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THE TREE-RING RECORD OF SEVERE SUSTAINED DROUGHT[1]

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ABSTRACT: Frequent and persistent droughts exacerbate the problems caused by the inherent scarcity of water in the semiarid to arid parts of the southwestern United States. The occurrence of drought is driven by climatic variability, which for years before about the beginning of the 20th century in the Southwest must be inferred from proxy records. As part of a multidisciplinary study of the potential hydrologic impact of severe sustained drought on the Colorado River, the physical basis and limitations of tree rings as indicators of severe sustained drought are reviewed, and tree-ring data are analyzed to delineate a "worst-case" drought scenario for the Upper Colorado River Basin (UCRB). Runs analysis of a 121-site tree-ring network, 1600-1962, identifies a four-year drought in the 1660s as the longest-duration large-scale drought in the Southwest in the recent tree-ring record. Longer tree-ring records suggest a much longer and more severe drought in 1579-1598. The regression estimate of the mean annual Colorado River flow for this period is 10.95 million acre-feet, or 81 percent of the long-term mean. The estimated flows for the 1500s should be used with caution in impact studies because sample size is small and some reconstructed values are extrapolations.
(KEY TERMS: meteorology/climatology; water resources planning; dendrohydrology; drought planning; Colorado River; time series analysis; tree rings; water supply.)

INTRODUCTION

Periods of short-term or prolonged deficiency in precipitation, generally known as droughts, are such common occurrences in global climatic regimes that it would be rare indeed to find a time when the earth was drought-free. Even so, drought is difficult to define in terms that apply to all circumstances. For example, Sastri *et al.* (1982) reported finding no fewer than 60 definitions of drought in the literature, based on the nature of water requirements and the time of need for plants and animals. Assessment of the probability in the Southwest is likely to become more urgent as the burgeoning population places increasing demand on both supplies and distribution systems and as changing climate possibly narrows the gap between water demand and available supply. Although droughts are related to changes in large-scale atmospheric circulation (Namias, 1955), the circumstances that result in extended periods of dry weather are neither clearly understood nor predictable. Until these parameters are more clearly defined, a logical approach to assessing the probability of drought is to examine climatological and hydrologic records.

Perhaps the best example of persistent or recurrent drought in the gaged hydrologic records of the southwestern United States is the 1950s, when precipitation and streamflow were consistently low in a band from southern California to Texas (Thomas, 1962). For information on droughts before the late 1800s, we are forced to rely on proxy indicators of climate. Commonly used indicators are stratified sediments in streams, lakes, and swamps; pollen profiles; layered ice cores; and tree rings (Hecht, 1985). Advantages of tree-ring data over other types of proxy data include accurate dating to the year, ease of collection and replication, and preservation of low-frequency and high-frequency variations.

The tree-ring record of drought history in the Southwest is examined in this paper as part of a multidisciplinary study of the potential hydrologic impacts of severe sustained drought (SSD) on the Colorado River. The objectives are (1) to discuss the physical basis and limitations of tree rings as indicators of hydrologic drought, (2) to delineate spatial and temporal characteristics of Southwest drought from tree-ring data, and (3) to supply the SSD project with a

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"worst-case" scenario for extreme hydrologic drought on the Colorado River. The primary source of tree-ring data for this scenario is a tree-ring reconstruction of annual flow of the Colorado River at Lees Ferry, Arizona, 1520-1961 (Stockton and Jacoby, 1976). We approach the tree-ring material in this paper with a widening time-window – covering studies based on relatively short but well-replicated data and then proceeding to the longer but spatially patchy tree-ring evidence. We first discuss physical and statistical points important to the interpretation of tree-ring records as indicators as hydrologic drought.

TREE RINGS AS INDICATORS OF SEVERE SUSTAINED DROUGHT

The discipline concerned with the use of tree rings for dating past events is known as *dendrochronology.* Two subdisciplines, *dendroclimatology* and *dendrohydrology,* have developed rapidly during recent years and involve the reconstruction of climatic and hydrologic events. This rapid development has been made possible by the evolution of high-speed computers capable of handling large amounts of data and by the application of sophisticated statistical methods for studying complex relationships between tree-ring variables and climatic or hydrologic parameters. A comprehensive review of the theory and methods of dendrohydrology can be found elsewhere (Loaiciga *et al.,* 1993). The following discussion is limited to aspects of dendrohydrology dealing with the delineation of severe sustained drought.

Tree-ring chronologies reflect the complex of climatic and environmental conditions at the sites where samples were taken. Although this complex includes nonclimatic influences such as insect infestations, fires, and logging, the desired climatic signals can be maximized by careful site selection. Maximum response to precipitation can best be obtained by sampling trees on relatively well-drained, dry sites, where low soil moisture is likely to be the main environmental factor limiting growth (Fritts, 1976).

Tree-ring series from properly selected sites are effective proxy indicators of hydrologic drought because precipitation and evapotranspiration are key variables in the water balances of the tree and the river basin (Figure 1). The physical principles of the system in which precipitation is transformed to river discharge are fairly well understood, although modeling the physical relationships is often difficult because of the complexity of the geology and surface characteristics of the watershed and uncertainty about the spatial distribution of precipitation. The biological system in which precipitation is transformed into ring-width variations is much more poorly understood, but the direction of the relationships is predictable for certain species and site-types. Cambial growth of drought-sensitive trees is frequently limited by low internal water-potential, which in turn is affected by soil moisture in the root-zone and evaporative demand of the atmosphere (Kozlowski, 1971). Weather conditions favoring decreased watershed runoff (low precipitation and high evapotranspiration) also favor decreased water potential in the tree. The empirical evidence for a relationship is significant correlation between tree-ring variables and hydrologic variables in diverse climatic regimes (Schulman, 1956; Smith and Stockton, 1981; Cook and Jacoby, 1983; Cleaveland and Stahle, 1989).

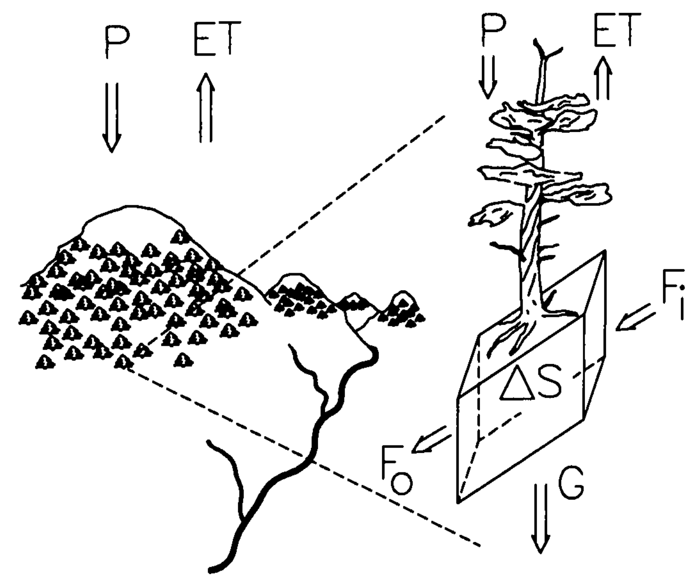

Figure 1. Sketch Illustrating Water-Balance Components Important in Tree-Ring Reconstruction of River Flow. Variables are precipitation (P), evapotranspiration (ET), surface and subsurface inflow and outflow (F_i and F_o), percolation to ground water (G), and change in soil moisture (ΔS).

