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Tree-Ring Data: Valuable Tool for Reconstructing Annual and Seasonal Streamflow and Determining Long-Term Trends

CHARLES W. STOCKTON AND WILLIAM R. BOGGESS

Two examples are discussed that demonstrate how information derived from the annual growth rings of certain tree species can be used as a proxy source of data to extend hydrologic records back in time. In the first case, tree-ring reconstructions of the annual flow of the upper Colorado River show that the period of record used as a basis for the 1922 Colorado River Compact was anomalously wet, in fact, the wettest comparable period in the entire 450 yr of reconstructed annual discharge at Lee Ferry, Arizona. The full impact of this overestimated flow has yet to be felt. In the second example, data from 13 carefully selected sites were used to reconstruct the annual and seasonal flows of the Salt and Verde Rivers back to 1580. These two rivers, draining some 13,000 miles^2 in central Arizona, furnish water for municipal, industrial, and agricultural use as well as hydroelectric power for the metropolitan Phoenix area. Future water supply and flooding potential are both critical problems due to rapid escalation of population. Results show that several periods of prolonged low flows have occurred that were more severe than any comparable period since 1890. These low-flow periods have an apparent recurrence interval of about 22 yr on the Salt River. Also, the gaged records contain an above-average number of high seasonal and annual flows when compared with the entire 400 yr of reconstruction.

Planning and design for controlling and managing water are predicated on the analysis of historic data to determine both the magnitude and the frequency of annual water yields that have been measured over a finite period of time. In general, statistical procedures used to forecast annual flows are hampered by the relatively short time span covered by instrumented records. This is true throughout the Western Hemisphere and especially so in most developing countries, where hydrologic records are essentially nonexistent. Even where reliable records are available, there is no assurance that they represent a truly random sample and that the occurrence of hydrologic events throughout the period is based on some probability distribution. As a consequence, statistical descriptions may contain considerable bias and produce erroneous results.

In most instances, probability distributions are uniquely defined by the mean ($\bar{X}$), a measure of central tendency; the variance (S^2), a measure of the average spread of events around the mean; and skewness (G), a measure of the asymmetry of the distribution of events around the mean. For many runoff and tree-ring series, the variables are normally distributed (G approaches zero) and the probability distribution is adequately described by $\bar{X}$ and S^2.

In developing first-order autoregressive models of runoff time series, the first-order correlation (r_1), a measure of short-term persistence, is used along with the mean and variance. The population values of these statistics are usually unknown and must be estimated from existing records. From Monte Carlo simulations involving thousands of trials on each of several probability functions for various values of n and γ (the number of observations and the population coefficient of skew), Wallis, Matalas, and Slack (1) demonstrated that the distributions of $\bar{X}$ and S^2 and G are functions of n, λ, and the probability function. Although $\bar{X}$ is an unbiased estimate, both S^2 and G are biased estimates of population values, the degree of bias being a function of n, γ, and the probability distribution.

It follows that errors in estimating population parameters due to short periods of record are preserved in any synthetic series that is generated from the available data. For example, Rodriquez-Iturbe (2) showed that in annual runoff records of 40 yr or less, there may be an error of 2 to 20 percent in estimating the first-order correlation, which is probably related to the inadequacy of short periods of record for estimating the low-frequency persistence in climatologic data.

Another complicating factor is that the possible effects of climatic change in probability distributions are largely ignored. This is due in part to the guidelines for determining flood-flow frequency issued by the Hydrology Committee of the U.S. Water Resources Council (WRC) (3). In the guidelines, it is stated that

> there is much speculation about climatic change. Available evidence indicates that major changes occur in the time scales of thousands of years. In hydrologic analyses it is conventional to assume that flood flows are not affected by climatic trends or cycles. Climatic time invariance was assumed in developing this guide.

Contrary to the WRC statement, there is considerable evidence that climate is nowhere invariant and that the variability is not a random function of time (4). For example, the world has experienced both cooling and warming during the past century. The overall trend has been toward warming; there has been a greater tendency for change in the higher northern latitudes. According to Hansen and others (5), the higher northern latitudes warmed about 0.8°C between 1880 and 1940, whereas the lower southern latitudes increased only 0.3°C. Cooling, especially in the northern latitudes, followed in the 1940s but the trend reversed on a global basis in the mid-1960s. The same authors point out that global temperatures are now about equal to the 1940 peak and suggest that the common misconception that temperatures are cooling is based on experiences in the Northern Hemisphere.

