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Tree Ring Analysis of Surplus and Deficit Runoff in the White River, Arkansas

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A 281-year reconstruction of White River calendar year runoff at Clarendon, Arkansas, was developed from a regional average of nine tree ring chronologies in Oklahoma, Missouri, and Arkansas (including six post oak and three bald cypress chronologies). Inhomogeneity of the gaged runoff series prior to 1930 was detected with two independent double mass analyses, comparing the gaged data with Arkansas state average annual precipitation and the regional tree ring chronology average. The homogeneous runoff data from 1930 to 1980 were calibrated with the average tree ring data using regression. The variance of the reconstruction increases significantly during the twentieth century and may reflect climatic change and/or anthropogenic disturbances in the watershed. Years of surplus and deficit runoff are nonrandomly distributed in both the gaged and reconstructed series. This nonrandomness appears to be caused primarily by interannual persistence of runoff extremes, which may provide a basis for some improvement of probabilistic forecasts of annual runoff for the White River.

INTRODUCTION

The demand for 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 south central 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 south central 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 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, manuscript in preparation, 1989), 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 Texas has also been investigated [*U.S. Army Corps of Engineers*, 1982].

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 discontinuous nature of surplus flows would impose serious planning and design constraints on the possible use of this water resource component. Because gaged runoff data are limited to the twentieth 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].

Proxy tree ring data are often well 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 well 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 oak (*Quercus stellata*) and bald cypress (*Taxodium distichum*) chronologies located in and near the White River Basin to estimate annual runoff for the White River at Clarendon, Arkansas, from A.D. 1700 to 1980. The gaged and reconstructed runoff data are then analyzed in terms of (1) the timing, distribution, and duration of surplus and deficit runoff, (2) possible interannual persistence of surplus or deficit runoff levels, (3) possible periodicity in the annual runoff data, and (4) any secular changes in the mean or variance of the runoff data that might have implications for hydrological management in the White River Basin. These studies are warranted, in part, because analyses of contemporaneous gaged and reconstructed runoff data indicate that the reconstruction is not systematically biased in the range of above and below average runoff amounts used to define surplus and deficit flows.

STUDY AREA

The White River is the principal drainage of the Ozark Plateau and Western Lowlands of Arkansas and Missouri and has served as the focus of historical settlement and twentieth century economic development in the region. A sharp change in the hydrologic profile of the stream occurs at

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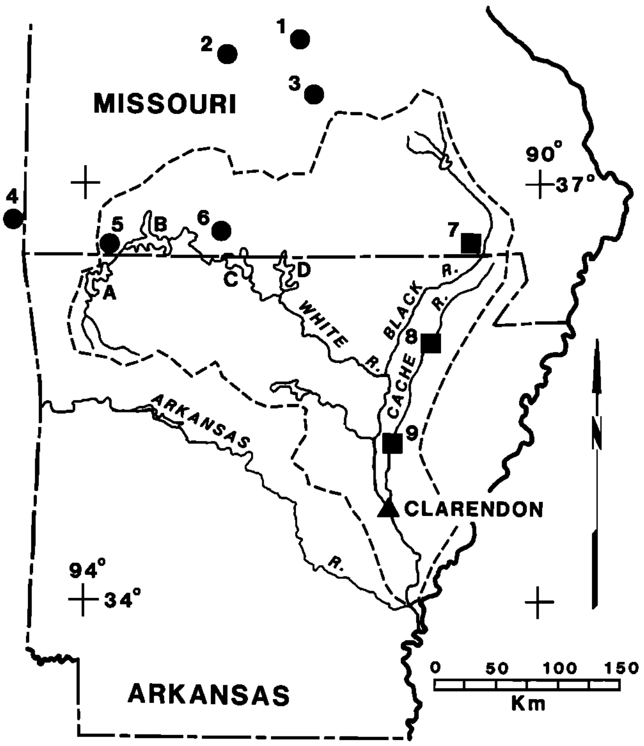

Fig. 1. Locations of the tree ring chronologies used in reconstruction of White River annual runoff at Clarendon, Arkansas (triangle). The six post oak chronologies (circles) are 1, Little Maries River, Missouri; 2, Hahatonka, Missouri; 3, Democrat Ridge, Missouri; 4, Neosho River, Oklahoma; 5, Roaring River, Missouri; 6, Clayton Ridge, Missouri; and the three bald cypress chronologies (squares) are 7, Allred Lake, Missouri; 8, Egypt, Arkansas; and 9, Black Swamp, Arkansas. The four largest impoundments built prior to 1980 in the White River Basin (dashed line) are A, Beaver; B, Table Rock; C, Bull Shoals; and D, Norfork.

the confluence with the Black River, where the White leaves the uplifted Ozark Plateau and enters the Western Lowlands of the lower Mississippi alluvial valley (Figure 1). The Clarendon gaging station is located below the confluence of the Cache River and, consequently, reflects the combined discharge from the Ozark and Western Lowland portions of the basin, an area of 66,187 km^2. However, the 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 Survey*, 1984], and these projects have promoted both the economic development of the central Ozarks and agricultural productivity along the lower White River. The volume of 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.

PREVIOUS RESEARCH

Properly developed tree ring chronologies are particularly well suited 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 [*Fritts*, 1976; *Stockton and Boggess*, 1980]. A number of previous studies have employed proxy tree ring data to extend relatively short streamflow records. In reconstructing annual runoff in the Colorado River, *Stockton* [1975] found that the long-term mean was only about 13.5 MAF (16.6 km^3) year^{-1} between 1564 and 1962, some 2.0 MAF (2.5 km^3) 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 practical value 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 variables associated with past lake levels.

The use of tree ring data to investigate long streamflow series in the south central 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. Individual red cedar up to 700 years old have been reported from the Ozark Plateau [*Guyette*, 1981] and hold great promise as long proxy hydrological series.

GAGING DATA

The U.S. Army Corps of Engineers discharge record at Clarendon (Table 1) was selected for reconstruction because it is the longest in Arkansas (1900–1988), it provides a reasonable integration of runoff 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 postwar reservoir development. Discharge data are normally estimated from gage height measurements using annually revised rating tables. Clarendon discharge data were not available from 1921 to 1930, but instead, a single rating table representing low water conditions in 1917 and high water levels in 1927 was used to compute discharge from 1921 to 1930 (S. A. Lehr, Jr., personal communication, 1987). White River runoff (in cubic kilometers per calendar year) was then calculated by multiplying the annual mean daily discharge

TABLE 1. Monthly and Annual Mean Daily Discharge (Cubic Feet Per Second), Clarendon, Arkansas.