Because snowmelt and precipitation in the cooler months are major contributors to streamflow in the West, the prospects for streamflow reconstruction would be bleak if winter moisture could not influence tree growth. The tree-growth response to precipitation is fortunately not limited to precipitation in the season of active cambial growth. Studies have consistently shown that tree-ring series from the semiarid Southwest are significantly correlated with precipitation in the cool months preceding the beginning of annual cambial growth (e.g., Schulman, 1956; Fritts, 1976; Smith and Stockton, 1981). One reason for the cool-season response is that soil moisture recharged during the winter is available for use by the tree at the beginning of the growing season. Moreover, a snowpack can extend this period of influence later into the spring. Another reason for a cool-season response is that biological processes important to the water and energy balances of the tree (e.g., photosynthesis, respiration, food storage) are not restricted to the cambial growing season but continue year-round.

Two statistical properties of tree-ring data that bear on the ability of reconstructions to identify and quantify SSD are "age trend" and autocorrelation. For typical drought-sensitive trees in open-growth stands, ring-width generally decreases with age of the tree after an initial period of juvenile growth. The decrease, which is at first steep and then more gradual, is at least partly a geometrical phenomenon: the crown stabilizes in growth, and a fairly constant annual wood increment is deposited on an increasingly large circumference. Biological changes associated with aging might also be expected to impart a gradual change in annual wood production over the life of the tree. The trend associated with the enlarging circumference and aging is a nonclimatic feature and must be mathematically removed before the tree-ring series can be used in hydrologic reconstruction.

The form of the mathematical curve used to detrend ring-width series varies widely with the study objectives and the site characteristics. For climatic studies, the general approach is to detrend conservatively to remove as little low-frequency climatic information as possible (Cook *et al.*, 1990). A modified negative exponential curve or straight line with negative slope has been found empirically to fit the age trend well for many ring-width series from open-growth sites in the semiarid western United States (Fritts, 1976). A consequence of detrending with monotonically decreasing curves such as these is that any real monotonic climatic trend covering the lifetime of the tree cannot be detected in the final tree-ring chronology. Information on shorter-wavelength climate variations – for example, reduced mean precipitation extending over several decades – will still be retained in the chronology.

Tree-ring series after detrending are often still positively autocorrelated (Meko *et al.*, 1993). Biologically-induced autocorrelation might be expected in tree rings because of carryover processes such as root dieback, multi-year needle retention, and food storage (Fritts, 1976). Likely consequences of autocorrelation are a lag in the response of tree growth to the transition from favorable moisture conditions to drought, and a lag in the recovery to normal growth after the end of a drought. Dendrochronologists frequently "prewhiten" – or mathematically remove the autocorrelation from – tree-ring data before using them in reconstructions in an effort to circumvent this problem (Meko and Graybill, 1995). Another approach is to include lagged tree-ring series as predictors in the reconstruction models (Stockton *et al.*, 1985). Neither approach probably completely reverses the distorting influence of the biological filtering of climate by the tree-growth system. Because the biological processes building autocorrelation into tree rings presumably operate similarly over the tree's lifetime, autocorrelation is perhaps less of a problem when reconstructions are used in a *relative* sense to compare properties of reconstructed droughts, rather than in an *absolute* sense to infer hydrologic statistics, such as the maximum number of consecutive years that river flow is below some specified threshold.

Most modern tree-ring reconstructions of hydrologic variables have been based on linear regression models (e.g., Cook and Jacoby, 1983; Cleaveland and Stahle, 1989; Meko and Graybill, 1995). The standard error of prediction, a calibration statistic, can be used to quantify the uncertainty in the reconstructed values, and validation on independent data can be used to guard against model overfitting (Meko and Graybill, 1995). Two factors must be considered, however, in judging the accuracy of the long-term reconstructions from calibration-period and verification-period statistics. First, the standard error of prediction does not apply for years in which the tree-ring data are outside the multivariate cloud of points defined by the predictor data for the calibration period (Weisberg, 1985). Reconstructed values for those years are classified as extrapolations rather than interpolations and should be flagged as such in reconstructions (e.g., Graumlich and Brubaker, 1986; Meko and Graybill, 1995). This is an important point since episodes of SSD identified in the reconstruction are likely to be based on extrapolations if the episodes are more severe than any droughts observed in the instrumental period. Second, reconstructed values in the earliest parts of a reconstruction might be more uncertain than those in the calibration and verification periods because the sample size (number of trees) of a tree-ring chronology typically decreases toward the beginning of the chronology (Meko and Graybill, 1995). Guidelines currently used to avoid noise amplification due to sample-size changes in building chronologies (Wigley *et al.*, 1984) were not available at the time many chronologies in existing tree-ring networks were developed.

In the application of tree rings to river-flow reconstruction, it should be recognized that tree-ring data are point samples, while river flow is a spatially integrated measure of moisture. Just as multiple rainfall gages are desirable in rainfall-runoff modeling, multiple tree-ring sites are desirable for river-flow reconstruction. Unlike rain-gage siting, however, tree-ring sampling must be opportunistic and must take into account the importance of site-type to the sensitivity of tree-growth to moisture variations. The opportunistic aspect of the problem is that trees with the desired properties (e.g., suitable species, great age, minimal influence by fire and disease) might not be available in the primary runoff-producing part of the basin. To complicate matters, the strongest precipitation signal in Southwestern conifers is frequently found not at higher elevations where most runoff originates but at the relatively dry lower forest border, where low soil moisture is more likely to be a major limiting factor to growth (Fritts, 1976). Tree-ring sampling for SSD studies in a river basin should include some sites in all major runoff-producing areas, or at least in nearby areas whose climatic variations closely parallel those of the runoff-producing areas.

DROUGHT HISTORY FROM RECENT TREE-RING RECORDS

Recent tree-ring records are defined here as those that extend no further back in time than about 1600 with acceptable sample replication. The period after 1600 is characterized by a rapid expansion in the spatial coverage of tree-ring chronologies in the western United States. The beginning of the 17th century is also a critical dividing point – as will be shown – because chronologies that do not extend to earlier years fail to sample a major drought at the end of the 16th century.

