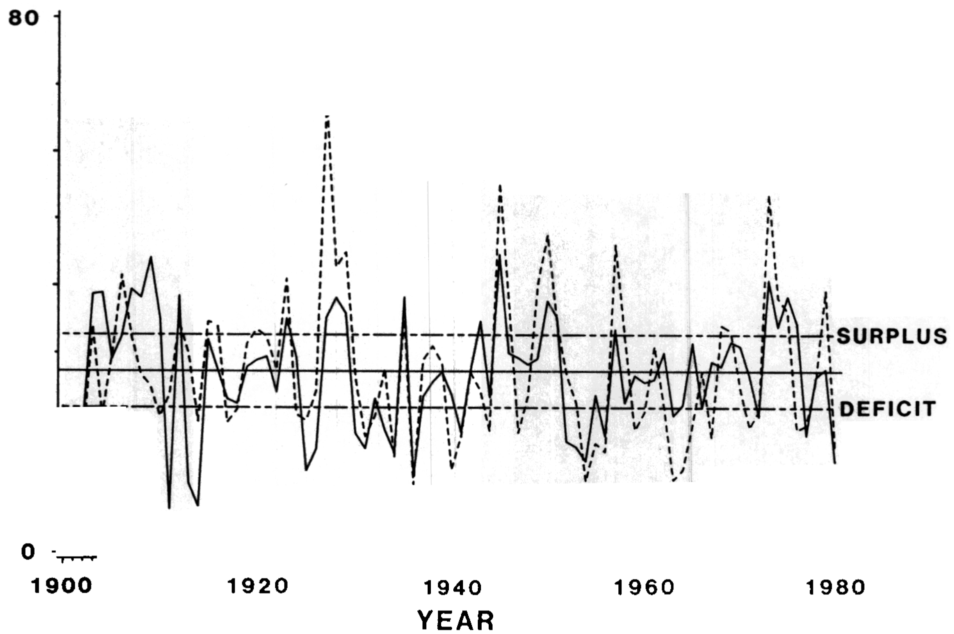

Figure 3. Reconstructed (solid line) and observed (dashed line) annual runoff (Jan.-Dec.) of the White River at Clarendon, Arkansas, for the calibration and verification periods. The solid horizontal line is the 1900-1980 gaged mean, and the two horizontal dashed lines are the surplus and deficit runoff thresholds (120 percent and 80 percent of the gaged mean, respectively).

B. Tree-Ring Data

Nine high quality tree-ring chronologies were selected from the 50 now available in the Southcentral United States [Stahle et al. 1985a, 1985b] on the basis of proximity to the White River Basin, tal length of record, and correlation with White River discharge. nine chronologies are based on two species, post oak and baldcypress, from well-drained upland and poorly drained wetland habitats, respectively, and both species exhibit strong sensitivity to drought during and before the growing season [Stahle and Hehr, 1984; Stahle et al., 1985a]. The direct correlation between post oak growth and moisture anomalies is consistent with the xeric nature of their upland sites, and it has been known for more than half a century that the moisture signal in tree growth can often be maximized by selecting native trees from these well drained upland positions [Douglass, 1920]. The direct correlation between the radial growth of swamp-grown baldcypress was discovered more recently [Bowers, 1973; Stahle et al., 1985a, 1988], and extends the range of drought sensitive tree species into a distinctive and widespread bottomland environment.

Each tree-ring chronology represents a mean value function of the detrended ring width measurement series available for each year from 30 to 50 trees per site, usually with two radii per tree. Chronology development started with the absolute crossdating of each radius [Stokes and Smiley, 1968] and the measurement of each dated ring to 0.01 mm. The series of annual ring width measurements were then detrended and transformed to dimensionless indices using the ARSTAN program [Cook, Holmes et al., 1986]. This procedure removes biological growth trends related to increasing tree age [Fritts, 1976], and the flexibility of the spline curves fitted to the measurement series was strictly controlled to avoid removing more long-term variance than absolutely necessary. Low order serial correlation present in the annual ring width series of most trees was largely removed from each tree-ring chronology using autoregressive (AR) modeling procedures [Cook, 1985] Finally, it was necessary to remove some remaining long-term variance trend in the derived chronologies, which appears to be due, in part, to changing chronology sample size and an age-related decline in growth vigor of oaks [e.g., Stahle and Cleaveland, 1988; Blasing et al., 1988].

