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DENDROHYDROLOGY AND LONG-TERM HYDROLOGIC PHENOMENA

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Abstract. Dendrohydrology provides accurate methods for studying long-term hydrologic variability at regional scales. A substantial literature and body of knowledge exists, attesting to the value of tree ring based hydrologic reconstructions to discern patterns of long-term hydrologic variability. Application studies encompass drought analysis, analysis of extremes, periodicity of rare hydrologic phenomena, regional interdependence of surface moisture conditions, and, in general, the probabilistic analysis of key hydroclimatic variables such as runoff, precipitation, and temperature. The probabilistic analysis includes distributional properties, frequency duration analysis, severity of events, and spatial variability of hydrologic indicators. This paper reviews some fundamental aspects of dendrohydrology, with a perspective on its value to hydrologists in pursuit of an understanding of long-term hydrologic spatial-temporal behavior and provides also a selective citation of previous work conducted within the dendrohydrologic discipline.

INTRODUCTION

The science of dendrohydrology is concerned with the study of past, long-term, hydrologic phenomena based on tree growth hydroclimatic reconstructions. Dendrohydrology requires an understanding of the relationships between hydrologic variables of primary interest (e.g., precipitation, runoff, near-surface temperature, evapotranspiration, ground water, and soil moisture) and the biological response of trees to the ambient conditions affected by those hydrologic variables. The biologic response of trees to hydrologic "forcing" is recorded primarily in the widths of tree rings, although other measurable indicators of biologic response, such as latewood density, are also useful in dendrohydrologic analysis.

Dendrohydrologic studies require a thorough understanding of (1) the interaction between tree stands and surrounding hydrologic conditions reflected by the balance of precipitation, runoff, groundwater, evapotranspiration, and other hydrologic fluxes and (2) the ecological conditions and their effect on the biologic response of trees. Ecological conditions affecting trees include soil fertility, plant competition, forest stand development, diseases and insect pests, wildfire incidence, environmental pollution (of air, water, or soil), and sunlight availability, to cite key ones that are related to surface and near-surface hydrologic conditions. One example of the interdependence between ambient hydrology and ecologic conditions affecting tree growth is given by the population explosion of certain insect pests (a good example is the spruce budworm native to North America) propitiated during dry and warm weather that further decimates trees during periods of low moisture [*Klee*, 1991]. As a second example of hydrologic-ecologic linkages impacting tree growth, excessive precipitation, a precursor of floods and associated soil erosion, can be responsible for soil nutrient removal and consequent slowing in the growth rate of trees. These two examples suggest that radically different hydrologic conditions (i.e., dry and wet), when combined with ecological conditions, can affect the biological response of trees, imprinted in tree ring widths, in a similar manner.

The previous examples point to the complexity of differentiating the hydrologic forcing from the nonhydrologic hydroclimatic signal in biologic response indicators such as tree rings. In spite of the complexities associated with the interpretation of biological response indicators, dendrohydrologic studies have demonstrated the feasibility of discerning the approximate role of hydrologic forcing from tree ring chronologies, developed from trees growing under adequate hydroclimatic and ecological conditions. Therefore it has been possible to infer long-term hydrologic conditions that prevailed over past centuries (and in some cases over the last millenium or beyond),

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well before the establishment of hydrologic instrumental records.

The value of such long-term hydrologic records is of great significance in (1) water resource assessment, (2) the basic scientific understanding of hydrologic behavior and atmospheric moisture circulation over broad regions, and (3) in the prediction of hydroclimatic responses to greenhouse warming trends. This review paper is a survey of the science of dendrohydrology and its contributions to the understanding of long-term hydrologic variability. Limited space has forced us to be selective in our citations, and emphasis has been given to previous works that highlight the value of hydroclimatic reconstructions in the understanding of long-term hydrologic variability.

DENDROHYDROLOGY AND HYDROCLIMATIC RECONSTRUCTIONS

Tree Rings as Hydroclimatic Indicators

Long-term patterns of hydrologic variability are of key importance in the planning of water resources systems [*Loaiciga and Marino*, 1991]. Because of the vital role of the hydrologic cycle in the biosphere, the understanding of past hydrologic fluctuations is essential in interpreting a broad variety of anthropological, ecological, and natural physical phenomena. Instrumental records of precipitation and runoff, unfortunately, are of limited length in most areas of the world, including those where hydrologic variability has greatest economic and ecological impact. The arid American southwest is an example, where precipitation and streamflow records do not exceed 150 years, and where streams of major historical significance, such as the Colorado and Sacramento rivers, have been gaged only since the early 1900s. Older records of precipitation dating back to the late 1600s in western Europe [*Lamb*, 1977] and long records of runoff (in excess of 1000 years in the Nile river and dating back to 622 A.D. at the Roda gage [*Hurst*, 1952]) are not sufficient to assess past fluctuations in regional hydrologic regimes, given inherent spatial hydrologic variability. Reliance on limited point measurements of precipitation and runoff would introduce severe (spatial) bias and inaccurate inferences on past hydrologic fluctuations.