Analysis of spatial patterns of tree-growth for the period 1705-1979 from a network of 248 moisture-sensitive chronologies scattered over the coterminous United States indicates that the regional tree-ring signal for drought is especially strong in chronologies from the interior western United States (Meko *et al.*, 1993). Two of the nine U.S. tree-ring regions identified by Meko *et al.* (1993) are relevant to this study because they flank the Upper Colorado River Basin (UCRB) on the north and south. A region centered on south-central Montana includes a broad area from Idaho across Montana and Wyoming to the western edge of the Great Plains. The region includes the Wind River Mountains, which contribute runoff to the Green River tributary of the Colorado River. A region centered on Arizona includes all of Arizona and New Mexico, and southern parts of California, Nevada, Utah, and Colorado. The northern parts of the this region include several southern drainages of the UCRB.

The time-series plots of the two regional tree-growth series show little agreement in the timing of major low-growth anomalies in the far northern and southern parts of the interior western United States (Meko *et al.*, 1993 – Figure 12). The regional variability in timing of the most severe droughts as measured by moisture conditions averaged over several years is illustrated in a listing of the lowest 5-year, 10-year, and 20-year means for the Arizona and Montana regional tree-growth series and three regional hydrologic reconstructions from the interior western United States (Table 1). The hydrologic reconstructions have different periods of time coverage and represent (1) annual precipitation variations in northeastern Nevada, (2) annual streamflow variations of the Salt River, whose runoff comes mainly from east-central Arizona, and (3) annual streamflow variations of the upper Gila River, whose runoff comes mainly from southwestern New Mexico. The Salt River reconstruction is grouped here with the "recent" tree-ring records despite the 1580 starting date because the early years of record are based mainly on the juvenile growth portion of only a few tree-ring samples (Smith and Stockton, 1981).

Both the Arizona regional growth series and the Gila River reconstruction point to a period in the current century – the 1950s – as the most severe sustained drought in the tree-ring record. The lowest 20-year running mean centered on the 1950s for the Gila River was less than two-thirds the long-term mean annual flow. The same period is not, however, the record reconstructed low-flow period in terms of either 10-year or 20-year means on the Salt River, despite the small separation distance (less than about 100 km) between the main runoff-producing areas of the Salt River and upper Gila River. Such apparent inconsistencies might be explained by climatic or watershed differences. For example, the upper Gila watershed has a greater summer rainfall component than the watershed of the Salt River, and the Salt River is more strongly influenced by snowmelt. The tree-ring data summarized in Table 1 clearly point to a difficulty of identifying any one period of "most severe" sustained drought applicable to multiple basins in the Southwest in the years since 1600.

To summarize large-scale spatial aspects of drought in the southwestern United States for the period 1600-1962, we have assembled a 121-site network of moisture-sensitive chronologies and tabulated drought-related properties of the data by runs analysis (Salas *et al.*, 1980). We grouped the sites into 2° x 3° latitude-longitude grid cells and used the departures of growth themselves as indicators of "dendroclimatological drought." Species of dubious quality for drought information (e.g., *Pinus aristata* from high elevations) were excluded from the network.

TABLE 1. Driest 5-Year, 10-Year, and 20-Year Periods in Tree-Ring Reconstructions From the Interior Western United States.

Series	Period	Lowest Means[1]		
		5-Year	10-Year	20-Year
Arizona[2]	1705-1979	1879-1883	1773-1782	1946-1965
Montana[2]	1705-1979	1756-1760	1931-1940	1800-1819
NE Nevada[3]	1600-1982	1957-1961 (81)	1652-1661 (86)	1860-1879 (91)
Gila River[4]	1663-1985	1818-1822 (42)	1947-1956 (56)	1943-1962 (64)
Salt River[5]	1580-1979	1666-1670 (43)	1728-1737 (51)	1721-1740 (65)

[1]Beginning and ending years of lowest n-year means; for reconstructions, number in parentheses is n-year mean expressed as percentage of long-term mean.
[2]Regionally average tree-ring series centered on Arizona and Montana (Meko *et al.*, 1993).
[3]Reconstructed annual precipitation for Northeastern climatic division of Nevada (Smith, 1986).
[4]Reconstructed annual discharge of Upper Gila River, Arizona and New Mexico (Meko and Graybill, 1995).
[5]Reconstructed annual discharge of Salt River, Arizona (Smith and Stockton, 1981).

Cell-average series were computed by averaging chronologies within cells, and regional "West" and "Southwest" series were subsequently computed by averaging over cells. The two-step procedure avoids biasing the regional-average series toward dense clusters of sites. The tree-ring sites, cells, and regional boundaries are shown on the map in Figure 2. The "Southwest" region comprises the block of 20 cells bounded on the west approximately by the western border of Arizona; the "West" region comprises the remaining 15 cells. Seven of the 35 cells in the grid have no tree-ring sites, leaving a total of 28 active cells. Drought was defined to occur when a regional series dropped below its 0.2 quantile – the value exceeded in 80 percent of the years from 1600 to 1962.

Time series plots of the regional series are roughly parallel but differ markedly in some time periods (Figure 3). For example, drought hit the Southwest region but not the West region in 1902, 1904, and 1954-56; and hit the West region but not the Southwest region in the 1790s.

Following the terminology of runs analysis, a run of n consecutive years below the 0.2 quantile was defined as an "n-year drought," and the severity of the drought was measured by its run-sum: the sum of the deficits below the 0.2 quantile over the n years. The duration and severity of all multi-year droughts in the two regional series are listed in Table 2. The longest run in the current century was three years in both regions: 1954-1956 in the Southwest and 1959-1961 in the West. The longest run in the full-length series was four years (1667-1670) in the Southwest and six years (1843-1848) in the West.

Persistent droughts in the two regions were generally not synchronous. A simple tabulation of the number of droughts in each century in the Southwest region matched by droughts in the West region is shown below:

1600s	0	of	3
1700s	2	of	3
1800s	2	of	5
1900s	0	of	1

Any attempt to designate a particular drought as "most severe" is necessarily subjective because drought has many properties, all of which cannot be quantified by a single analytical method. Using runs analysis with the specified drought threshold on this particular data, the most severe sustained drought in the Southwest region for the time period 1600-1962 is 1667-1670. This drought had the largest run-length and run-sum. The 1660s drought has previously been noted as the lowest five-year running mean in the Salt River reconstruction (Table 1).