When the nine residual series were averaged, this regional average series had weak serial correlation (r_{-1} =-0.13), apparently due to reinforcement of weak persistence in the separate chronologies. The average was modeled as an AR(3) process to derive a serially random predictor chronology for calibration [Meko, 1981]. Serial correlation in unmodeled -ring time series appears to arise primarily from biological factors (e.g., food storage, crown area, root area) [Fritts, 1976], but some persistence may also be due to climatic forcing. To enhance reconstruction fidelity in the frequency domain, the autoregressive properties of the Clarendon runoff series were added to the serially random tree-ring based estimates to complete the reconstruction [Meko, 1981] (see below).

C. <u>Calibration and Verification</u>

An empirical approach was used to identify the best predictor variables and time interval to calibrate the tree-ring and annual runoff series. The tree-ring and runoff data were both prewhitened prior to calibration, and marginally significant first-order serial correlation = 0.22, $P < 0.10$) was modeled as an AR(1 process and removed from the runoff series. Principal components analysis [Cooley and Lohnes, 1971] of the nine chronology network was performed and the amplitude series of the first two eigenvectors (with eigenvalues > 1.0, that retain 44.6 percent and 16.5 percent of the variance in the tree-ring data set, respectively) were entered into stepwise multiple regression with annual runoff from 1930 to 1980 [Draper and Smith, 1981]. This approach explained less variance in the gaged data than bivariate regression between the gaged runoff series and an average of the nine tree-ring chronologies. In addition, loadings on the second eigenvector all negative for post oak chronologies and positive for baldcypress chronologies, suggesting that physiological or ecological differences unrelated to hydrometerological conditions may be involved in the tree-ring variance associated with the second eigenvector. For these reasons, the regional average of the nine chronologies was used to reconstruct annual runoff.

In an attempt to further assess the homogeneity of the gaged data, and to select the most reliable subperiod for calibration, the tree-ring data and the annual runoff data were entered into linear regression for four subperiods, 1900-1929, 1930-1951, 1952-1980, and 1930-1980. These subperiods were selected in light of the apparent inhomogeneity in the Clarendon data before 1930, and the possible impact of Bull Shoals and other large impoundments on the tree growth - runoff relationship after

1951. The coefficients and statistics computed in these four regression analyses are listed in Table 1, and the tree-ring data explain the most runoff variance for the period from 1930 to 1951 and the least from 1900 to 1929. The regression slope and intercept (Table 1) computed during these two subperiods are significantly different ($P < 0.05$; Steel and Torrie, 1980; SAS Institute Inc., 1985) which, with double mass analysis, suggests that the gaged series is heterogeneous. Also, regression results indicate that post-war reservoir construction in basin has perturbed the natural relationship between climate and runoff. The regression model from the 1930 to 1980 period explains 50 percent of the annual runoff variance and was used to derive the transfer function to reconstruct runoff from 1700 to 1980 for the following reasons there is no statistical difference between the regression coefficients calculated for 1930 to 1951 and 1952 to 1980; (ii) serious inhomogeneity is not apparent in the discharge data after 1930; (iii) although the explained variance is maximized from 1930 to 1951, a sample size of only 22 years may not be adequate to insure a stable regression relationship

It should also be noted that calibrations based on separate averages of the upland post oak and bottomland cypress chronologies each explained 38 percent of the annual runoff variance from 1930 to 1980, twelve percent less than was explained by an average of both species. This is consistent with the assumption that runoff from the Ozark Plateau and Western Lowlands is reflected primarily by the post oak and baldcypress chronologies, respectively, and that each region can contribute independently to White River discharge measured at Clarendon.

The transfer function used to reconstruct White River annual run off was

$$\hat{Y}_t = 49.54\ X_t - 23.10 \qquad (2)$$

where $\hat{Y}_t$ is reconstructed runoff for year t in $km^3\ year^{-1}$ and X_t is the regional average of the nine tree-ring chronologies for year t. The standard errors of the slope and intercept are 6.95 and 6.98 $km^3\ year^{-1}$ respectively. The AR(1) persistence model determined for the gaged runoff series (AR(1) coefficient = 0.22) was then added to the estimated series. The addition of persistence changes the reconstructed mean slightly, so the reconstruction was adjusted to maintain the equality of the observed and reconstructed means during the calibration interval (1930-1980).