There are natural proxy records of hydroclimatic behavior encoded in sediments in stream channels [*Ely and Baker*, 1985], lakes and swamps [*Olausson and Olsson*, 1969; *Swain et al.*, 1983], ice layers [*Langway*, 1967; *Dansgaard and Tauber*, 1969], fossil pollen profiles [*Goodwin*, 1956; *Webb and Bryson*, 1972], and tree rings (see *Ferguson* [1968], *Ferguson* [1969], and *La Marche and Harlan* [1973] for tree ring chronologies extending over several millenia), to cite some of the most widely used proxy records [*Lamb*, 1982]. Tree ring widths have, however, a relatively strong association to hydrologically significant variables (such as precipitation and runoff) conducive to relatively accurate year-to-year reconstruction of long-term hydrologic variability. This is specially true in temperate and subpolar regions, where certain species of long-living trees integrate hydroclimatic conditions well with other genetic and physiologic factors to leave an identifiable trace of past hydrology in the tree ring widths. Patterns of tree ring growth, however, vary markedly for different climates and species. Trees in moist tropical climates with no markedly different seasons generally show no growth rings. In a temperate climate, however, *Stahle et al.* [1985] developed a tree ring chronology from baldcypress trees *(Taxodium distichum)* found in floodplain swamps. Other studies [see *Lamb*, 1977, p. 54] have reported that certain species of trees found in the highlands of Kenya develop thin dark-colored rings whenever, and as often as, dry spells occur. During droughts, the growth in these trees ceases. As soon as monthly precipitation exceeds specific thresholds, tree ring growth resumes producing light-colored wood. An additional variant of tree growth behavior has been documented in trees in Java, in which tree ring growth appears to be annual and apparently driven by growth differences between the wetter and drier halves of the year [*Lamb*, 1977].

Proxy records other than tree rings, such as alluvial deposits along streambeds, are valuable in the dating and magnitude assessment of past episodic hydrologic events, like floods [see *Ely and Baker*, 1985]. Although this latter type of information is of hydrologic interest, it does not convey the year-to-year hydrologic information so essential in assessing the frequency, distribution, duration, and persistence of hydrologic phenomena. It is the natural and consistent seasonal response to hydrologic forcing during or prior to growing seasons of certain species of trees under appropriate environmental conditions that makes tree rings so well suited for year-to-year hydrologic reconstructions.

Response and Transfer Functions

Scientists have long recognized the linkage between surface climatic conditions and tree ring width patterns [*Douglass*, 1920], but the methodology to reconstruct past hydrology from tree ring chronologies is relatively recent, and it is in a continuous state of change, as technology and techniques for analysis of tree rings continues to improve [*Stokes and Smiley*, 1968; *Fritts et al.*, 1971; *Fritts*, 1976; *Haston et al.*, 1988; *Briffa et al.*, 1992; *Cook and Kairiukstis*, 1990; *Yamaguchi and Woodhouse*, 1992]. Tree ring chronologies have been used to reconstruct a number of important hydrologic variables in a variety of studies [*Stockton*, 1971]. Of primary interest to this review are reconstructions of runoff and precipitation, since they have the most direct connection to surface water availability and to the elusive concept of hydrologic

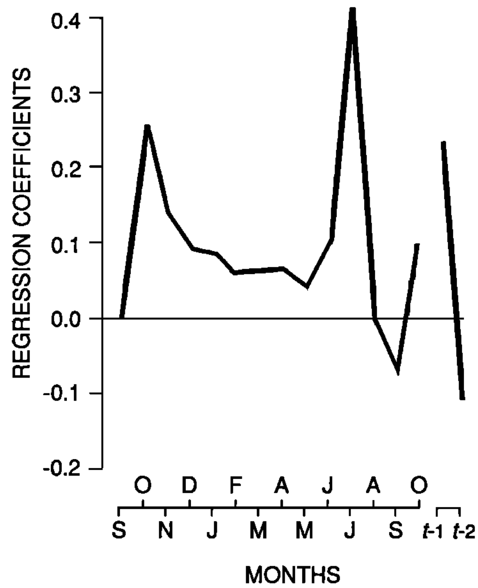


Figure 1. Response function for Scots Pine to temperature in Tornetrask, Sweden [after *Briffa et al.*, 1990].