The growing consensus among climatologists is that global temperatures will continue to rise due to the greenhouse effect of increases in atmospheric carbon dioxide caused by man. There is no unanimity of opinion on the magnitude or speed of such changes, but Hansen and others (5) suggest that a rise of about 2.5°C is possible during the next century for a scenario of slow energy growth and a mixture of fossil and nonfossil fuels. Such a rise in global temperatures would be almost unprecedented, and the results would be disastrous for many parts of the world. Any changes that might occur in the next century are well within the time frame for hydrologic planning, and their likely occurrence raises an important question: Can hydrologists and engineers ignore climatic variability as a parameter for planning and design?

Because existing climatic and hydrologic records are not old enough to reflect climatic variability and trends, one must turn to some source of proxy data to document the occurrence and persistence of these changes. The most commonly used sources include layered ice cores; pollen profiles developed from bog, swamp, or lake sediments; stream geometry, stratigraphy, and morphology; and tree rings. The first three sources can generally be extended farther back in time than tree rings, but they cannot be precisely dated and lack the capacity to preserve high-frequency (short-term) variations. In contrast, tree rings can be accurately dated as to the year of formation and preserve both high- and low-frequency (long-term) variations. Also, the climatic information stored in tree rings is annually cumulative, and samples can be replicated to a much greater extent than the other sources.

A disadvantage of tree-ring series is that they rarely extend back in time more than 400-500 yr and the climatic signals by species growing under a wide variety of climatic conditions are not equally strong or clearly defined. The trees most responsive to climatic variation in the United States are some of the relatively long-lived species growing in the West, especially those on arid sites. It is not surprising that the study of tree rings (dendrochronology) developed in the Southwest, and much of the past work pertains to western conditions.

Earlier applications of dendrochronology were largely confined to dating archaeological materials such as wood or charcoal from ancient Indian dwellings. More recently, much progress has been made in using tree-ring series to reconstruct past climates (dendroclimatology) and hydrologic events (dendrohydrology). Two aspects of our work in dendrohydrology are discussed here. The first illustrates how streamflow records from an anomalously wet period were used as a basis for the 1922 Colorado River Compact. Second, we show how tree-ring data can be used to reconstruct annual and seasonal flows of the Salt and Verde Rivers in Arizona.

RECONSTRUCTION TECHNIQUES

The techniques used in both climatic and hydrologic reconstructions involve advanced statistics and modeling, especially in the area of time-series analysis. These and the computer techniques involved are not discussed here; they have been described in detail by Stockton (6), Fritts (7), and Stockton and Boggess (8).

It is especially important to recognize two aspects of tree-ring analysis. First, each ring must be precisely dated. This cannot be done by merely counting rings. Instead, a tedious and time-consuming process called crossdating is essential to account for possible multiple or locally absent rings. Second, measured ring widths cannot be used directly in statistical analyses because rings tend to become narrower as trees senesce and grow older. This growth trend is removed by fitting an appropriate least-squares curve to provide a ring-width index (measured ring widths are divided by corresponding curve values to provide the index). In addition to removing the growth trend, this procedure reduces all ring widths to a uniform mean value (value of 1). When plotted against time, the ring-width indexes form a new stationary time series known as a standardized ring-width chronology. These procedures are discussed in detail by Fritts (7, Chapter 6).

Another analytical problem that must be dealt with in developing tree growth-climate relationships is that of persistence (autocorrelation) in tree-ring series. This results because growth during a particular year is influenced not only by conditions during that year but perhaps also by antecedent conditions during one or more preceding years. For instance, in a favorable year an excess of photosynthate more than that required for growth and other metabolic processes will carry over and produce a positive effect on the next year's growth. Conversely, an unfavorable year will likely represent the opposite. Available food reserves will be depleted for the onset of growth in the following year.

Autocorrelation is estimated in a manner similar to that for the product-moment correlation coefficient, except that instead of determining the relationship between two variables, x and y, the relationship between x and x - i is calculated, where i is the amount of lag. Autocorrelation may be removed from some time series by regressing the response at time t with that at t - 1. The effect of t - 1 is then subtracted from the response at time t (9). Meko (10) discusses in detail how the resulting autoregressive (AR) process can be applied to tree-ring series to remove the effect of soil moisture and biological carryovers. It should be noted that persistence also exists in many climatic time series; there is a tendency for clustering of wet and dry years.

A period of overlap between historic hydrologic or climatic data and the tree-ring series is essential. A part of the overlapping record is used to develop statistical relationships between the two series (calibration). The remaining record provides a basis for verifying the accuracy of the established relationship (verification). If the relationship appears valid, transfer functions are developed to extend the hydrologic series back in time based on the existing tree-ring series.