To evaluate the accuracy and stability of the reconstruction, the subperiod calibrations based on 1930 to 1951 and 1952 to 1980 (with co-efficients that are not statistically different from the 1930 to 1980 transfer function) were also used to reconstruct annual flow during the alternate period for which statistically independent gaged runoff data is available (1952-1980 and 1930-1951, respectively). Several statist-ical comparisons were made between the gaged and reconstructed runoff values during the verification periods (Table 1). The correlations and first difference correlations are both strongly positive and highly significant (Table 1), demonstrating strong covariance of observed and reconstructed series outside the period in which regression forces an optimum relationship. The sign tests [Conover, 1980] indicate signif-icant skill in reconstructing the direction of departures from the mean

(P<0.10) and paired t-tests [Steel and Torrie, 1980] reveal no significant difference between the average of reconstructed and observed runoff (Table 1).

The final verification test used was the reduction of error (RE) statistic which compares the actual and estimated runoff during the verification period with the actual mean runoff during the calibration interval, and is a measure of information gained by using the regression estimates of runoff rather than simply the mean of runoff during the calibration interval [Gordon, 1982; Blasing et al., 1988]. Values of the RE theoretically range from $-\infty$ to +1.0, and any positive value is considered significant ($P < 0.05$, $N>10$) [Gordon and LeDuc, 1981]. The RE statistics calculated on the actual and reconstructed runoff data are +0.38 and +0.60. The positive RE statistics indicate that the reconstruction is contributing unique paleohydrological information.

The reconstruction has also been compared with the independent gaged data from 1900 to 1929 that was not used in any calibration Table 1, Fig. 3). Although this early runoff data may be systematically biased relative to the post-1929 data, it can still be useful for independent verification of the reconstruction. All verification tests are passed, although the correlations are lower than found for 1930-1951 and 1952-1980, and the RE is low, but still positive (Table 1)

The descriptive statistics in Table 2 indicate that the reconstruction reproduces the mean and variance properties of the independent runoff data reasonably well, but examination of Fig. 3 reveals specific limitations of the regression estimates. The reconstructed runoff series

TABLE 2. Statistical characteristics of observed and reconstructed annual runoff of the White River at Clarendon, Arkansas.

Statistic	Observed 1900 - 1980	Observed 1930 - 1980	Reconstructed 1900 - 1980	Reconstructed 1930 - 1980	Reconstructed 1700 - 1980
Number of years	81	51	81	51	281
Mean[a]	27.22	25.97	26.55	25.97	26.29
Standard deviation[a]	10.99	10.83	8.83	7.61	7.69
Maximum[a]	68.05	55.37	44.61	44.61	45.69
Minimum[a]	10.27	10.27	6.61	11.53	6.61
Range[a]	57.78	45.10	38.00	33.08	39.08
Median[a]	25.81	24.38	27.48	26.41	26.79
Coefficient of Variation	40.4%	41.7%	33.3%	29.3%	29.3%
Serial Correlation	0.22ns[b]	0.17ns[b]	0.16ns[b]	0.09ns[b]	0.20***
Skewness	.03	0.85	-0.18	0.22	-0.03
Kurtosis	.58	0.39	-0.54	-0.38	-0.37
Distribution Normal	Yes[c]	Yes	Yes	Yes	Yes

[a] km^3 $year^{-1}$.
[b] Not significant, $P > 0.05$
[c] $P < 0.08$.
*** $P < 0.001$.

does not fully reproduce the extremes apparent in the gaged data, particularly positive extremes. The worst estimated annual runoff value is 1927, which is the largest annual runoff amount ever measured in the White River Basin. This indicates that the tree-ring estimates of the magnitude of high runoff periods contain the greatest errors, probably due largely to inability of trees to respond linearly to very wet conditions [Fritts, 1976]. Fortunately, the point at which estimation errors become large appears to be well above the surplus threshold set at 120 percent of the mean (Fig. 3). This indicates that the reconstruction should be useful for investigations of the history and timing of surplus flows defined conservatively as less than 130 percent of the long-term mean. Of course, the surplus issue also involves interest in the absolute magnitude of surplus flows, but reconstruction errors associated with the largest runoff amount (Fig. 3) indicates that the reconstruction should be interpreted cautiously in terms of the absolute magnitude of surplus flows

PRINCIPAL FINDINGS AND SIGNIFICANCE

A. Reconstructed White River Runoff: 1700 to 1980

The reconstructed annual runoff for the White River at Clarendon from 1700 to 1980 is presented in Fig. 4 and Appendix 2. The descriptive statistics for the gaged and reconstructed series are presented in Table 2. The variance and range statistics are highest for the gaged data, illustrating the underestimation of runoff extremes by the reconstruction. The skewness and kurtosis of the gaged runoff are also both larger than for the reconstruction, but both series approximate a normal