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1900	16,400	25,000	41,400	22,300	29,100	24,100	14,300	6,500	7,900	6,900	15,600	29,100	19,900
1901	20,000	23,400	36,800	39,100	27,800	7,900	4,500	3,700	3,300	2,800	2,900	7,000	14,900
1902	6,200	17,800	37,000	34,800	15,500	10,700	13,400	5,400	5,500	5,100	7,500	49,100	17,400
1903	45,100	54,000	132,100	65,400	34,900	75,100	17,300	10,400	6,000	6,500	5,100	5,200	38,000
1904	13,000	31,100	30,100	82,100	39,200	30,500	22,100	10,300	6,700	4,900	3,900	4,200	23,000
1905	7,200	9,500	30,800	41,300	80,900	62,700	29,800	47,200	20,200	14,700	19,000	31,700	33,100
1906	61,600	77,800	42,800	122,000	49,000	22,800	14,300	18,800	18,100	37,500	27,100	69,300	46,500
1907	147;800	58,400	57,700	41,900	122,200	73,800	23,100	10,200	8,000	6,600	10,500	12,300	36,500
1908	26,100	41,300	77,500	78,200	127,900	53,500	16,200	11,400	8,200	7,700	7,000	20,700	29,900
1909	12,000	29,700	88,600	47,800	50,600	36,700	25,500	10,900	6,400	5,300	7,500	14,500	28,000
1910	15,000	12,300	34,100	35,100	29,200	41,900	31,800	16,600	9,500	30,800	10,300	6,900	22,900
1911	15,100	18,500	26,500	53,400	54,800	8,800	7,000	39,600	45,300	13,500	9,600	25,200	26,500
1912	39,400	35,300	77,900	127,200	96,500	25,600	25,000	8,800	6,400	6,800	10,600	6,400	38,800
1913	67,000	77,900	33,700	90,900	33,700	9,700	7,000	7,500	6,800	13,500	25,400	31,700	33,400
1914	21,900	33,100	45,100	43,600	51,700	11,900	6,800	5,500	14,500	9,600	6,500	15,700	22,100
1915	18,800	45,000	75,000	34,500	25,100	44,200	26,300	29,900	99,900	18,100	14,400	35,200	38,700
1916	101,400	164,800	46,500	42,700	32,900	23,900	15,300	7,400	6,200	5,600	5,300	12,400	38,200
1917	26,200	15,200	29,000	52,000	43,800	41,300	17,000	12,400	7,400	5,200	4,700	8,900	21,900
1918	8,200	31,400	19,600	29,400	76,200	53,900	9,400	5,900	8,300	7,300	12,800	27,800	24,100
1919	66,400	28,400	43,200	34,400	34,200	49,300	22,900	7,700	5,900	17,500	47,600	62,600	35,100
1920	47,100	57,700	40,700	80,300	78,000	65,400	14,700	11,300	16,000	10,300	12,000	18,600	37,500
1921	26,700	32,800	54,400	106,000	107,800	24,300	15,200	11,500	7,800	6,600	10,700	30,100	36,200
1922	24,800	18,200	58,800	136,600	75,900	15,400	9,800	6,600	4,900	4,600	5,000	7,400	30,700
1923	22,200	97,000	80,200	63,400	80,200	115,000	22,500	9,800	10,700	7,600	12,100	29,800	45,900
1924	36,900	26,500	23,400	24,800	33,600	57,700	25,700	17,100	9,000	7,100	6,200	12,000	23,300
1925	14,300	16,400	24,800	15,600	21,100	8,100	6,200	5,100	5,500	40,100	74,400	34,200	22,200
1926	22,000	41,700	40,800	50,000	19,000	10,000	6,600	10,300	16,000	31,400	33,900	44,400	27,200
1927	71,800	125,800	63,400	207,000	138,400	107,800	32,800	40,100	25,000	34,200	26,700	41,700	76,200
1928	54,400	34,200	33,300	81,800	81,800	91,600	107,800	18,000	15,000	10,000	13,400	32,000	47,800
1929	36,400	81,800	81,800	104,200	127,600	89,800	25,800	11,000	7,800	7,200	14,300	15,600	50,300
1930	77,400	97,000	43,500	21,300	33,100	17,700	6,800	5,800	8,200	12,300	11,200	19,000	29,400
1931	10,300	24,200	46,900	38,000	28,100	17,000	9,800	14,200	8,900	6,100	6,600	24,900	19,600
1932	72,700	77,900	31,000	30,600	11,600	8,900	14,800	6,500	4,700	4,400	6,000	7,000	23,000
1933	56,000	42,900	36,000	54,500	84,000	35,600	8,500	8,800	12,300	9,400	9,600	13,700	30,900
1934	19,700	9,700	20,800	72,500	16,400	8,200	5,200	4,500	8,300	6,400	6,400	15,400	16,100
1935	23,000	35,200	56,000	99,200	64,400	97,600	46,400	11,200	6,600	6,600	13,200	20,200	40,000
1936	10,400	8,200	12,400	21,900	13,200	5,700	5,200	3,100	4,400	16,200	22,300	14,700	11,500
1937	96,400	102,000	35,000	23,400	42,600	23,200	14,500	7,700	8,100	11,400	11,300	16,900	32,400
1938	29,700	77,800	82,300	86,700	44,600	44,400	14,200	10,100	5,500	4,500	12,500	8,500	34,700
1939	15,500	69,900	84,300	64,600	61,500	40,600	20,800	7,900	5,500	4,600	5,200	5,800	31,900
1940	7,300	11,400	14,900	36,600	40,200	10,500	7,600	7,500	6,000	4,400	5,500	15,500	14,000
1941	26,000	29,100	15,400	23,300	27,400	8,700	6,300	5,200	5,600	20,000	46,400	23,100	19,600
1942	39,100	41,000	49,000	60,500	49,500	24,900	12,400	11,300	11,100	6,100	28,200	31,500	30,300
1943	65,600	15,400	22,400	38,400	75,900	73,800	11,700	6,000	4,400	4,200	5,000	4,700	27,300
1944	6,300	20,600	47,600	57,600	54,100	18,900	7,200	5,300	5,000	5,600	4,800	12,700	20,500
1945	20,800	18,600	139,300	215,100	93,500	116,800	56,100	10,500	10,500	24,600	22,300	15,800	62,000
1946	60,700	61,600	64,900	41,000	59,000	83,400	14,200	12,400	8,000	6,500	33,800	56,400	41,700
1947	35,800	17,000	13,700	34,800	48,900	29,000	13,200	6,900	5,800	6,000	12,300	18,400	20,200
1948	35,000	29,900	64,900	48,100	22,900	18,700	30,100	16,100	8,500	6,300	10,700	24,300	26,300
1949	58,300	156,000	79,500	66,200	25,700	32,300	30,100	12,100	9,400	30,400	22,800	28,000	45,100
1950	114,000	121,000	67,900	54,100	83,200	61,100	23,600	28,500	39,900	15,900	17,300	16,600	53,200
1951	32,800	42,100	81,100	46,200	37,400	21,100	46,200	24,700	15,400	11,300	30,500	72,400	38,400
1952	65,500	38,300	56,600	74,200	46,800	14,900	8,600	7,400	6,800	5,500	7,900	26,700	29,900
1953	18,200	31,000	53,700	55,800	66,800	24,400	10,800	9,500	8,600	8,700	8,800	7,100	25,200
1954	15,200	20,500	15,900	17,700	30,800	11,600	8,200	7,300	4,700	4,100	4,000	5,400	12,100
1955	12,100	12,100	30,300	45,200	28,600	31,800	19,100	11,400	9,000	7,700	7,000	7,500	18,500
1956	7,500	59,500	33,100	17,000	21,600	14,500	11,900	9,300	7,900	7,000	7,400	9,800	17,000
1957	14,200	44,400	32,900	78,400	99,400	86,700	46,500	49,800	35,500	26,100	53,500	52,500	51,600
1958	34,500	28,400	39,300	67,300	91,200	36,000	25,200	27,400	17,400	13,600	24,100	26,900	35,800
1959	21,000	38,100	38,900	26,400	18,100	18,000	12,100	10,700	10,600	13,200	17,100	25,600	20,700
1960	37,400	32,300	35,200	22,600	36,000	41,400	22,000	12,400	9,900	8,200	8,500	17,600	23,600
1961	16,100	19,300	51,000	82,400	85,900	46,500	31,200	24,400	10,100	8,200	10,100	29,800	34,700
1962	32,500	42,200	58,100	49,200	32,500	12,700	13,100	10,500	15,200	13,000	9,000	10,400	24,700
1963	9,900	9,900	26,800	14,100	10,800	23,600	12,100	10,000	7,400	7,000	7,300	8,100	12,300
1964	6,200	8,800	50,500	59,100	24,300	10,600	10,200	11,200	9,700	10,000	8,800	19,200	14,000
1965	24,100	34,900	29,800	40,800	23,200	20,200	15,900	13,600	18,500	14,800	10,000	11,000	21,400
1966	52,500	47,000	42,400	29,100	79,000	30,300	17,100	20,400	14,700	10,700	10,200	10,900	30,400
1967	17,300	18,100	21,100	15,500	32,600	19,300	19,500	14,100	9,700	11,800	16,300	36,900	19,400
1968	41,800	47,900	39,300	66,100	78,800	40,200	26,700	17,300	13,000	17,200	21,900	47,200	38,100
1969	74,100	112,800	60,800	66,600	46,100	19,800	14,900	12,400	11,000	10,500	9,800	12,400	37,200
1970	27,700	18,300	29,800	28,700	63,900	21,100	14,300	20,800	16,600	23,700	32,000	31,800	27,600
1971	44,500	41,500	38,900	15,200	18,200	15,600	10,900	14,500	10,000	9,600	8,100	24,500	21,000