Because of the nature of tree growth, each annual ring represents an integration of environmental and physiological factors over 1 yr or more. For this reason, streamflow reconstructions are generally limited to annual values. With exceptionally good data collected near runoff-producing sites, seasonal flows can often be successfully estimated. Peak flows can only be inferred in that they might be expected to occur more frequently when annual or seasonal flows are well above the long-term mean.

COLORADO RIVER STUDY

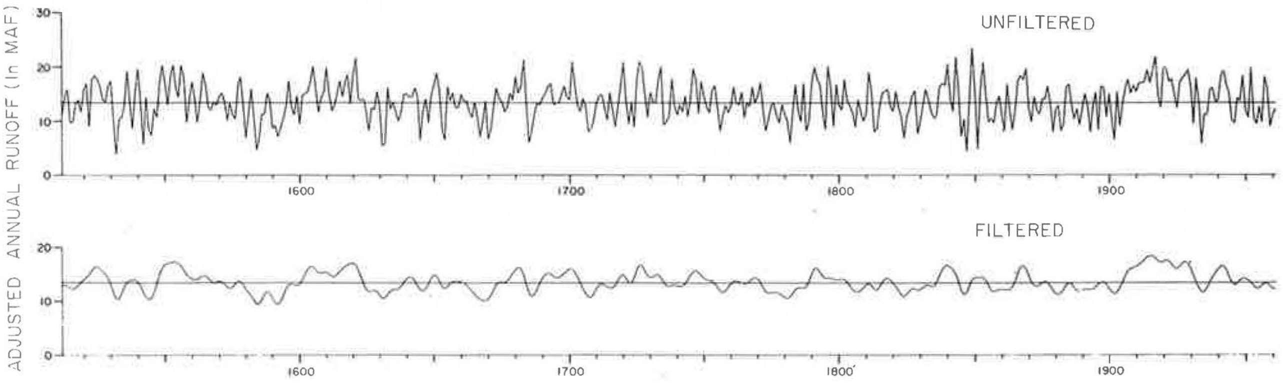
As pointed out earlier, most statistical analyses involving hydrologic data assume that the period of record adequately represents the infinite number of past events. This assumption of randomness may or may not be correct. That it may not be correct is dramatically illustrated by results of a study reported variously by Stockton (6), Stockton and Jacoby (11), and Stockton and Boggess (8, pp. 266-273) in which the flow of certain streams in the upper Colorado River basin was reconstructed by using tree-ring data.

The Colorado River is the major source of surface water for much of the southwestern part of the United States. Flowing some 1,440 miles from the high mountains of Colorado to the Gulf of Lower California, the river traverses some of the most arid land in the country. Its annual flow of about 14 million acre-ft (maf) is modest when compared with that of the Mississippi (440 maf) or the Columbia (180 maf), yet more water is exported from the basin (about 5 maf) than from any other river basin in the United States. Most of the flow originates in the upper basin where an estimated 85 percent of the flow is generated on 15 percent of the land area.

In 1922 the estimated annual flow of the Colorado River was allocated equally between the upper and lower basins--7.5 maf to each. A later treaty guaranteed a 1.5-maf allotment to Mexico. The compact was based on a sustained flow of 17.5 maf at Lee Ferry, Arizona (12, pp. 79-95). The flow at Lee Ferry was estimated from fragmentary data, dating in part back to 1896, on some of the tributary streams in the upper basin.

The tree-ring reconstructions, dating back to 1564, were based on data collected from up to 30 sites located near runoff-producing areas. The reconstructed average annual flow was about 13.5 maf, far short of the 17.5 maf on which the compact was based. Why the large discrepancy? As stated earlier, the records used for the compact were fragmentary and were extrapolated from tributaries to the main stream at Lee Ferry. More important, the reconstructions show that the period of record was anomalously wet--the wettest indeed for the entire 450 yr covered by the reconstructions [Figure 1 (up-

Figure 1. Long-term hydrograph of annual runoff at Lee Ferry, Arizona, based on average of results of two reconstructions.



per graph, actual year-by-year values; lower graph, same data but with high-frequency components--those with period less than 10 yr--removed)]. It is of interest to note that the measured flow of the river at Lee Ferry for the period 1930-1974 is 13.78 maf. If the high flows of the early part of the century are included (1906-1974), this increases to an estimated 15.17 maf. Thus the reconstructions appear to be a good representation of the actual behavior of the river as well as to have shown the bias toward wetness in the data used for the compact. The full impact of the overestimated flow has yet to be felt, because the upper basin has not used its full allocation.