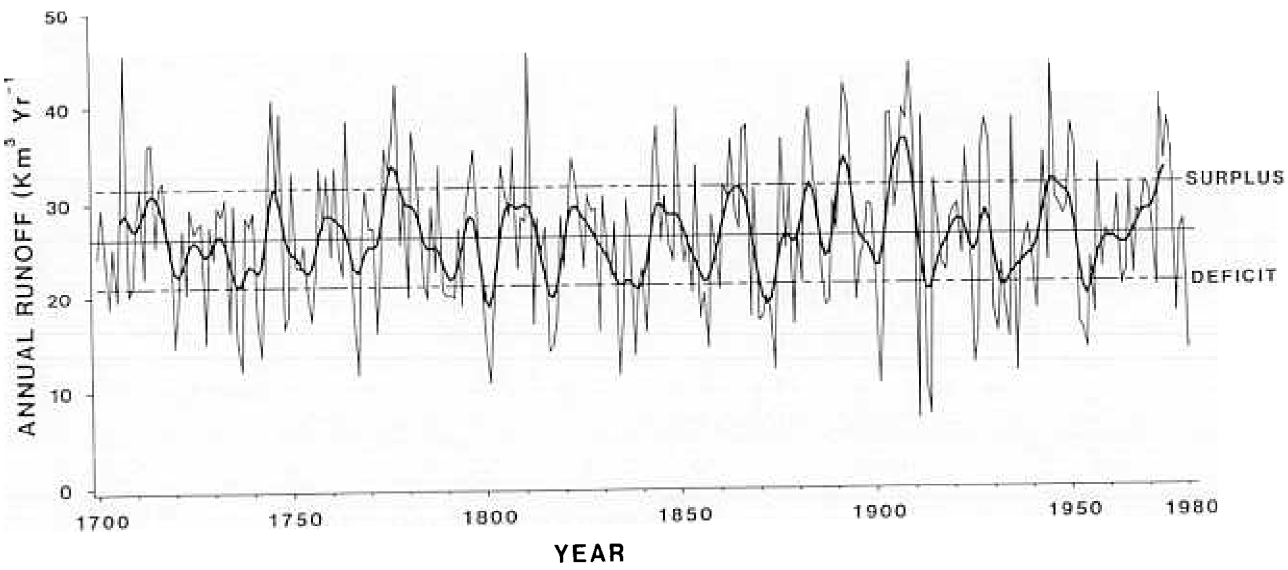

Figure 4. Reconstructed annual runoff plotted with a low-pass filter that removes variance at frequencies of less than eight years (Fritts, 1976). The solid horizontal line is the 1700-1980 reconstructed mean, and the two horizontal dashed lines are the threshold used in the analysis of surplus and deficit runoff (120 percent and 80 percent of the mean, respectively).

distribution. The gaged and reconstructed mean runoff for the period 1930 to 1980 are less than the reconstructed long-term mean from 1700 to 1980, but these differences are not statistically significant [Steel and Torrie, 1980].

Examination of Fig. 4 suggests a long-term trend in annual runoff from 1800 to 1900, but there is no significant linear trend from 1700 to 1980. There does appear to be a substantial increase in runoff variance around 1900, which is statistically confirmed by an F-test on the ratio of reconstructed variances from 1700 to 1899 and 1900 to 1988 ($P<0.05$) [Steel and Torrie, 1980]. The four lowest, and two of the four highest reconstructed annual runoff values occur in the twentieth century. Assuming that the ratio of actual to reconstructed runoff variance is time stable, the White River appears to have experienced more variable runoff during the twentieth century than over the preceding 200 years. This apparent change in runoff variability may be due to an actual climate change [e.g., Kutzbach, 1970], may reflect anthropogenic disturbances to the remnant old-growth forests sampled, or may reflect large scale anthropogenic disturbances to the watershed (e.g regional land clearing, acid rain deposition, or CO_2 fertilization). Efforts to detrend the variance of the tree-ring time series could also cause an increase in twentieth century variance [Blasing, et al., 1988] but our variance detrending was cautious and is probably not responsible.

The filtered reconstruction (Fig. 4) suggests that prolonged (5- to 10-year) low and high runoff departures tend to alternate in an oscillatory manner, but these oscillations are too irregular for direct po ıd

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tially (suggested by Fig. 3), and should provide some insight into the secular variability of surplus flows in the White River system.