TABLE 1. (continued)

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1972	19,800	12,900	13,800	22,600	41,500	13,800	14,500	13,800	11,000	15,700	55,800	50,700	23,900
1973	47,400	65,800	75,100	107,900	136,100	52,500	34,500	32,700	32,500	19,300	20,800	95,700	60,100
1974	60,000	70,700	67,000	53,400	50,200	56,600	29,200	24,300	22,600	18,500	28,000	32,500	42,600
1975	53,600	54,200	74,000	114,900	65,300	23,200	15,900	17,700	18,400	14,400	13,100	21,500	40,400
1976	27,200	24,200	24,800	23,200	20,000	25,600	34,600	19,900	12,200	13,900	11,800	8,900	20,600
1977	12,900	12,200	27,300	58,200	20,700	10,600	11,800	10,000	13,900	20,900	23,900	35,100	21,500
1978	30,500	27,300	43,200	53,800	49,400	26,000	15,400	10,300	16,700	8,600	15,000	50,300	28,900
1979	40,600	31,000	77,400	100,400	96,000	50,500	29,500	27,800	21,600	17,300	15,800	18,600	43,900
1980	23,900	18,200	26,200	40,200	24,400	17,600	14,100	10,000	7,700	7,500	10,900	12,800	17,800

data (in cubic feet per second, Table 1) by 8.93005×10^{-4}.

Correlations between monthly, seasonalized, and calendar year runoff with the available tree ring chronologies [*Stahle et al.*, 1985*b*] were used to determine what fraction of the year might be most successfully reconstructed. Annual runoff was used because it produced the highest correlation with tree ring data and is normally distributed with a first-order persistence structure [*Box and Jenkins*, 1976]. The seasonalized series were not normal and had more complicated persistence structures.

Double mass analysis [*Kohler*, 1949; *Burnash and Ferral*, 1980] and station history criteria were used to identify the most reliable portions of the full Clarendon streamflow record (1900–1980). Normally, a long, homogeneous streamflow series would be matched with the Clarendon data for double mass analysis but, unfortunately, such a reliable control series is not available. Instead, total annual precipitation averaged for the state of Arkansas from 1900 to 1980 [*Karl et al.*, 1983] was used, following a procedure suggested by *Cook and Jacoby* [1983]. The state precipitation series was transformed by a linear regression transfer function into predicted discharge by

$$\ln \hat{Q}_t = 4.786 + 0.001524\, P_t \tag{1}$$

where $\ln \hat{Q}_t$ is the natural logarithm of estimated annual mean daily discharge of year t in cubic meters per second and P_t is the state average annual total precipitation of year t in millimeters.