SALT-VERDE RECONSTRUCTIONS

In addition to the Colorado River study, tree-ring data have been used to reconstruct streamflow on the Rio Limay and Rio Neugguen in Argentina (13), eight rivers in western Tasmania (14), and the Salt and Verde Rivers in Arizona (15). Results from the Salt and Verde Rivers are discussed here.

Basin Characteristics and Water Demand

The basins of the Salt and Verde Rivers include some 13,000 miles^2 in central Arizona. The two rivers converge at Granite Reef, north of Phoenix, to form the largest tributary of the Gila, which then flows southwesterly to join the Colorado at Yuma. Both rivers originate in the high mountains at altitudes of approximately 12,000 ft. Precipitation ranges from more than 32 in. in the higher mountains to less than 8 in. in the more arid portions and occurs as winter storms from Pacific frontal systems or as convective thunderstorms during the summer. The latter make minimal contributions to streamflow.

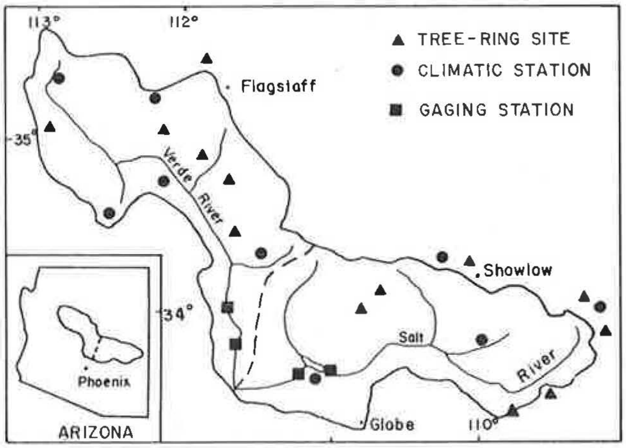
The Salt and Verde Rivers are the main source of water for metropolitan Phoenix as well as for a large area of irrigated agriculture. Six dams, which have a combined storage of about 2.08 maf, have been constructed on the two rivers. Four of these produce hydroelectric power. The water and power resources are managed by the Salt River Project, the oldest multipurpose reclamation project in the country.

The demand for water has escalated since World War II, accompanying the phenomenal population growth of the Phoenix area. Flooding, always a threat in the Salt River Valley, has become an even greater problem because of the conversion of agricultural land to urban developments. Population growth shows no sign of decreasing, and there is increasing concern over both future water supply and flooding potential. A basic tenet in both issues is whether the period of record, although relatively long, adequately represents the long-term flow characteristics of the rivers. Our study, requested and supported by the U.S. Army Corps of Engineers, was designed to provide information on this important point.

Data Sources

The locations of stream-gaging stations, climatic stations, and tree-ring sites are shown in Figure 2. Data from the gaging station near the town of Roosevelt, operational since 1914, were used to calibrate the streamflow records. Although a gage located about 16 miles downstream from the one near Roosevelt operated during 1901-1913, data from the two could not be combined because such data represented considerably different drainage areas. Nevertheless, the earlier data, along with estimates of flow from data at Arizona Dam for the period 1883-1913, were valuable because they could be used to verify the relative magnitude of flows outside the 1914-1979 calibration period. Also, the period 1883-1913 included some of the largest discharges ever recorded for the two rivers.

Figure 2. Locations of tree-ring sites, climatic stations, and gaging stations.



The gage below Bartlett Dam on the Verde River was established in 1895. The flow below the dam, however, has been regulated by Bartlett and Horseshoe reservoirs since their completion in 1939 and 1943, respectively. Monthly discharges after 1939 were corrected by adding net monthly changes in reservoir capacity published by the U.S. Geological Survey to the reported monthly flow at the gage. A gaging station was established below Tangle Creek in 1945 that represents the inflow into the Verde reservoir system. The drainage area between the two gages is insignificant, so the Tangle Creek gage was used after 1945 to avoid errors in estimating reservoir contents associated with the gage below Bartlett Dam.

Tree-ring samples were collected from 13 locations, as shown in Figure 2. Each sample consisted of two cores from a least 10 trees per site. Sites were selected to maximize both the climatic sensitivity and the length of the tree-ring series. Generally the most climatically sensitive trees are those growing on open, exposed sites with shallow soils whose moisture supply is solely from precipitation. Tree species sampled included ponderosa pine (*Pinus ponderosa* Laws) and pinyon pine (*Pinus edulis* Englm.).

Data from selected climatic stations were analyzed to determine relationships among precipitation, runoff, and tree growth. Stations were chosen for the length and quality of their records. Data from Roosevelt, White River, Springerville, and Pinedale were used to represent the Salt River basin, whereas Jerome, Seligman, Williams, Natural Bridge, and Prescott were chosen for the Verde.