If the intervals between surplus flows are randomly distributed, they should approximate an exponential distribution, and this hypothesis can be tested with the Lilliefors criterion [Conover, 1980]. The distribution of intervals between surplus years (≥ 120 percent of the mean) the test of randomness for gaged runoff from 1900 to 1980 ($P<0.05$) and for reconstructed runoff from 1700 to 1980 ($P<0.01$) The reconstructed data also fail when tested from 1900 to 1980 ($P<0.01$) Inspection of test results indicates that the gaged series fails Lilliefors test primarily because surplus runoff events tend to cluster into successive years (high incidence of one year intervals between surplus run- Three consecutive years of surplus occur three times (1927-1929 1949-1951, and 1973-1975). In the reconstruction, four consecutive years of surplus occur (1774-1777, 1891-1894), and six of nine years are estimated to have had surplus runoff from 1774 to 1782.

The longest interval without surplus runoff in the gaged series was 11 years, occurring from 1957 to 1968, and ten consecutive years, from 1935 to 1945, were also recorded (Fig. 4). The reconstructed runoff series indicates that prolonged periods of 27 years (1717 to 1744), 20 years (1823 to 1843), and 11 years (1811 to 1822) without surplus runoff have occurred in the White River Basin since 1700. The underestimation of actual runoff amounts by the reconstruction is a potential problem to a threshold analysis of surplus or deficit flow, but does not appear to be a serious limitation to this study because (i estimation error

uted when compared to an exponential distribution with Lilliefors test ($P<0.01$). The clustering of low runoff years also appears to explain this non-randomness, with several examples of successive drought years lasting from two to five years in the period from 1700 to 1980. During the driest periods the reconstruction indicates that deficit flows occurred in as many as six of seven years from 1868 to 1874, and six of 10 years from 1785 to 1794. The recurrence of these historic dry periods over the White River Basin would no doubt place severe strain on the highly developed surface water supply system, even though this system has been designed and managed with severe short-term drought as a primary consideration. On the positive side, the longest interval between deficit runoff was seven years in the observed data (1947 to 1954) and 12 years in the reconstructed data prior to the twentieth century 1708 to 1720 and 1841 to 1853) (Fig. 4). Most of these periods without deficit flow were characterized by a high incidence of surplus runoff.

The non-random interannual distribution of surplus and deficit runoff events in the White River Basin appears to be a product of large scale climatic variability. Some of this variability may eventually be tied to more slowly changing boundary conditions of the atmosphere such as sea surface temperatures, or the El Niño/Southern Oscillation. If such associations can be demonstrated, they may permit some improvement in long-term hydrological forecasts once a change in the related boundary condition is detected. In lieu of a better understanding of the atmospheric conditions sesponsible for extended periods of surplus or deficit runoff in the White River Basin, we have attempted to identify statistical ru rui hi

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data indicate that surplus and deficit flows are not randomly distributed through time. This implies that regimes of unusually low or high flows can become established and persist for two or more years, as has been witnessed during the twentieth century (e.g., low runoff was recorded for three consecutive years in 1900-1902, 1954-1956, and 1963-1965; high runoff occurred three consecutive years in 1927-1929, 1949-1951, and 1973-1975). Periods as long as 27 years without surplus runoff occur in the reconstructed record. Non-random occurrence of surplus and deficit runoff years may also imply a systematic component to the atmospheric conditions that govern discharge in the White River and elsewhere in the Southcentral United States (e.g., Stahle and Cleaveland, 1988). This interannual persistence of low and high runoff regimes, and the presence of spectral peaks in the 14.0 to 18.67 year period range, were both also detected in independent climate and tree-ring data sets from Texas [Stahle and Cleaveland, 1988] and suggest a large-scale macroclimate control. If the physical mechanism (or mechanisms) responsible for this apparent persistence of climate indices and runoff in the Southcentral United States can be identified, it could lead to improved forecasting of runoff extremes

This study demonstrates that tree-ring data can be useful for applied hydrological analysis in the Central United States, including detection of inhomogeneity in gaging records. With the extensive network of existing chronologies, and the development of longer red cedar and baldcypress chronologies, there is considerable potential to extend these hydrological applications in both time and space.