The regression was significant ($P < 0.0001$) and accounted for 57% of the streamflow variance in the interval 1900 to 1980. An exponential function of $\ln \hat{Q}_t$ (reversing the logarithmic transformation) is cumulatively plotted against measured discharge (Figure 2*a*) and reveals apparent inhomogeneity in the Clarendon data. The double mass plot indicates a visible change in slope before 1930, with relatively minor fluctuations thereafter in spite of extensive hydrological development in the basin (Figure 2*a*).

As an independent check, another double mass analysis using the regional average tree ring index was performed (Figure 2*b*). The results closely resemble the first analysis, although minor changes in slope, possibly associated with regulation of the river, seem slightly more accentuated after 1943. The regional tree ring series may be preferable to Arkansas state precipitation as a control for double mass analysis because it is more centered on the basin. This analysis suggests that many of the moisture sensitive tree ring chronologies now available throughout much of North America [*Stockton et al.*, 1985] could be used to directly test the homogeneity of hydrological records.

Possible causes of the runoff inhomogeneity may involve one or more of the following: (1) early twentieth century logging and land clearing in the basin may have disturbed the relationship between precipitation, infiltration, and runoff, (2) the spring flood of 1927 was the largest recorded in the White River and lower Mississippi Valley and may have significantly altered the watershed characteristics and/or channel geometry of the White River near Clarendon, (3) the

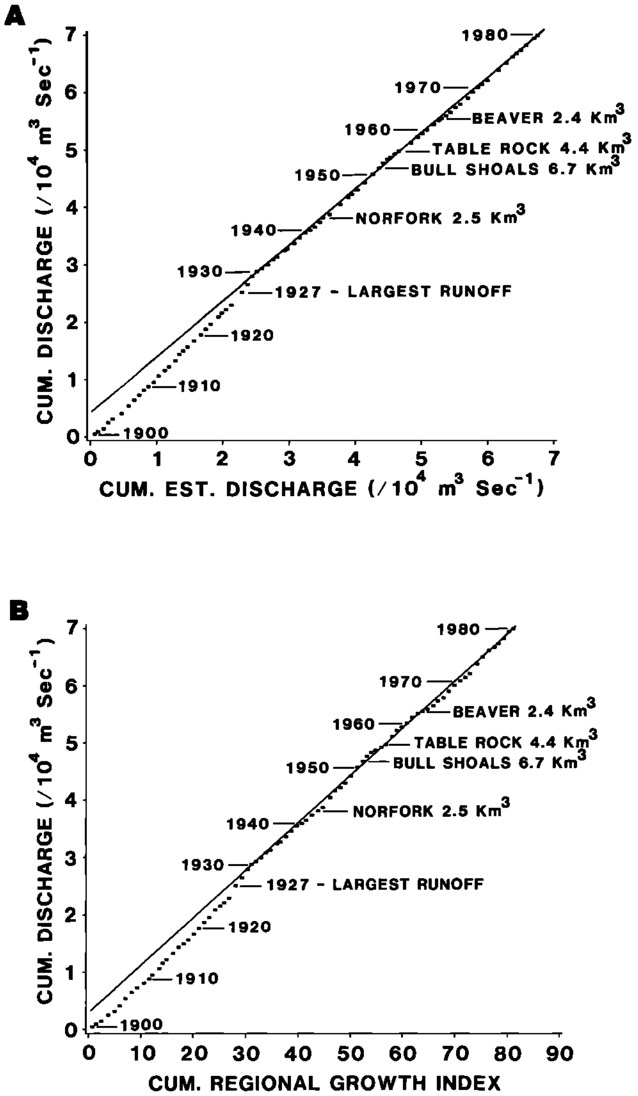

Fig. 2. Double mass analysis of White River cumulative annual mean daily discharge (January–December) measured at Clarendon, Arkansas (a) versus cumulative estimated discharge (see text), and (b) versus cumulative regional tree growth index. Sloping reference lines help define the extent of inhomogeneity. Annotations indicate major reservoir closure dates (with associated impoundment capacity) and the year of largest gaged runoff (1927).

TABLE 2. Calibration and Validation Statistics

Calibration				Validation					
Period	R^2_{adj} [a]	B_0	B_1	Period	Correlation[b]	Sign Test[c] Positive	Sign Test[c] Negative	t Test[d] Difference of Means	Reduction[e] of Error
1930–1951	0.62[f]	−25.94	52.98	1952–1980	0.64[f]	19[g]	10	1.06[h]	+0.38
1952–1980	0.37[f]	−19.51	45.46	1930–1951	0.78[f]	15[g]	7	1.09[h]	+0.60
1930–1980	0.50[f]	−23.10	49.54	1900–1929	0.49[i]	23[i]	7	0.91[h]	+0.08

B_0 is the intercept and B_1 is the slope of the regression equation.
[a]Multiple correlation coefficient squared, adjusted for loss of degrees of freedom [*Draper and Smith*, 1981].
[b]Pearson correlation coefficient [*Steel and Torrie*, 1980].
[c]One-tailed test on the agreement between the signs of departures from the mean (positive equals agreement, negative equals disagreement [*Conover, 1980*].
[d]Two-tailed paired observation test for the difference between the gaged and reconstructed means [*Steel and Torrie*, [1980]. Failure to reject H_0 is the optimum result [*Gordon*, 1982].
[e]Reduction of error statistic [*Fritts*, 1976]. Any positive number is considered significant [*Gordon and LeDuc*, 1981].
[f]$P \leq 0.001$.
[g]$P \leq 0.10$.
[h]Not significant ($P > 0.05$).
[i]$P \leq 0.01$.

variance of the gaged runoff data increases significantly from 1900–1925 to 1926–1955 ($P < 0.01$, based on an F test) and may reflect regional climate change [e.g., *Kutzbach*, 1970], (4) the Corps of Engineers rating table may not properly estimate the missing discharge data from 1921 to 1930, and (5) the statewide precipitation data used for analysis could be responsible, since the precipitation data prior to 1931 are based on weighted single station records but after 1931 use averages of climatic divisions [*Karl et al.*, 1983]. Tests on the precipitation series, however, show no significant change in either the mean or variance between the two periods.