Analysis of Data

Reconstruction of stream discharge from tree-ring data is based on the generally accepted assumption that both are responding to the same climatic input (temperature, precipitation, evapotranspiration, and so on). To determine the relationships between climate and discharge and climate and tree growth, we used principal-component analysis (PCA), a method that allows a large field of correlated data to be expressed as a smaller number of uncorrelated variables called eigenvectors. A spatial array of M stations each having the same number (N) of data points will yield the smaller of either M or N eigenvectors. Each eigenvector will contain M components corresponding to the number of stations, or variables, and will account for a portion of the total variance (16). The sum of the products of an eigenvector generated by PCA with the values of its components for a given year yields a value called the amplitude for that year (17).

The amplitudes corresponding to the eigenvectors of monthly climatic data for several stations within the Salt and Verde basins represent modes of temperature and precipitation that are independent in time and weighted spatially over each of the basins. These amplitudes were entered as predictor variables in a multiple-linear-regression (MLR) analysis with the $\log_{10}$ transform of annual discharge to determine water-balance models. A $\log_{10}$ transform was performed because the original discharge data were log normally distributed and their use in an MLR with normalized predictor variables would have resulted in the estimation of negative values for low-flow years. The use of the transform increased the variance explained by a few percent for each model, most likely because of the dampening in variance resulting from the $\log_{10}$ transformation.

Under the general assumption that discharge and tree growth respond to climatic stimuli in a similar manner, the record of past climate contained in the tree-ring series was substituted as proxy data to reconstruct records of annual runoff. Streamflow records were reconstructed by using the tree-ring series as independent predictors in an MLR with the $\log_{10}$ discharge data for the period of gaged record. In all MLRs only those variables that were significant at the 99 percent confidence level and that resulted in an increase in R^2, adjusted for the loss of a degree of freedom caused by entering the variable (18), were entered in the prediction equations.

The streamflow reconstructions were analyzed for periodic components by using spectral-analysis methods (19). The series was lagged by 100 yr and the Parzen weighting function was employed, as detailed in the computer program of Aarons and Reagan (20). The confidence limits for the spectral density function were determined in accordance with the technique described by Chatfield (21).

Results and Discussion

Because the discharge reconstructions for the two rivers are quite similar, and in the interest of brevity, only the results for the Salt River basin are discussed here. Important differences between the two basins will be noted.

The results of the calibration of the Salt River discharge and tree-ring data are summarized in the third column of Table 1. Because the most important precipitation influencing both discharge and tree growth occurs in the winter months, two separate calibrations were used; the discharge for October through April and that for December through March were reconstructed in addition to the total annual flow. Because all of the tree-ring series were not of the same length, separate prediction equations were developed for each of the common data periods to maximize the length of the reconstructed records. The reconstructed annual discharge is plotted along with the actual gaged data in Figure 3 (calibration period is 1914-1979).