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APPENDIX

Table -1. Clarendon, Arkansas, Monthly and Annual Mean Daily Discharge ft^3 sec^{-1}).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct			Annual
1900	16400	25000	41400	22300	29100	24100	14300	6500	7900	6900	15600	29100	19900
1901	20000	23400	36800	39100	27800	7900	4500	3700	3300	2800	2900	7000	14900
1902	6200	7800	37000	34800	15500	10700	13400	5400	5500	5100	7500	49100	17400
1903	45100	54000	132100	65400	34900	75100	17300	10400	6000	6500	5100	5200	38000
1904	13000	31100	30100	82100	39200	30500	22100	10300	6700	4900	3900	4200	23000
1905	7200	9500	30800	41300	80900	62700	29800	47200	20200	14700	19000	31700	33100
1906	61600	77800	42800	122000	49000	22800	14300	18800	18100	37500	27100	69300	46500
1907	47800	58400	57700	41900	122200	73800	23100	10200	8000	6600	10500	12300	36500
1908	26100	41300	77500	78200	127900	53500	16200	11400	8200	7700	7000	20700	29900
1909	12000	29700	88600	47800	50600	36700	25500	10900	6400	5300	7500	14500	28000
1910	15000	12300	34100	35100	29200	41900	31800	16600	9500	30800	10300	6900	22900
1911	15100	18500	26500	53400	54800	8800	7000	39600	45300	13500	9600	25200	26500
1912	39400	35300	77900	127200	96500	25600	25000	8800	6400	6800	10600	6400	38800

Table Continued

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1913	67000	77900	33700	30900	33700	9700	7000	7500	6800	13500	25400	700	33400
1914	21900	33100	45100	43600	700	1900	5800	5500	4500	9600	5500	15700	22100
1915	18800	45000	75000	34500	25100	44200	26300	29900	99900	18100	14400	35200	38700
1916	101400	54800	46500	42700	32900	23900	15300	7400	6200	5600	5300	12400	38200
1917	26200	15200	29000	52000	43800	1300	7000	12400	7400	5200	4700	5900	21900
1918	5200	31400	19600	29400	76200	53900	9400	5900	8300	7300	12800	27800	24100
1919	66400	28400	43200	34400	34200	49300	22900	7700	5900	7500	47600	52600	35100
1920	47100	57700	40700	80300	78000	65400	14700	1300	16000	10300	12000	18600	37500
1921	26700	32800	54400	106000	107800	24300	15200	1500	7800	5600	10700	30100	36200
1922	24800	18200	58800	136600	75900	15400	9800	6600	4900	4600	5000	7400	30700
1923	22200	97000	80200	63400	80200	15000	22500	9800	10700	7600	12100	29800	45900
1924	36900	26500	23400	24800	33600	57700	25700	100	9000	7100	5200	12000	23300
1925	4300	16400	24800	15600	100	8100	6200	5100	5500	40100	74400	34200	22200
1926	22000	700	40800	50000	19000	10000	5600	10300	16000	31400	33900	44400	27200
1927	1800	125800	53400	207000	138400	07800	32800	40100	25000	34200	26700	700	76200

Table Continued.

Year	Jan	Feb	Mar	Apr	May	Jun			Sep		Nov	Dec	Annual
1928	54400	34200	33300	81800	81800	91600	107800	18000	15000	10000	13400	32000	47800
1929	36400	81800	51800	104200	127600	89800	25800	1000	7800	7200	14300	15600	50300
1930	77400	97000	43500	21300	33100	17700	6800	5800	8200	12300	1200	19000	29400
1931	10300	24200	46900	38000	28100	7000	9800	4200	8900	6100	6600	24900	19600
1932	72700	77900	31000	30600	1600	3900	14800	6500	4700	4400	6000	7000	23000
1933	56000	42900	36000	54500	84000	35600	8500	8800	12300	9400	9600	13700	30900
1934	19700	9700	20800	72500	16400	3200	5200	4500	8300	6400	6400	15400	16100
1935	23000	35200	56000	39200	64400	97600	46400	1200	6600	6600	13200	20200	40000
1936	10400	8200	12400	21900	13200	5700	5200	3100	4400	16200	22300	4700	1500
1937	36400	102000	35000	23400	42600	23200	14500	7700	8100	1400	1300	16900	32400
1938	29700	77800	82300	86700	44600	44400	14200	10100	5500	4500	12500	8500	34700
1939	15500	59900	34300	54600	1500	40600	20800	7900	5500	4600	5200	5800	31900
1940	7300	1400	4900	36600	40200	10500	7600	7500	6000	4400	5500	15500	14000
1941	26000	29100	15400	23300	27400	8700	6300	5200	5600	20000	46400	23100	19600
1942	39100	1000	49000	60500	49500	24900	12400	1300	100	6100	28200	31500	30300