TREE RING DATA

Nine tree ring chronologies were selected from the 50 now available in the south central United States [*Stahle et al.*, 1985*b*] on the basis of their proximity to the White River Basin, total length of record, and correlation with White River runoff. The nine chronologies are from two species, post oak and bald cypress, growing in well-drained upland and poorly drained wetland habitats, respectively. Both species exhibit strong sensitivity to drought during and before the growing season [*Stahle and Hehr*, 1984; *Stahle et al.*, 1985*a*]. 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 locations [*Douglass*, 1920]. The direct correlation between the radial growth of swamp-grown bald cypress was discovered more recently [*Bowers*, 1973; *Stahle et al.*, 1985*a*, 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*, 1985; *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 to, in part, changing chronology sample size and an age-related decline in growth vigor of oaks [e.g., *Stahle and Cleveland*, 1988; *Blasing et al.*, 1988]. A detailed explanation of the methods used to develop the tree ring chronologies is available in the paper by *Stahle et al.* [1985*b*].

When the nine residual series were averaged, the regional average series had weak serial correlation (r_{-1} to r_{-3} = −0.13, −0.04, and −0.11, respectively), apparently due to reinforcement of weak negative 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 tree ring time series appears to arise primarily from biological factors (e.g., food storage, crown area, root mass) [*Fritts*, 1976], but some persistence may also be due to climatic forcing.

CALIBRATION AND VALIDATION

The tree ring and annual runoff data were calibrated only from 1930 to 1980 because of the apparent inhomogeneity in the gaged runoff data prior to 1930. The gaged runoff data was modeled as a first-order autoregressive process [*Box and Jenkins*, 1976]. AR(1) persistence was removed from the gaged runoff series prior to calibration to improve efficiency of the regression analysis [*Draper and Smith*, 1981]. Linear regression analysis between the prewhitened tree ring and gaged runoff series from 1930 to 1980 explains 50% of the annual runoff variance (Table 2).

The transfer function used to reconstruct White River annual runoff was

$$\hat{Y}_t = -23.10 + 49.54\, X_t \tag{2}$$

TABLE 3. Statistical Parameters of Gaged and Reconstructed Annual Runoff of the White River at Clarendon, Arkansas

Statistic	Gaged 1930–1980	Reconstructed 1930–1980	Reconstructed 1700–1980
Number of years	51	51	281
Mean[a]	25.97	25.97	26.29
Standard deviation[a]	10.83	7.61	7.69
Maximum[a]	55.37	44.61	45.69
Minimum[a]	10.27	11.53	6.61
Range[a]	45.10	33.08	39.08
Median[a]	24.38	26.41	26.79
Serial correlation	0.17[b]	0.09[b]	0.20[c]
Skewness	0.85	0.22	−0.03
Kurtosis	0.39	−0.38	−0.37
Distribution normal	Yes	Yes	Yes

[a]Statistic in cubic kilometers per year.
[b]Not significant, $P > 0.05$.
[c]$P < 0.001$.

where $\hat{Y}_t$ is reconstructed runoff for year t in cubic kilometers per year and X_t is the regional average of the nine tree ring chronologies for year t. The standard errors of the intercept and slope are 6.98 and 6.95 km^3 yr^{-1}, respectively. The residuals from regression are uncorrelated (autoregression = −0.02, $P < 0.01$, Durbin-Watson statistic) [*Draper and Smith*, 1981]. The AR(1) persistence observed in the gaged runoff series (AR(1) coefficient = 0.22) was then added to the reconstructed series [*Meko*, 1981]. Given the complicated biological persistence present in the tree ring chronologies, adding the autoregressive properties of the gaged data to the white noise reconstruction should provide the best estimate of annual runoff at all frequencies [*Meko*, 1981].

It should also be noted that calibrations based on separate averages of the upland post oak and bottomland cypress chronologies each explained 38% of the annual runoff variance from 1930 to 1980, 12% 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 bald cypress chronologies, respectively, and that each region can contribute independently to White River runoff measured at Clarendon.

A data-splitting procedure [*Snee*, 1977] was used to validate the stability of the regression model developed to calibrate the tree ring and annual runoff data (Equation (2)). The predictor and predictand data from 1930 to 1980 were split into two subperiods (1930–1951 and 1952–1980), and separate transfer functions generated for each subperiod were used to develop two additional runoff reconstructions. The reconstruction based on the transfer function for the 1930 to 1951 subperiod was then compared with the statistically independent gaged runoff data from 1952 to 1980, and vice versa. Several statistical comparisons were made between the actual and reconstructed runoff series for these two subperiods, and the regression coefficients derived for the two subperiod transfer functions were compared (Table 2). The runoff reconstruction based on the full calibration period was also compared with the independent gaged runoff data from 1900 to 1929. These early runoff data appear to be systematically biased relative to the post-1929 data, but they are still useful for independent validation of the reconstruction.

The only nonstandard validation test used was the reduction of error (RE) statistic, which compares the actual and estimated runoff during a validation period with the actual mean runoff during a 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 on the basis of Monte Carlo experiments ($P < 0.05$, $N > 10$) [*Gordon and LeDuc*, 1981]. The RE statistics calculated for the two validation subperiods are +0.38 and +0.60 (Table 2), indicating that the subperiod reconstructions are contributing unique paleohydrological information. The other validation tests listed in Table 2 are also statistically significant and indicate that the subperiod transfer function estimates are stable when compared with independent runoff data.

The validation of the two subperiod models against independent data suggests that the full calibration model (Equation (2)) is also time stable because there is no statistical difference between the regression coefficients of any of these models. This inference is supported by comparisons between the full calibration reconstruction and the independent runoff data from 1900 to 1929 (Table 2). All validation tests are again passed, even though the test results are lower than for the two later subperiods. The inhomogeneity of the early runoff data may be responsible in part for the lower validation scores.