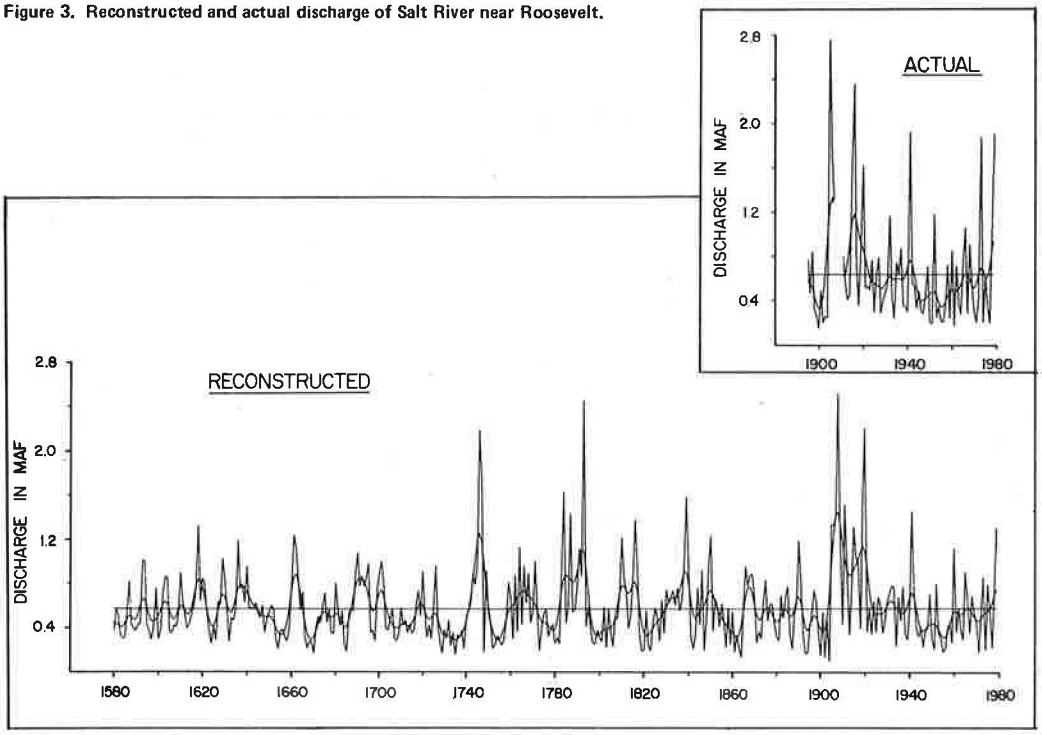
The reconstructed values were tested against actual gaged flow by simple linear regression that used both the early independent data from 1895-1907 and that from 1911-1913 and the data from the 1914-1979 calibration period (columns B of Table 1). A reduction in R^2 from the original prediction equation occurred in every case. This reduction was due to the underestimation of major flows in 1905 and 1916 and also because the earlier data were from a larger drainage area. The flows predicted for 1908 and 1920 were of the same magnitude as those for 1905 and 1916, respectively, which implied an apparent lag in prediction of 3 to 4 yr for those two high flows. A likely explanation for this lag is that the period 1899-1904 was very dry, as shown by both precipitation and streamflow records. Also, cores from sample trees showed minimal or no measurable diameter growth during portions of the period. Although 1905 was a wet year, the annual ring widths did not show maximum response to this moisture until 1908. This lag was undoubtedly caused by an exhaustion of food reserves in the trees during these 6 yr of hot, dry weather. The 2 yr preceding 1916 were also very dry; many of the sample trees experienced only minimal diameter growth. During such extended dry periods, photosynthesis is inhibited by the lack of moisture and respiration rates are increased by high temperatures. This combination depletes the food reserves available for growth. Once moisture is again available, these depleted food reserves must be replenished before ring widths show a maximum response. The longer period of lag associated with these two high flows was not removed by the time-series analysis because it was unrelated to the autocorrelation structure associated with a more common 1- or 2-yr lag. Instead it appears to be a nonstationarity associated only with very wet years following drier periods.

Table 1. Results of regressions between actual gaged data and predicted flows for Salt River near Roosevelt.

		Original Regression (R^2)	Regression B		Regression C		Regression D	
Season	Common Period		R^2	SE (acre-ft 000s)	R^2	SE (acre-ft 000s)	R^2	SE (acre-ft 000s)
Annual	1702-1979	0.728	0.593	336	0.757	260	0.730	221
	1630-1979	0.666	0.435	396	0.617	326	0.637	257
	1620-1979	0.643	0.387	413	0.558	350	0.579	276
	1580-1979	0.535	0.390	411	0.564	348	0.534	290
Oct.-April	1702-1979	0.717	0.586	293	0.729	237	0.712	191
	1680-1979	0.704	0.480	328	0.673	260	0.750	178
	1630-1979	0.686	0.525	314	0.679	258	0.708	192
	1620-1979	0.641	0.425	345	0.513	317	0.614	221
	1580-1979	0.527	0.361	364	0.540	308	0.524	246
Dec.-March	1702-1979	0.665	0.497	240	0.706	184	0.724	132
	1680-1979	0.633	0.342	275	0.577	220	0.703	138
	1620-1979	0.604	0.425	257	0.522	227	0.630	154
	1580-1979	0.490	0.341	275	0.498	240	0.517	176

Notes: SE = standard error of estimation.
R^2-values are adjusted for loss in degrees of freedom.

Figure 3. Reconstructed and actual discharge of Salt River near Roosevelt.



Because the predicted values for 1908 and 1920 most likely represent moisture conditions in 1905 and 1916, respectively, they were substituted for the values for those years, and the regressions were performed again (columns C, Table 1). In each case the value of R^2 was much closer to that obtained in the $\log_{10}$ prediction equation for the period 1914-1979. Separate regressions were performed between the gaged and reconstructed data from the period 1921-1979, and the results are shown in columns D of Table 1. The R^2-values obtained were in agreement with those derived from the original prediction equation and the regressions with the two high flows transposed, which also indicated that the longer period of lag for the two high flows was responsible for the majority of the reduction in R^2.