Table Continued

Year	Jan	Feb	Mar	Apr			Jul		Sep		Nov	Dec	Annual
1943	55600	15400	22400	38400	75900	73800	700	6000	4400	4200	5000	4700	27300
1944	6300	20600	47600	57600	54100	18900	7200	5300	5000	5600	4800	12700	20500
1945	20800	18600	139300	215100	93500	16800	56100	10500	10500	24600	22300	15800	52000
1946	50700	51600	54900	41000	59000	33400	14200	12400	8000	5500	33800	56400	700
1947	35800	7000	13700	34800	48900	29000	13200	6900	5800	6000	12300	18400	20200
1948	35000	29900	64900	48100	22900	18700	30100	16100	8500	6300	10700	24300	26300
1949	58300	156000	79500	56200	25700	32300	30100	12100	9400	30400	22800	28000	45100
1950	14000	21000	57900	100	83200	100	23600	28500	39900	15900	7300	16600	53200
1951	32800	42100	100	46200	37400	100	46200	24700	15400	1300	30500	72400	38400
1952	55500	38300	56600	74200	46800	14900	8600	7400	5800	5500	7900	26700	29900
1953	18200	1000	53700	55800	56800	24400	10800	9500	8600	8700	6800	100	25200
1954	15200	20500	15900	7700	30800	1600	8200	7300	4700	100	4000	5400	12100
1955	12100	12100	30300	45200	28600	31800	19100	1400	9000	700	7000	7500	18500
1956	7500	59500	33100	7000	21600	14500	1900	9300	7900	7000	7400	9800	7000
1957	4200	44400	32900	78400	99400	86700	16500	49800	35500	100	53500	52500	1600

Table Continued

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1958	34500	28400	39300	57300	91200	56000	25200	27400	17400	13600	100	26900	35800
1959	21000	100	38900	26400	18100	18000	12100	10700	10600	13200	100	25600	20700
1960	37400	32300	35200	22600	36000	400	22000	12400	9900	8200	8500	7600	23600
1961	16100	19300	51000	82400	85900	46500	1200	24400	10100	8200	10100	29800	34700
1962	32500	42200	58100	49200	32500	12700	13100	10500	15200	13000	9000	10400	24700
1963	3900	3900	26800	14100	10800	23600	12100	10000	7400	7000	7300	8100	12300
1964	6200	8800	50500	59100	24300	10600	10200	1200	9700	10000	3800	19200	14000
1965	24100	34900	29800	40800	23200	20200	15900	13600	18500	14800	10000	1000	21400
1966	52500	47000	42400	29100	79000	30300	100	20400	4700	10700	10200	10900	30400
1967	7300	18100	100	15500	32600	19300	19500	100	9700	1800	16300	36900	19400
1968	41800	47900	39300	66100	78800	40200	26700	7300	13000	17200	21900	47200	38100
1969	74100	12800	50800	66600	46100	19800	14900	12400	1000	10500	9800	12400	37200
1970	27700	18300	29800	28700	63900	100	4300	20800	16600	23700	32000	31800	27600
1971	44500	1500	38900	15200	18200	15600	10900	4500	10000	9600	8100	24500	21000
1972	19800	12900	13800	22600	1500	13800	14500	13800	1000	15700	55800	50700	23900

Table Continued.

Year	Jan	Feb		Apr	May	Jun					Nov	Dec	Annual
1973	47400	55800	75100	107900	136100	52500	34500	32700	32500	19300	20800	95700	60100
1974	60000	70700	67000	53400	50200	56600	29200	24300	22600	18500	28000	32500	42600
1975	53600	54200	74000	14900	55300	23200	15900	17700	18400	14400	13100	21500	40400
1976	27200	24200	24800	23200	20000	25600	34600	19900	12200	13900	1800	5900	20600
1977	12900	12200	27300	58200	20700	10600	1800	10000	13900	20900	23900	35100	21500
1978	30500	27300	43200	53800	49400	26000	15400	10300	16700	8600	15000	50300	28900
1979	40600	1000	77400	100400	96000	50500	29500	27800	21600	17300	15800	18600	43900
1980	23900	18200	26200	40200	14400	7600	100	10000	7700	7500	10900	12800	17800

APPENDIX 2

Table 2-1. Clarendon, Arkansas, Reconstructed Annual Runoff (km^3 $year^{-1}$).