A comparison between the descriptive statistics of the gaged runoff data from 1930 to 1980 and the 281-year reconstruction (based on Equation (2)) confirms that the reconstruction reproduces the mean and variance properties of the gaged runoff data reasonably well (Table 3). The gaged runoff mean from 1930 to 1980 is less than the long-term reconstructed mean from 1700 to 1980, but these differences are not statistically significant [*Steel and Torrie*, 1980]. Skewness and kurtosis for the gaged runoff are higher than for the reconstruction, but both series approximate a normal distribution. However, the variance and range statistics, and the time series plot of gaged and reconstructed runoff from 1930 to 1980 (Figure 3) reveal specific limitations of the

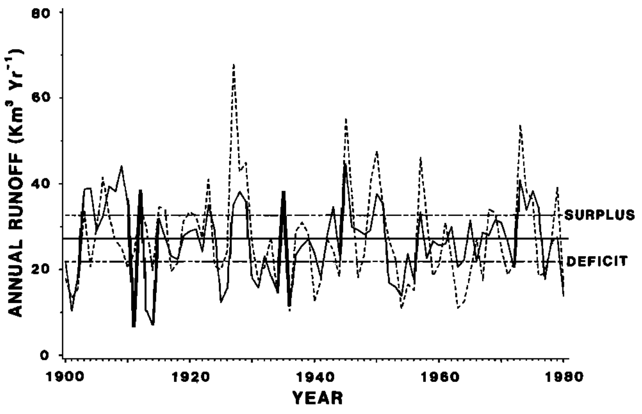

Fig. 3. Gaged (dashed line) and reconstructed (solid line) annual runoff (January–December) of the White River at Clarendon, Arkansas. The reconstruction is based on the 1930–1980 calibration period. The solid horizontal line is the 1900–1980 gaged mean, and the two horizontal dashed lines are the surplus and deficit runoff thresholds (120 and 80% of the 1930–1980 gaged mean, respectively).

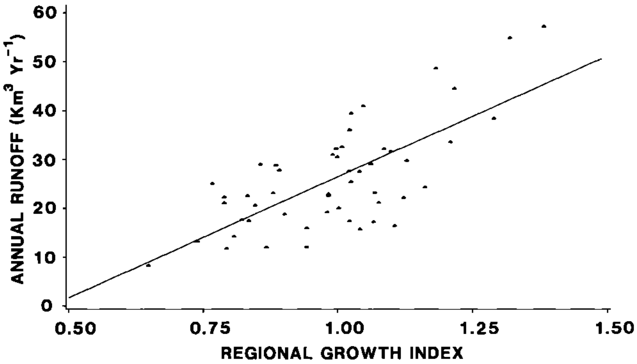

Fig. 4. Scattergram of gaged White River annual runoff versus the regional tree ring index values for the period 1930 to 1980. The regression model (solid line) is defined in equation (2).

reconstruction. The variance and range are higher for the gaged data, indicating that the reconstruction does not fully reproduce the gaged runoff extremes, particularly the positive extremes (Figure 3). 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 largely due to inability of trees to respond linearly to very wet conditions [*Fritts*, 1976]. In spite of this underestimation of the highest runoff levels, inspection of the scattergram between gaged runoff and the regional tree ring average for the calibration period (Figure 4) suggests that the systematic underestimation of high runoff amounts does not become a serious problem until annual runoff reaches approximately 38 km^3 yr^{-1}. This level represents about 140% of the gaged mean and is the largest value for gaged runoff that falls below the regression line in Figure 4. This indicates that the runoff reconstruction should be useful for an investigation of the history of surplus flows, which are defined for this analysis as runoff $\geq$120% of the mean runoff. The results of the surplus analysis discussed below, however, are not sensitive to changes in the surplus threshold ranging from 110 to 130% of the runoff mean. Nevertheless, the surplus issue also involves interest in the absolute magnitude of surplus flows, and the estimation errors associated with the largest runoff amounts (Figure 3) indicate that the reconstruction should be interpreted cautiously in terms of the actual magnitude of surplus flows.

RECONSTRUCTED WHITE RIVER RUNOFF: 1700 TO 1980

The reconstructed annual runoff for the White River at Clarendon from 1700 to 1980, based on the full calibration model (1930 to 1980, Equation (2)), is presented in Figure 5 and Table 4. Examination of Figure 5 suggests a long-term positive 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 1980 ($P < 0.05$) [*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 reconstructed runoff variability may be due to climatic change [e.g., *Kutzbach*, 1970] and/or anthropogenic disturbances to the watershed and remnant old growth forests sampled (e.g., regional land clearing, acid deposition, and 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 conservative and is probably not responsible.

The significant increase in reconstructed runoff variance during the 20th century is regarded as inconclusive evidence for climatic change in light of the possible alternative explanations, but the significant shorter-term changes in gaged runoff variance (discussed above) imply that longer-term variance changes are possible and may merit planning consideration.

Possible long-term changes in mean runoff levels were tested between nine consecutive 30-year intervals, beginning in 1700 and ending in 1969. Mean runoff reconstructed for the 30 years from 1880 to 1909 (29.66 km^3 yr^{-1}) is signifi-

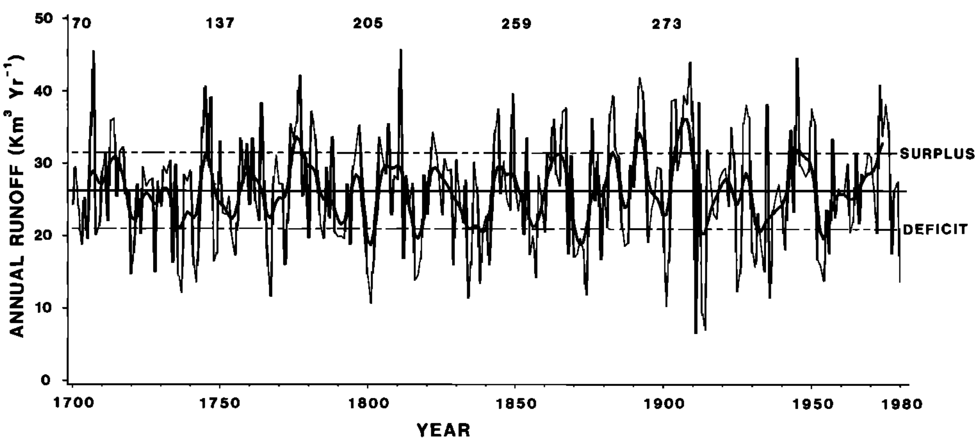

Fig. 5. Reconstructed annual runoff plotted with a low-pass filter (solid curve) that removes variance at frequencies of less than 8 years (*Fritts*, 1976]. The solid horizontal line is the 1700–1980 reconstructed mean, and the two horizontal dashed lines are the thresholds used in the analysis of surplus and deficit runoff (120 and 80% of the reconstructed mean, respectively). The number of tree ring specimens in the regional average is indicated above the plot. Note the 17 different episodes with at least two consecutive years of surplus runoff and the 20 different episodes of consecutive deficit runoff.