The most severe sustained drought is much less clearly defined in the West region. The longest drought, which occurred in the 1840s, did not have the largest run-sum:

Drought Years	Run Sums
1843-1848	0.49
1653-1655	0.62
1782-1783	0.50

Furthermore, drought assessment in the West region is extremely sensitive to the arbitrary level of drought threshold. If the threshold is relaxed slightly from the 0.2 quantile, for example, droughts of 1752-1754 and 1756-1757 merge into a single six-year drought from 1752 to 1757. A previous tree-ring reconstruction for the Sacramento River identified the

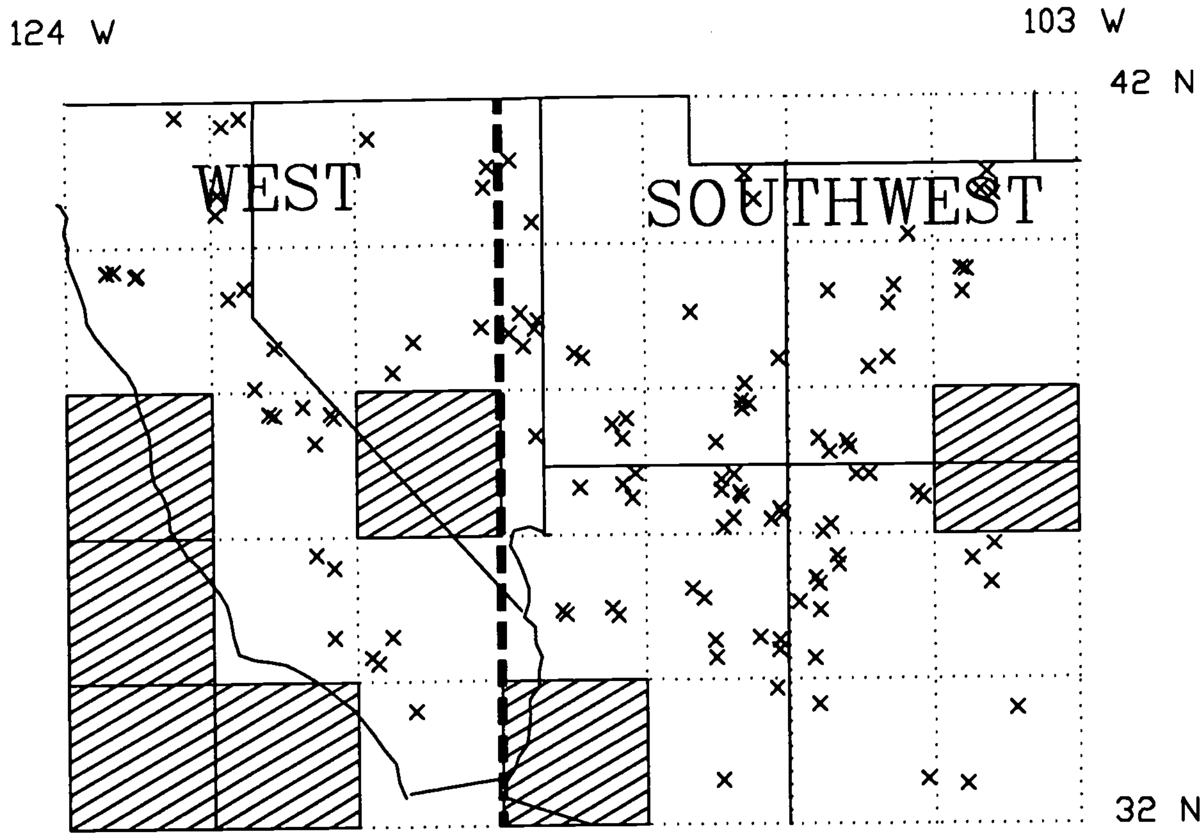

Figure 2. Map Showing Tree-Ring Sites Used in Grid-Cell Tabulation of "Dendroclimatological" Drought in West and Southwest Regions. Site locations are marked by "x," cell boundaries by dotted line, and boundary between West and Southwest regions by thick dashed line. Hatched cells contain no tree-ring sites.

1930s as the most severe low-flow period since AD 1560 and the 1840s as a period unique for drought duration (Earle and Fritts, 1986). Extreme drought severity in the 1840s has also been reported in a reconstruction of precipitation for central California (Michaelsen *et al.*, 1987).

DROUGHT HISTORY FROM LONG TREE-RING RECORDS

The available network of tree-ring sites in the western United States becomes sparse before 1600, but crude inferences about spatial patterns of drought are still possible. Fritts (1965) inferred changes in moisture conditions, 1501-1940, over western North America from contours of decadal-average growth departures over a 26-site network, and commented on severe drought conditions near the end of the 16th century:

– 1566-1585: Dry conditions intensify in the Southwest and northern Rockies; a major drought develops until it finally extends throughout the entire West.

– 1581-1605: Dry conditions become more restricted to the Rocky Mountain areas as moist conditions develop in the Rio Grande and Gila River Basins and in the Northwest.

Tree-ring information on drought becomes increasingly localized before 1500 as the network of available tree-ring sites becomes more sparse. On the Colorado Plateau, archaeological studies are a rich source of very long tree-ring chronologies. The archaeological history of the Southwest is a kaleidoscope of the rise and fall of ancient civilizations with the availability of water. Douglass (1935) concluded from an analysis of tree-ring data from living trees and archaeological wood samples from the Mesa Verde area that the most severe drought in the period 700-1930 occurred from 1276 to 1299. He named this period "The Great Drought," a term which has persisted through time. Although there is no unanimity of opinion, many archaeologists believe that this period of severe sustained drought resulted in the abandonment of large centers of Pueblo culture.