The standard errors of estimation are also included in Table 1. The values for the 82-yr regression with the high flows transposed (columns C) are probably more representative of the standard errors of the estimated flows themselves. The values obtained without transposing the two high flows (columns B) are more representative of the standard errors associated with the flows predicted for a particular year. Because the magnitude of a high historical flow is more important in terms of design than the year in which it occurred, the standard errors in columns C are probably more realistic estimates of the standard errors in magnitude for flows estimated outside the calibration period.

Statistical analyses performed on the gaged and predicted discharge records and the results for the annual reconstruction are shown in Table 2. The first four moments of the actual and predicted records for the period 1914-1979 were nearly identical for each the models, which indicates that the reconstructions provide reliable estimates of the distribution of annual and seasonal flows. Frequency distributions of both gaged and predicted records for the 1914-1979 period are shown in Figure 4. From a design standpoint, the problems associated with the lag in prediction of certain high seasonal flows are not important when the distributions alone are considered.

Table 2. Results of statistical analyses of reconstructed and actual annual discharge of Salt River near Roosevelt.

Data	Period	Mean (acre-ft 000s)	Standard Deviation (acre-ft 000s)	Skewness	Kurtosis
Actual	1914-1979	626.8	480.0	1.81	3.11
Reconstructed	1914-1979	588.1	371.9	1.89	5.01
	1580-1979	576.6	343.9	2.02	9.64
	1580-1659	547.4	227.4	1.12	4.29
	1660-1739	514.9	249.1	0.84	3.12
	1740-1819	623.3	431.3	2.01	8.12
	1820-1899	544.4	274.3	0.94	4.74
	1900-1979	639.1	451.4	1.81	7.21

Figure 4. Frequency distributions of actual (open bars) and reconstructed (hachured bars) stream flow of Salt River near Roosevelt.

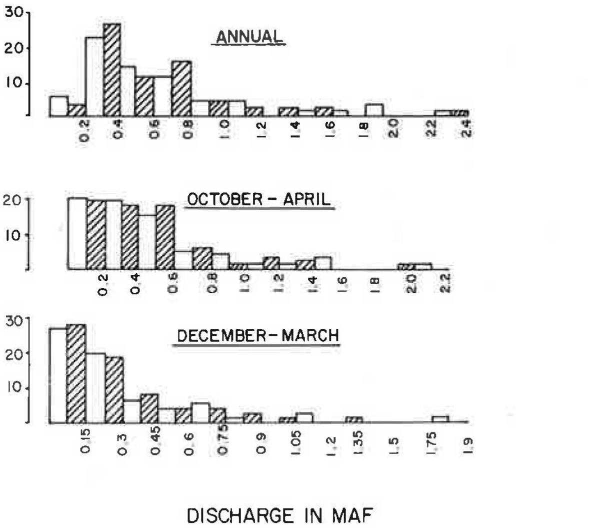


Figure 5. Spectral density function for October-April discharge of Salt River near Roosevelt.

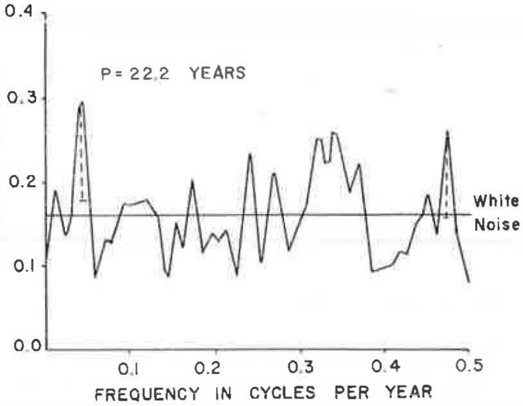


Table 3. Comparison of selected actual and reconstructed flows of Salt River near Roosevelt.

Flow Year	Season	Actual (maf)	Avg Actual Occurrence	Reconstructed (maf)	Avg Reconstructed Occurrence
1905	Annual	2.76[a]	1 in 80	2.52	1 in 400
	Oct.-April	2.28[a]	1 in 80	2.17	1 in 200
	Dec.-March	1.51[a]	1 in 40	1.39	1 in 400
1916	Annual	2.36	1 in 40	2.21	1 in 133
	Oct.-April	2.08	1 in 40	1.88	1 in 100
	Dec.-March	1.78	1 in 80	1.26	1 in 200
1941	Annual	1.93	1 in 27	1.45	1 in 40
	Oct.-April	1.42	1 in 20	1.38	1 in 57
	Dec.-March	1.08	1 in 16	0.99	1 in 100
1979	Annual	1.91	1 in 20	1.30	1 in 22
	Oct.-April	1.59	1 in 27	1.12	1 in 31
	Dec.-March	1.08	1 in 20	0.80	1 in 57

Notes: Average occurrence is the number of times the flow was equaled or exceeded divided by the period of record. Actual period of record is 1900-1979; reconstructed period is 1580-1979.