TABLE 4. Reconstructed Annual Runoff (Cubic Kilometers Per Year), Clarendon, Arkansas.

Decade	0	1	2	3	4	5	6	7	8	9
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
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	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
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
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	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	11.43	17.32	30.16	25.40	13.41	20.88
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									

cantly greater ($P < 0.05$) than runoff in the preceding and following 30-year periods (25.06 and 24.36 km^3 yr^{-1}, respectively). Because the 30-year periods tested were not selected on an a posteriori basis, these results suggest that long-term changes in mean annual runoff have occurred in the White River Basin over the past 281 years. The possible recurrence of such long-term changes in runoff could have major consequences for water resource management in the basin.

The filtered reconstruction (Figure 5) 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 extrapolation into the future. Spectral and cross-spectral analyses were used to test for possible periodicity in the runoff data and fidelity of the reconstruction [*Jenkins and Watts*, 1968]. Cross-spectral analysis for the period 1930 to 1980 indicates that the reconstructed series is coherent with the gaged runoff over most of the spectrum. The coherency between the gaged and reconstructed series drops below the 95% confidence level only in the lowest frequency band, between 0.0 and 0.063 cycles yr^{-1} (∞ to 16-year period, lags = 8, bandwidth = 0.157 cycles yr^{-1}; Hamming Window) [International Mathematical and Statistical Libraries (*IMSL*) *Inc.*, 1982]. The two series are in phase at all frequencies, and the gain function is relatively flat [*Jenkins and Watts*, 1968]. These results indicate that the reconstruction provides a unbiased estimate of the actual runoff data at frequencies above 0.063 cycles yr^{-1} and should be suitable for investigating possible periodic components in annual runoff.

None of the spectral peaks in the gaged or reconstructed runoff series from 1930 to 1980 are significant. However, the spectral density of reconstructed runoff from 1700 to 1980 achieves statistical significance ($P < 0.05$) between periods of 14.0 and 18.67 years (lags = 28, degrees of freedom = 25, bandwidth = 0.045 cycles $year^{-1}$, Hamming Window) [*IMSL Inc.*, 1982]. This periodicity explains 16% of the reconstructed runoff variance, but because it is not clearly duplicated in the gaged record, it must be viewed with caution. It should be noted, however, that *Stahle and Cleaveland* [1988] found similar spectral peaks in actual and reconstructed drought index data for Texas, *Meko et al.* [1985] found a complex periodicity including these frequencies in tree ring series from Iowa, and *Currie* [1981] has defined an 18.6-year lunar nodal periodicity in North American climatic records.

ANALYSIS OF SURPLUS AND DEFICIT RUNOFF

Figure 4 indicates that the relationship between tree growth and runoff is linear up to approximately 38 km^3 yr^{-1}. If the threshold value for surplus (or deficit) runoff is set below this value, the long-term reconstruction can be used to analyze the history and dependability of surplus flow, which are practical issues with obvious relevance to the management of surface water supplies in the White River Basin. A statutory definition of the concept of surplus water has been established by the *Arkansas Legislature* [1985], incorporating forecasts of future demand and the satisfaction of several preconditions before interbasin transfers can be considered. This statutory definition is too complex for operational application in this analysis, so we arbitrarily defined surplus as runoff $\geq$120% of the long-term mean runoff. This threshold is a heuristic choice and could be set higher or lower (e.g., a draft study of the Upper White River Basin by the *U. S. Army Corps of Engineers* [1988] identifies runoff above approximately 90% of the mean annual runoff as surplus by the statutory definition). The conclusions of this study are not strictly linked to any specific definition of surplus or deficit runoff.

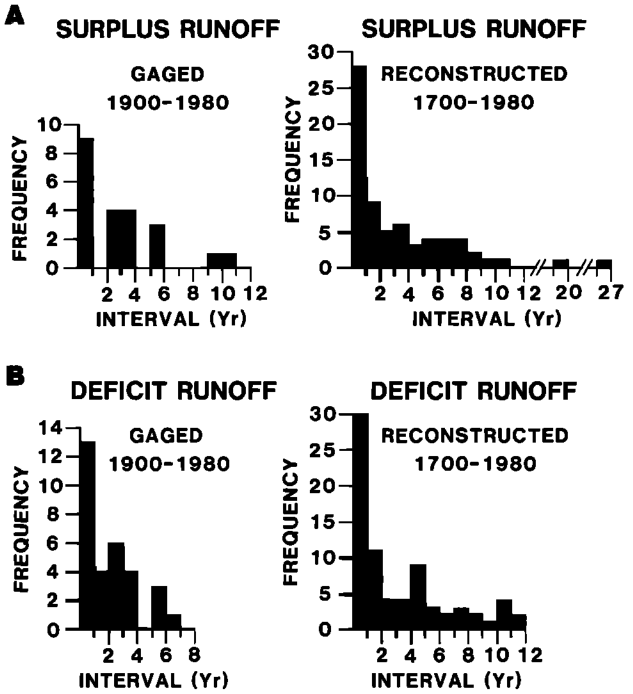

Fig. 6. Histograms of the intervals in years between (*a*) surplus, and (*b*) deficit annual runoff levels in the White River at Clarendon, Arkansas, for gaged (1900–1980) and reconstructed data (1700–1980). The surplus and deficit thresholds are defined as 120 and 80% of the gaged or reconstructed means, respectively.