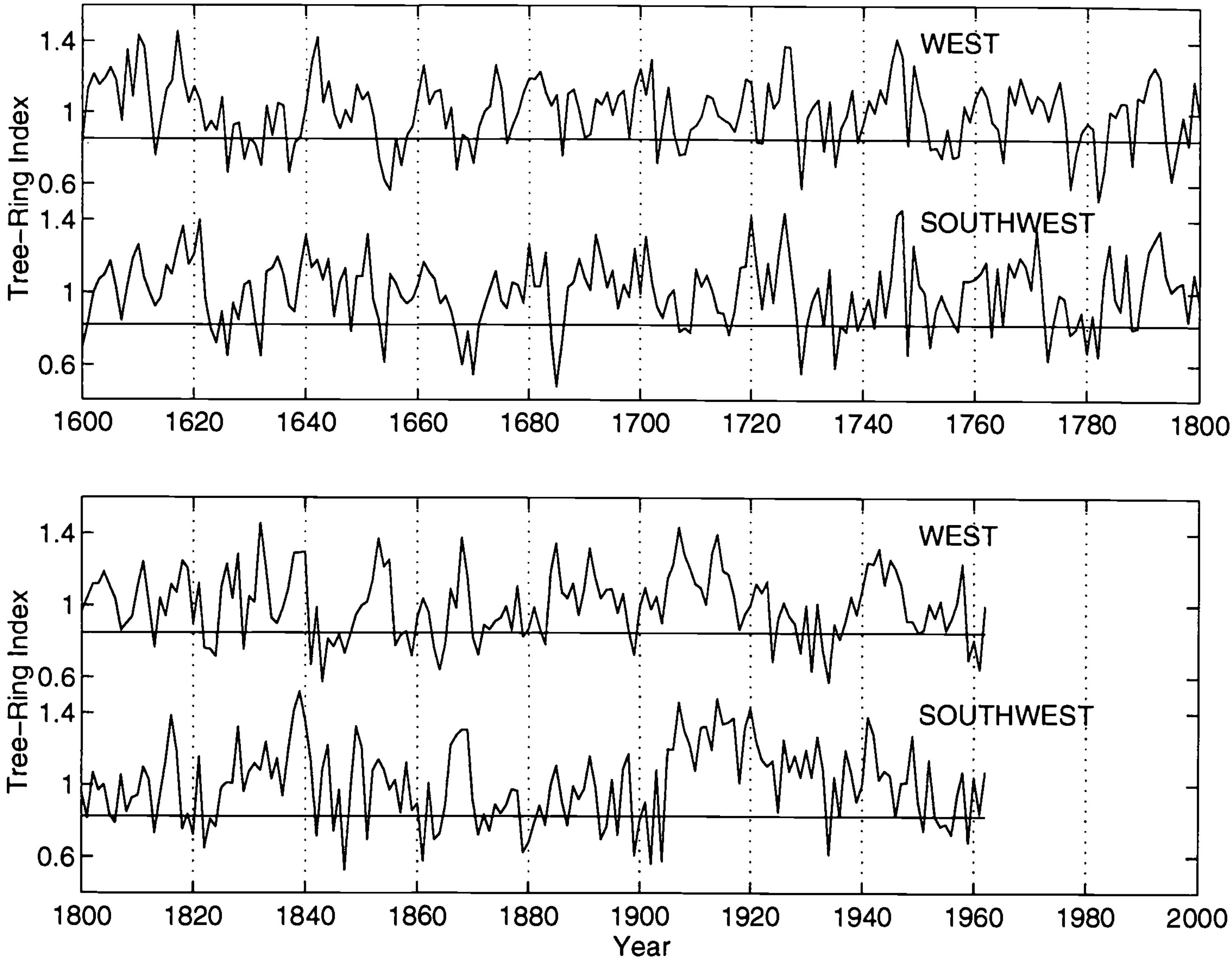

Figure 3. Regional-Average Tree-Ring Index for the West and Southwest Regions, AD 1600-1962. Y-axis indicates growth anomaly as fraction of normal growth (e.g., 1.0 is normal and 1.4 is 140 percent of normal). Horizontal line marks the 0.2 quantile – the index value exceeded 80 percent of the time.

Because of controversy concerning such climatic interpretations from tree-ring chronologies, Fritts *et al.* (1965) analyzed climate-tree growth relationships in the Mesa Verde area and made further climatic interpretations from an expanded tree-ring data base. The new results confirmed the existence of a "Great Drought" but placed it from 1273 through 1289. Although this was the most sustained dry period since 1273, several shorter but more severe droughts in terms of five-year means of tree-ring indices were identified between AD 512 and 1673.

Arroyo Hondo is another example of the importance of water availability to the development of ancient civilizations in the Southwest. Arroyo Hondo is a 14th-century pueblo at an elevation of 7,100 feet immediately west of the foothills of the Sangre de Cristo Mountains in north-central New Mexico. As part of a multidisciplinary study conducted by the School of American Research at Santa Fe, Rose *et al.* (1981) reconstructed the climate of the area by using tree-ring chronologies developed from living trees and archaeological material. Their work, along with other investigations, has made it possible to relate the development of Arroyo Hondo to climatic variations.

Arroyo Hondo was established around AD 1300 when precipitation was increasing after a 50-year period of below average years. Precipitation remained above the long-term mean for most of the first 35 years of settlement. The pueblo reached its maximum size during this period and was apparently one of the

TABLE 2. Regional Droughts Lasting Two or More Years as Identified by Runs Analysis.*

Southwest				West			
Start	End	N	Sum	Start	End	N	Sum
1623	1624	2	0.12	1631	1632	2	0.17
1667	1670	4	0.59	1627	1638	2	0.20
1684	1686	3	0.48	1653	1655	3	0.62
1707	1709	3	0.09	1707	1708	2	0.16
1777	1778	2	0.07	1721	1722	2	0.02
1788	1789	2	0.03	1752	1754	3	0.18
				1756	1757	2	0.18
				1777	1778	2	0.33
				1782	1783	2	0.50
				1794	1796	3	0.26
1822	1824	2	0.24	1822	1824	3	0.30
1863	1864	2	0.22	1843	1848	6	0.49
1879	1881	3	0.37	1856	1857	2	0.08
1893	1894	2	0.18	1863	1865	3	0.35
1899	1900	2	0.23	1870	1871	2	0.14
1954	1956	3	0.19	1933	1234	2	0.37
				1959	1961	3	0.38

*Summary based on time series, 1600-1962, plotted in Figure 3; headings defined in text.

largest communities in the area. Precipitation became quite variable around 1335, population began to decline, and the pueblo was virtually abandoned by 1345. After about 40 years of near-abandonment and coincident with another period of favorable precipitation, a second phase of settlement began. A new town was built on the ruins of the old, reaching maximum expansion in the early 1400s. Following a disastrous fire, the final occupation came to an end.

Rose *et al.* (1982) expanded the Arroyo Hondo work with tree-ring reconstructions of climatic variables for the southeastern Colorado Plateau and surrounding areas for the period 900-1970. Tree-ring records from archaeological samples and living trees were used in the analysis. The 20-year moving-average of reconstructed Palmer Drought Severity Index (PDSI) for the Northern Rio Grande climatic division, New Mexico, is plotted in Figure 4. A striking feature of the reconstruction is the relative severity of drought in the late 1500s in the context of the last thousand years. The lowest 20-year mean occurred in the period 1573-1592. During this time the average PDSI was below -2.0, which is classified as moderate drought in the PDSI system (Palmer, 1965). The same period contains seven consecutive years (1579-1585) of PDSI below -2.0. The next longest run of drought years is five, and the longest run in the period covered by instrumental data is four (1953-1956).

LATE-1500S DROUGHT IN THE UPPER COLORADO RIVER BASIN

The importance of the Colorado River as a source of water for agriculture, for hydroelectric power generation, and for municipal and industrial uses in the southwestern United States cannot be overstated. This 1,440-mile river flows through some of the most arid lands in the country, and its 244,000 square-mile drainage area includes parts of seven states and a small portion of Sonora and Baja California in Mexico. The Colorado has an average annual flow of just under 14 million acre feet (maf), much less than the Columbia and Mississippi Rivers. In spite of this relatively low flow, more water is diverted from the basin than from any other river basin in the United States. The river is an important source of supply for southern California and, with the Central Arizona Project, for the metropolitan areas of Phoenix and Tucson in Arizona.