[a] Includes the discharge of Tonto Creek.

The means for the 80-yr periods 1740-1819 and 1900-1979 were significantly greater than those for the three remaining periods at the 80 percent (or better) confidence level, yet they were not significantly greater than the 400-yr mean. This has important implications for water supply planning because it suggests that although the mean from the period of gaged record (1914-1979) was not significantly different from the 400-yr mean, it may not be a reliable estimator of the dependable annual supply. The mean annual flow from the three 80-yr periods of lower flow (1580-1659, 1660-1739, 1820-1889) may represent a more realistic value.

Several periods of sustained high and low flows are evident throughout the 400-yr reconstructions. The period 1905-1920 was the wettest in the entire reconstruction; almost all of the predicted flows were above the 400-yr mean. The only other period that approached the early 1900s in magnitude was from the mid-1780s through the mid-1790s.

Moving averages of 2, 5, 10, 25, and 50 yr were calculated in order to analyze the short- and long-term trends in the reconstructions. High flows in the early 1900s dominated the short- and long-term means of each seasonal reconstruction. The driest 5-yr period ended in 1670. This drought is known to have occurred over the entire Southwest and resulted in severe hardship for the Pueblo Indians living in the area (22). A sustained low-flow period lasting from 1728 until 1739 dominated the long-term low-flow means. During this period the average annual discharge was only 43 percent of the 400-yr mean, and in no year did the discharge exceed the mean value. The recurrence of such an extended dry period would have devastating consequences.

The spectral density function for the October-April reconstruction is shown in Figure 5. The lower 90 percent confidence level is plotted for two of the frequencies. The white-noise line is the spectral density function of a normally distributed random variable. The only significant value occurred at 22.2 yr and reflects the return of extended low flows. This is important from the standpoint of water supply because it implies that there is a tendency toward deficient streamflow every 22 yr. Mitchell and others (23, pp. 125-143) found a 22-yr periodicity in the occurrence of drought in the western United States and related it to the Hale solar cycle. A similar periodic component in gaged streamflow records for the entire United States has been noted by Langbein and Slack (24). This periodic low-flow tendency for the Salt River should be incorporated into future water supply planning efforts. It should be noted that the reconstructed discharge for the Verde River showed no significant periodicity. This most likely relates to the low-flow characteristics of the Verde, which is controlled by discharge from springs rather than climatic variations.

In terms of high-discharge events, water year 1979 was particularly troublesome to the city of Phoenix; the gaged October-April discharge of 1.59 maf for 1979 had been equaled or exceeded only three times since 1900. A high-discharge value was predicted for 1979 in all of the reconstructions. The predicted discharge was 1.12 maf and was equaled or exceeded 12 times during the past 400 yr. On the average, then, a seasonal flow of this magnitude was recorded in the actual data once every 30 yr, which indicated that the 1979 gaged flow was not anomalous. In general, there was an above-average number of high seasonal flows during the period 1900-1979 when it was compared with the long-term reconstruction. A summary of comparisons between flows from the periods of gaged and reconstructed records is shown in Table 3.

CONCLUSIONS

In the absence of gaged records, proxy data sources such as tree rings can be used to reconstruct hydrologic events back in time. Among the several sources of proxy data, tree rings are the most widely used and have the advantage of precise dating, site replication, and the preservation of both high- and low-frequency information. The chief disadvantage is that tree-ring reconstructions rarely extend back more than 500 yr.

Tree-ring reconstructions are particularly useful in determining whether a known period of record truly represents the infinite number of events that have occurred in the past. Planning models based on anomalously wet or dry periods are likely to produce erroneous results.

Climatically sensitive tree-ring series can be used to reconstruct annual and, in some instances, seasonal flows. Periods of above- or below-normal flows as well as long-term trends are quite evident in reconstructed hydrologic series. Because an individual tree ring integrates climatic and site factors for an entire year or more, peak flows cannot be reconstructed.

In general, ring widths reflect dry conditions better than wet ones. In a wet season, moisture in excess of that held in the soil profile is not translated into growth. This point is important in hydrologic reconstructions and also explains why narrow rings are better for diagnostic and crossdating purposes than wide rings.

Hydrologic information derived from tree rings has had limited use in water resources planning. Yet, in lieu of gaged records, there is at present no better source of information on both short- and long-term climatic variations. The development of an expanded, worldwide tree-ring data base could provide a valuable planning tool for hydrologists. This is especially true for parts of the world where gaged records are essentially nonexistent.

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