When the surplus threshold is set at 120% of the mean, it represents 31.48 km^3 yr^{-1} for the reconstruction (1700 to 1980), and 32.66 km^3 yr^{-1} for the gaged data (1900 to 1980). These levels are well below the point of systematic tree ring estimation error (suggested by Figure 4) 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% of the mean) fails the test of randomness for gaged runoff from 1900 to 1980 ($P < 0.05$) and for reconstructed runoff from 1700 to 1980 ($P < 0.01$) because of many consecutive years with surplus flow (Figure 6*a*). Three consecutive years of gaged surplus occur three times (1927–1929, 1949–1951, and 1973–1975). In the reconstruction, four consecutive years of surplus occur twice (1774–1777, 1891–1894), and six of nine years are estimated to have had surplus runoff from 1774 to 1782. However, the occurrence of consecutive surplus years is not limited to just a few wet perids. Two or more consecutive years of surplus occur six times in the gaged data (Figure 3) and 17 times in the full reconstruction (Figure 5).

The longest intervals without surplus runoff in the gaged data are 10 years (1935–1945) and 11 years (1957–1968) (Figure 3). The reconstructed runoff series indicates that prolonged periods of 27 years (1717–1744), 20 years (1823–1843), and 11 years (1811–1822) 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 (1) the relationship between the runoff and tree ring data does not appear to be seriously nonlinear below 140% of the long-term mean, (2) the nonrandom distribution of surplus and deficit runoff found in the long reconstruction is also present in the gaged data from 1900 to 1980, and (3) the nonrandom behavior of gaged and reconstructed surplus and deficit runoff does not appear to be sensitive to the specific thresholds employed in this analysis. Lilliefors test indicates that reconstructed surplus flows are nonrandomly distributed ($P < 0.05$) when surplus is defined as 110, 115, 125, and 130% of mean runoff, for the same reasons as the 120% definition (i.e., clustering of events and the presence of long intervals without surplus runoff).

The potential recurrence of periods of a decade or longer without any surplus runoff has profound implications for the possible application of surplus water. The periods when surplus flows are frequent may be equally important from a managerial perspective. Any control structures, contractual arrangements, or application of surplus water should be designed in part to reflect the high degree of temporal variability in this particular component of surface water supply.

A similar analysis of intervals between years of low flow or deficit runoff was also conducted. Using an arbitrary threshold of 80% of the long-term mean, low flows in the gaged data (1900 to 1980) are ≤21.78 km^3 yr^{-1} and are ≤20.99 km^3 yr^{-1} for the 281-year reconstructed series. The intervals between both gaged and reconstructed deficit runoff years were also nonrandomly distributed when compared to an exponential distribution with Lilliefors test ($P < 0.01$), and this conclusion does not change when deficit flow is defined as 70, 75, 85, or 90% of the mean. The clustering of low runoff years (Figure 6b) also appears to explain this nonrandomness, with twenty examples of successive drought years lasting from 2 to 5 years in the period from 1700 to 1980. During the driest periods the reconstruction indicates that deficit flows occurred in as many as 6 of 7 years from 1868 to 1874, and 6 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 7 years in the observed data (1947–1954) and 12 years in the reconstructed data prior to the twentieth century (1708–1720 and 1841–1853) (Figure 5). Most of these periods without deficit flow were characterized by a high incidence of surplus runoff.

Simple persistence could cause some of the nonrandomness in surplus and deficit flows. For this reason a serially random reconstruction (without persistence added) was also tested with the Lilliefors criterion. Both surplus and deficit levels differ significantly from an exponential distribution, showing nonrandom behavior ($P < 0.01$).

The nonrandom interannual distribution of surplus and deficit runoff events in the White River Basin may be a product of large-scale climatic variability. Some of this variability could 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 responsible for extended periods of surplus or deficit runoff in the White River Basin, we have attempted to identify statistical associations in the reconstructed runoff series that may have some actuarial value.

Interannual persistence of drought and wetness extremes has been identified in observed and dendrochronologically reconstructed drought index data in Texas [*Stahle and Cleaveland*, 1988]. The Clarendon gaged and reconstructed data was also tested for possible nonrandom consecutive occurrence of high and low runoff. The reconstructed runoff series was divided into five equally probable groups [*SAS Institute Inc.*, 1985], with the highest and lowest groups approximating surplus and deficit runoff, respectively. The highest runoff group was >32.9 km^3 yr^{-1} and the lowest was <19.1 km^3 yr^{-1}. When a runs test [*Draper and Smith*, 1981] was applied to reconstructed runoff from 1700 to 1980, the null hypothesis of random occurrence was rejected for both extreme high and low flows ($P < 0.01$). When gaged runoff from 1900 to 1980 was divided into five equally probable groups, the hypothesis of randomness was again rejected for both the highest and lowest runoff classes ($P < 0.05$).

The statistically significant consecutive occurrence of low and high flow runoff years apparent in both the gaged and reconstructed data may be useful for probabilistic forecasts of annual runoff in the White River. Evaluation of the gaged runoff record (1900–1980) divided into five equally probable classes indicates that once a high (or low) runoff year occurs, the probability that the following year will fall in the same category increases from 20 to 38%. The 281-year reconstruction shows the same increase in probability for high runoff years, while the probability increases from 20 to 34% that a year in the driest runoff category will be followed by another such year.

CONCLUSIONS

Analyses of both gaged and reconstructed White River annual runoff 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 several times during the twentieth century (e.g., low runoff was recorded for 3 consecutive years in 1900–1902, 1954–1956, and 1963–1965; high runoff occurred 3 consecutive years in 1927–1929, 1949–1951, and 1973–1975). At the other extreme, periods as long as 27 years without surplus runoff occur in the reconstructed record. The 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 climate and tree ring data sets not used in this study [*Stahle and Cleaveland*, 1988] and suggest a degree of large-scale climatic control. If the physical mechanism (or mechanisms) responsible for this apparent persistence of climate indices and runoff in the south central United States can be identified, it could lead to improved long-term forecasting of runoff extremes. In the interim, the nonrandom occurrence of runoff extremes may lead to improved probabilistic forecasts of annual runoff in the White River Basin.

This study has focused on the analysis of both gaged and tree ring reconstructed annual runoff in the White River. The analytical results based on the gaged and reconstructed data are quite consistent, which supports the validity of using tree ring chronologies as proxy hydrological records. With the extensive network of existing chronologies, and given the continued development of longer red cedar and bald cypress chronologies, there is considerable potential to extend the hydrological applications of tree ring data in the eastern United States.

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