The tree-ring history of drought in the UCRB is recorded in a reconstruction of annual flow of the Colorado River at Lees Ferry, Arizona, 1520-1961 (Stockton and Jacoby, 1976). The tree-ring collections for the study consisted of 30 different sites from the major runoff producing regions (Figure 5). These sites were selected primarily to sample the widely separate runoff-producing areas in the three major sub-basins – the Green River, the San Juan River, and the main stem of the Colorado River. Multivariate regression models were calibrated using linear functions of the

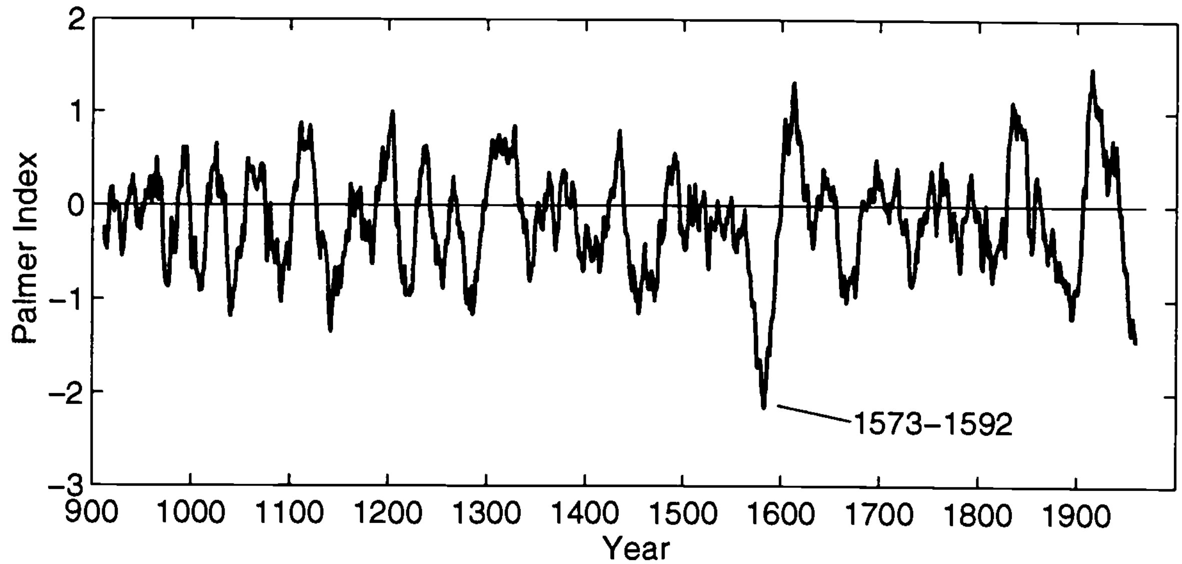

Figure 4. Twenty-Year Moving Average of Reconstructed July Palmer Drought Severity Index for the Northern Rio Grande Climatic Division, New Mexico (after Rose *et al.*, 1982). Values are plotted at mid-points of 20-year periods.

tree-ring data as predictors and the annual virgin flow record as the predictand. Various models were generated using different combinations of predictors, different model structures, and different versions of the virgin-flow record for calibration. The groups of chronologies used as predictors in the Lees Ferry reconstruction models are subsets of the sites marked in Figure 5. The groups include at least two chronologies from each of the major runoff-producing areas in Figure 5. The regression equations explained at least 75 percent of the variance of the observed flow in the calibration. Reconstructions from two of the more effective models were averaged to get the final reconstruction for the Colorado River at Lees Ferry, 1520-1961.

Stockton and Jacoby's (1976) reconstruction indicated that the estimated long-term mean annual flow of the Colorado River at Lees Ferry was only 13.5 maf – considerably less than the 16.2 maf annual flow estimated from gaged records early in this century and used as a basis for the Colorado River Compact. The reconstructed flow series also gives insight into the long-term history of SSD in the river basin. The time series of 20-year running means of the reconstruction contains several large-amplitude fluctuations on the order of 2 maf from the long-term mean (Figure 6).

If analysis of the series in Figure 6 is restricted to post-1600, the most severe sustained UCRB drought is centered in the 1660s, a period already identified in the Salt River reconstruction (Table 1) and the runs analysis (Table 2). Other low points in the smoothed Colorado River series also overlap

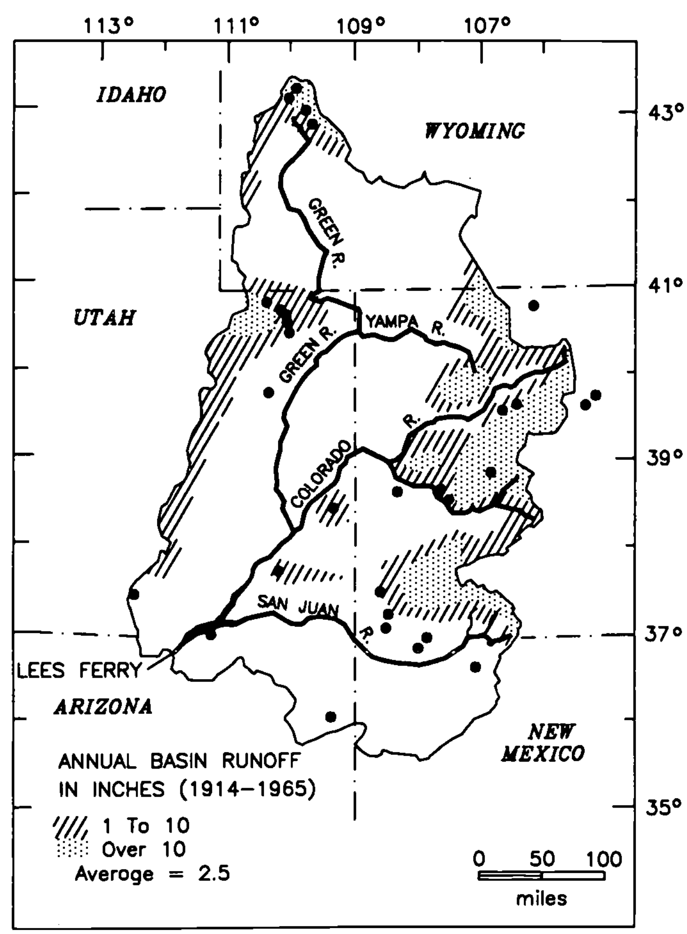

Figure 5. Map of Upper Colorado River Basin Showing Major Runoff-Producing (shaded), and Locations Tree-Ring Sites (dots), Used in a Reconstruction of Flow of the Colorado River at Lees Ferry, Arizona (after Stockton and Jacoby, 1976).