Decade	0	1	2	3	4	5	6	7	8	9
700	24.34	29.52	23.98	18.74	25.27	19.52	31.63	45.45	20.05	21.35
710	28.07	31.53	22.04	35.90	36.17	25.39	31.64	32.27	26.56	25.90
1720	14.66	19.96	27.12	20.23	29.46	26.79	27.58	27.91	15.00	27.52
1730	24.03	29.55	28.54	30.40	16.29	29.78	15.17	12.10	28.47	27.51
1740	29.03	7.48	13.55	22.24	33.62	40.63	30.23	39.14	16.43	17.93
1750	33.07	23.12	22.91	25.44	20.06	17.29	22.37	33.50	27.23	32.69
1760	24.23	33.46	24.99	22.09	38.39	26.08	17.72	11.62	26.38	31.11
1770	27.15	27.17	15.98	23.32	35.44	33.21	36.43	42.19	25.47	30.67
780	19.72	37.23	34.39	28.17	21.55	19.60	29.47	22.43	33.66	20.48
790	19.86	20.02	19.61	27.19	18.81	28.90	32.06	35.29	28.07	20.88
1800	14.54	10.62	18.23	24.86	33.65	30.73	28.50	35.49	22.86	28.36
1810	27.78	45.69	16.83	28.32	24.45	27.27	13.92	14.65	17.58	28.43
1820	22.94	29.02	34.37	31.83	28.40	22.89	30.64	28.98	29.16	15.97
1830	30.51	25.08	21.86	27.69	1.43	7.32	30.16	25.40	13.41	20.88

APPENDIX 2

Table 2-1. Clarendon, Arkansas, Reconstructed Annual Runoff (km^3 $year^{-1}$).

Decade	0	1	2	3	4	5	6	7	8	
1700	24.34	29.52	23.98	18.74	25.27	19.52	31.63	45.45	20.05	21.35
1710	28.07	31.53	22.04	35.90	36.17	25.39	31.64	32.27	26.56	25.90
720	14.66	19.96	27.12	20.23	29.46	26.79	27.58	27.91	15.00	27.52
730	24.03	29.55	28.54	30.40	16.29	29.78	15.17	12.10	28.47	27.51
1740	29.03	17.48	13.55	22.24	33.62	40.63	30.23	39.14	16.43	17.93
1750	33.07	23.12	22.91	25.44	20.06	17.29	22.37	33.50	27.23	32.69
760	24.23	33.46	24.99	22.09	38.39	26.08	17.72	11.62	26.38	31.11
770	27.15	27.17	15.98	23.32	35.44	33.21	36.43	42.19	25.47	30.67
1780	19.72	37.23	34.39	28.17	21.55	19.60	29.47	22.43	33.66	20.48
1790	19.86	20.02	19.61	27.19	18.81	28.90	32.06	35.29	28.07	20.88
1800	4.54	10.62	18.23	24.86	33.65	30.73	28.50	35.49	22.86	28.36
1810	27.78	45.69	16.83	28.32	24.45	27.27	13.92	14.65	7.58	28.43
1820	22.94	29.02	34.37	31.83	28.40	22.89	30.64	28.98	29.16	15.97
1830	30.51	25.08	21.86	27.69	11.43	7.32	30.16	25.40	13.41	20.88

Table 2-1, Continued.

Decade	0	1	2	3	4	5	6	7	8	9
1840	22.82	15.91	24.05	33.67	37.62	25.81	30.39	25.21	23.57	39.66
1850	27.49	23.43	26.15	20.16	33.56	17.38	20.07	14.22	28.44	24.83
1860	20.52	31.61	30.33	36.19	28.71	26.92	37.18	37.70	17.50	31.14
1870	17.05	17.52	19.75	18.11	11.85	25.04	36.22	24.90	31.23	16.72
1880	26.81	21.15	36.35	39.50	31.97	30.71	22.40	18.55	19.08	29.80
1890	26.76	34.61	41.99	39.80	31.49	19.16	23.68	25.37	29.55	29.33
1900	21.90	10.31	18.76	38.70	38.93	29.07	32.40	39.42	38.14	44.15
1910	35.02	6.61	38.45	10.48	7.01	31.95	27.48	23.03	22.35	27.90
1920	28.92	29.44	24.11	35.07	29.26	12.37	15.65	35.14	38.14	35.78
1930	17.97	15.69	23.16	18.51	15.06	38.23	11.53	23.48	25.67	27.19
1940	23.66	18.13	27.61	34.65	23.32	44.61	29.92	29.22	28.22	29.14
1950	37.66	35.18	16.75	15.91	13.80	23.69	17.59	33.44	22.51	26.59
1960	25.56	26.03	30.04	20.57	22.21	31.48	21.78	28.66	27.95	31.61
1970	30.92	26.41	20.42	40.85	33.80	38.34	34.24	17.63	26.41	27.60
1980	13.69									