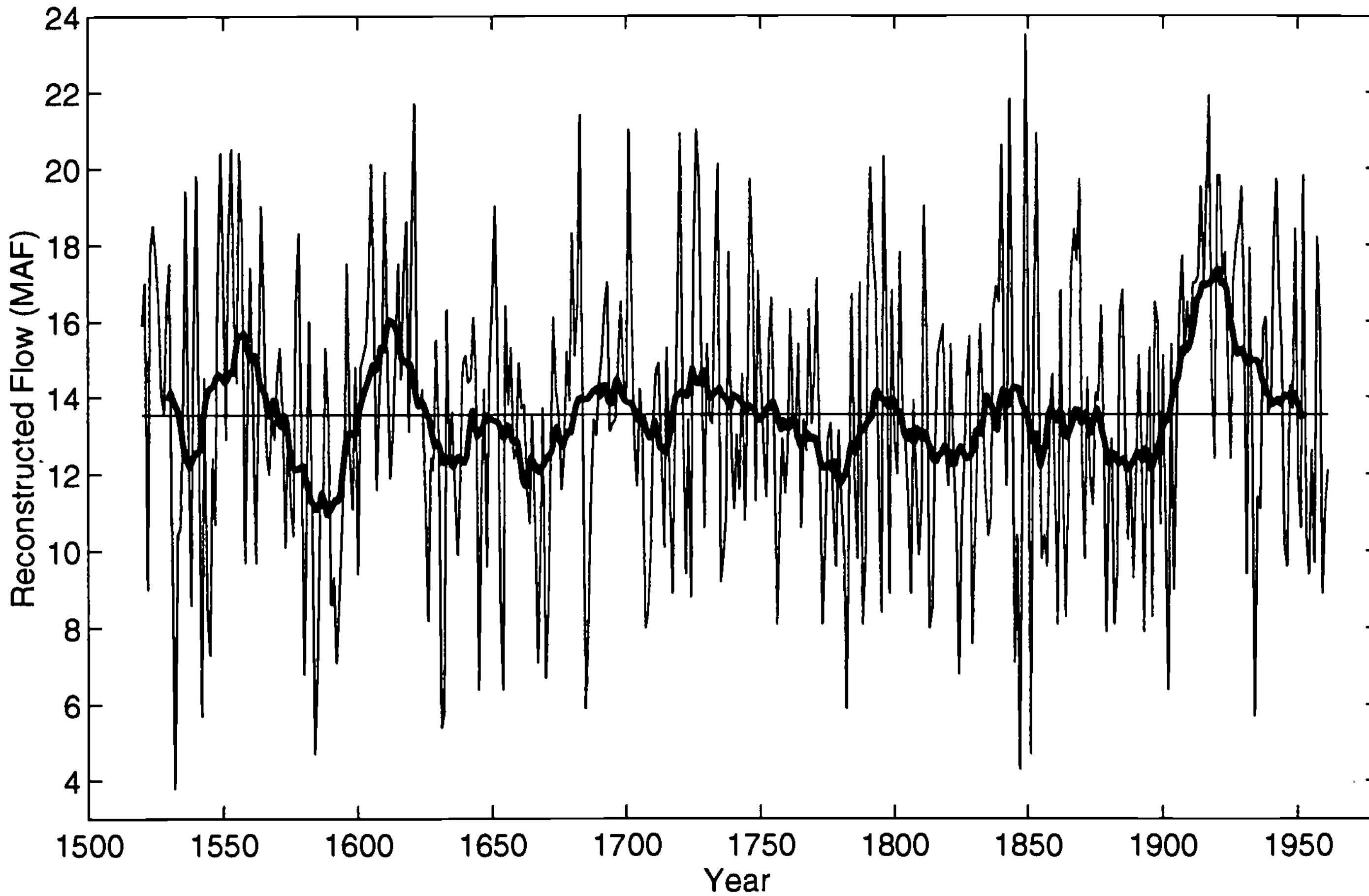

Figure 6. Annual Series and 20-Year Moving-Average of Reconstructed Flow of the Colorado River at Lees Ferry, Arizona. Units are million acre-feet (maf). Annual series covers 1520-1961. Moving-average series is plotted at midpoint of 20-year segment along x-axis (e.g., at 1910.5 for 1901-1920). Horizontal line marks long-term mean of annual series (13.5 maf). Source of data: Stockton and Jacoby (1976).

previously identified regional droughts – for example, the 20-year low in Montana tree growth (1800-1819) and the 10-year low in Arizona tree-growth (1773-1782).

The most interesting part of the Colorado River reconstruction occurs before 1600, when the smoothed series in Figure 6 dips to record lows. The ten lowest 20-year means all overlap the last decade of the 1500s. (Table 3). These 20-year means are much lower than at any other time in the reconstruction. The lowest is 10.95 maf, for the period 1579-1598. The late-1500s is also prominently represented in the list of ten lowest 5-year and 10-year running means.

Stockton and Jacoby (1976) commented on the 1500s drought in a assessment of time-series plots of tree-ring data from the UCRB:

> During the later part of the period from 1500 through 1600, an extensive drought occurred over most of the UCRB. All the tree-ring data series covering this time period show some evidence of this drought, but the magnitude and duration appear to vary in different parts of the Upper Basin. The longest and most severe drought appears to have occurred in the central portion of the UCRB (Upper Main Stem Area). The duration was somewhat reduced in both the northern and southern parts of the Upper Basin region.

Tree-ring records suggest that the drought of the late 1500s extended far beyond the boundaries of the UCRB. Evidence from the Upper Rio Grande Climatic Division, New Mexico, back to AD 900 has already been mentioned. Drought also apparently hit the Sacramento River Basin of California at about the same time. The reconstruction for the Sacramento River is slightly shorter than that for the Colorado River, extending back to 1560 (Earle and Fritts, 1986). The synchrony in time-series variations of reconstructed flow on the Colorado River and

TABLE 3. Lowest Reconstructed n-Year Means on the Colorado River (data after Stockton and Jacoby, 1976).

	5-Year		10-Year		20-Year	
Rank	Period	Flow (maf)	Period	Flow (maf)	Period	Flow (maf)
1	1590-1594	8.84	1584-1593	9.71	1579-1598	10.95
2	1583-1587	9.02	1583-1592	9.90	1580-1599	11.04
3	1667-1671	9.20	1585-1594	10.29	1575-1594	11.09
4	1589-1593	9.46	1663-1672	10.55	1576-1595	11.16
5	1531-1535	9.56	1773-1782	10.57	1581-1600	11.18
6	1591-1595	9.64	1662-1671	10.65	1574-1593	11.23
7	1666-1670	9.68	1579-1588	10.75	1573-1592	11.30
8	1542-1546	9.70	1582-1591	10.79	1583-1602	11.30
9	1541-1545	9.76	1580-1589	10.82	1578-1597	11.31
10	1580-1584	9.90	1586-1595	10.84	1582-1601	11.34

Sacramento River has been examined by Meko *et al.* (1991). Although the correlation coefficient between the two reconstructions is small (r=0.23, N=402 years), persistent drought sometimes occurred at the same time in the two basins. The extreme example of concurrent drought is the period 1579-1598 – the lowest 20-year mean on the Colorado River and the third lowest non-overlapping 20-year mean on the Sacramento River.

A map of the average tree-ring departures over the UCRB for the 1579-1598 period verifies that the drought was characterized by dry conditions in all major runoff-producing parts of the basin (Figure 7). For this analysis, 20-year running means were computed for each tree-ring chronology for the period 1520-1963; the 425 running means at each site were ranked in ascending order, and the percentile ranking of the 1579-1598 mean among the sample of 425 running means was computed. The 1579-1598 mean was below the 50th percentile (median) at all 18 tree-ring sites and was at the 6th percentile or lower at eight sites. At least one chronology in each of the major runoff-producing regions was at its 6th percentile or lower of growth during the drought. Driest conditions are inferred for the San Juan Basin and the headwaters of the main stem of the Colorado River.

We emphasize that streamflow reconstructions are estimates as opposed to measurements of past flow and that quantitative drought assessment from tree-ring studies should always be accompanied by an acknowledgment of uncertainty in the data. Uncertainty is common to all proxy indicators of climate. The expected error in reconstructions can vary greatly depending on the sensitivity of the tree-ring series to the hydrologic variable of interest. With a regression R^2 exceeding 0.75, the Colorado River reconstruction is a high-quality tree-ring reconstruction as measured

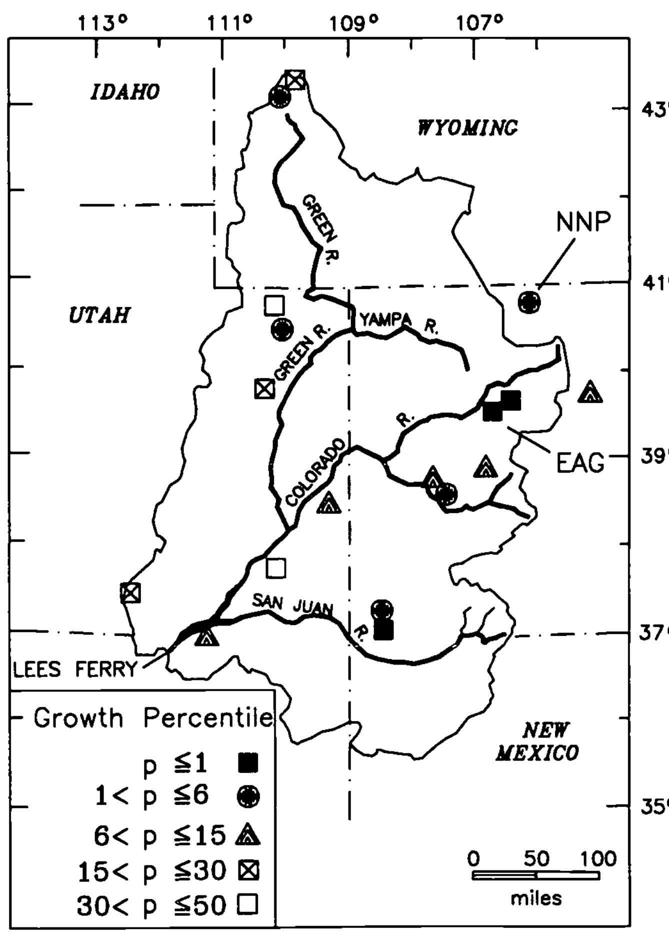

Figure 7. Spatial Pattern of 1579-1598 Tree-Growth Anomalies in the Upper Colorado River Basin. Symbols mark tree-ring anomalies at sites used by Stockton and Jacoby (1976) to reconstruct Colorado River flow at Lees Ferry, Arizona. Symbols are coded as percentile ranking of the 20-year-mean tree-ring index for 1579-1598 among all 20-year running means for the period 1520-1963. Labels "NNP" and "EAG" refer to sites mentioned in text.

by calibration statistics. Because of the shortness of the overlap period of the gaged-flow record and the tree-ring record, the regression model was not verified rigorously on independent data. The possibility that the calibration R^2 is inflated due to overfitting of the model cannot therefore be ruled out. Comparison of reconstructed values with a recent U.S. Bureau of Reclamation version of the natural-flow series based on gaged data indicates that, for the post-1905 period, the mean absolute error of the annual estimates is 1.7 maf and the standard deviation of the errors is 2.0 maf. It is reasonable to expect somewhat smaller errors in n-year means. For example, a simple regression of 10-year running means of the natural flow series against the reconstructed flow yields a standard deviation of errors of 0.46 maf. As mentioned previously, however, calibration-period statistics do not apply to regression estimates classified as extrapolations, and many of the extremely low reconstructed annual values in the late 1500s are probably extrapolations.

The reconstruction error in the 1500s could possibly be greater than suggested by regression statistics because of the drop in sample size (number of trees) in the early parts of the chronologies. The worst case for the 18 sites used in the reconstruction equations is New North Park, Colorado (NNP in Figure 7). The sample size at NNP drops from 21 cores in 1900 to one core in 1590. At the other extreme is the Eagle, Colorado, site (EAG in Figure 7), which has a sample size of 21 cores in 1900 and 19 cores in 1590. That this well-replicated chronology is one of three chronologies in its lowest percentile of growth in the late-1500s drought argues in favor of the reality of the reconstructed drought. Sample-size changes for the other chronologies are much less drastic than for NNP but are still substantial. For the 18 sites, the median ratio of the number of cores in 1900 to the number in 1590 is 2.6.

CONCLUSION

Tree-ring studies with varying time coverage and spatial resolution contribute to our knowledge of the history of severe sustained drought in the Southwest. Periods delineated as most severe sustained drought differ from basin to basin and region to region over the Southwest, as might be expected from the spatial variability of precipitation anomalies.

Although tree-ring coverage becomes spotty before 1600, evidence strongly points to a period in the late 1500s as a period of drought much more severe and prolonged than any drought in succeeding years. Tree-rings indicate that multi-decadal drought in the late 1500s simultaneously hit widely separate locations: the northern part of the Rio Grande drainage in New Mexico, the Colorado Rockies, and the drainage of the Sacramento River in the Sierra Nevada Mountains of California.

The term "most severe sustained drought" makes sense only in the light of a specific time-frame, geographic focus, and summary variable. As recommended in the June 8-9, 1989, meeting of the Severe Sustained Drought group in Boulder, Colorado, we have addressed the time-frame reliably sampled by tree-ring data, focused on the interior Southwest – especially the Upper Colorado River Basin – and adopted the 20-year moving average of reconstructed annual flow as the drought variable. Shorter droughts of great intensity may of course cause hardship in some parts of the study area, particularly those not tied in to distribution facilities of major water supply entities. A moderate prolonged shortage in precipitation over a period of 20 years or longer, however, could possibly stress water supplies even for systems with multiple years of reservoir storage, such as the Colorado River.

The most severe sustained drought in the tree-ring record for the UCRB occurred in 1579-1598. The tree-ring estimate of the severity of this drought as measured by 20-year-average flow is period is 10.95 maf, or 2.55 maf below the long-term reconstructed mean of 13.5 maf. We emphasize that the error in the reconstructed values of Colorado River flow for the 1500s might be considerably larger than suggested by regression statistics because some extremely low flows are probably extrapolations rather than predictions and because the number of trees in the early part of the chronologies is small. The uncertainty of the 1500s reconstructed values could possibly be reduced by building up the sample sizes of chronologies with additional collections of very old trees.

Tree-ring reconstructions are useful in the absence of other data in placing rough bounds on the expected variability of parameters such as the frequency, intensity, and duration of drought. Future climatic change could alter the framework within which reconstructions are interpreted. Consideration of climatic change, as might for example result from greenhouse warming, is beyond the scope of this paper. Natural climatic variability alone, however, is sufficiently large to pose possible problems for future water supply in the semi-arid regions of the southwestern United States.

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