drought, to be elaborated upon later. Numerous studies of hydrologic significance, however, have been conducted that involve hydroclimatic variables other than runoff and precipitation. Temperature, a fundamental ambient parameter in land energy balances and important climatic index, has been successfully reconstructed for periods in excess of 1000 years [*Briffa et al.*, 1990] in subpolar latitudes, and for periods spanning several centuries in a variety of temperate regions [see *Manley*, 1974; *Briffa et al.*, 1983, 1992].

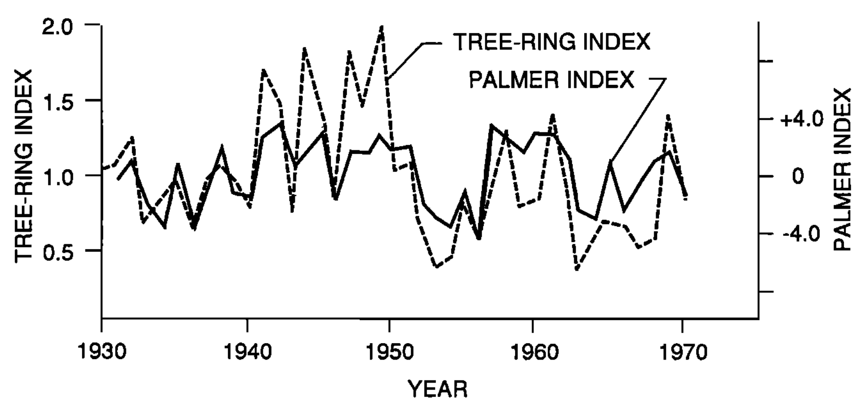
Figure 1, adapted from *Briffa et al.* [1990], shows the growth "response" of total ring width in Scots pine *(Pinus sylvestris L.)* from the Tornetrask region in northern Sweden to intra-annual temperature forcing for the period 1876–1925. The growth response, in effect a linear regression between the hydroclimatic variable (temperature, the predictor or independent variable) and the total ring width (the predicted or dependent variable) contains 14 monthly temperature predictors (from September of the year preceding ring formation through October following the growing season) plus two ring widths corresponding to the two preceding years ($t - 1$ and $t - 2$ in Figure 1). The latter two variables account for the strength of biological preconditioning of growth in any one summer by environmental and physiological conditions in previous seasons. It is seen in Figure 1 that warm conditions between May and July (particularly in July) seem to enhance tree ring growth as indicated by the relatively large values of the response regression coefficients for that period. It is also seen in Figure 1 that the biological preconditioning decays sharply with time as the response coefficient for year $t - 1$ is substantially larger than that for year $t - 2$.

This example of a response function demonstrates two important aspects of tree ring chronologies: (1) the interannual fluctuations in tree ring growth and (2) the dependence of current ring growth on past environmental and biological conditions (leading to the so-called phenomenon of persistence or autoregressive statistical structure in tree ring time series [*Hurst*, 1951; *Landwehr and Matalas*, 1986]). To be of use in reconstructions of past hydrology, conceptually at least, one must invert the response function to obtain what is termed a "transfer" function whereby the hydrologic variable of interest is regressed on growth indicator variables, for example, on tree ring widths. In practice, the transfer function can be developed directly via a variety of statistical techniques, the most prominent of which will be briefly discussed in a subsequent section.

Issues on Model Formulation

Before addressing dendrohydrological reconstructions of runoff and precipitation, the traditional variables of greatest hydrologic interest, it is instructive to cite a seminal reconstruction of meteorological drought using the Palmer drought severity index [*Palmer*, 1965] in the western United States from 1700 to 1930 by *Stockton and Meko* [1975]. The Palmer drought severity index is appealing for the purpose of meteorological drought characterization since it combines both precipitation and potential evapotranspiration in its quantification. Figure 2*a*, adapted from

Figure 2*a*. The 1930–1970 plot of July Palmer drought severity index and annual tree ring index near Kenton, Oklahoma [after *Stockton and Meko*, 1975].



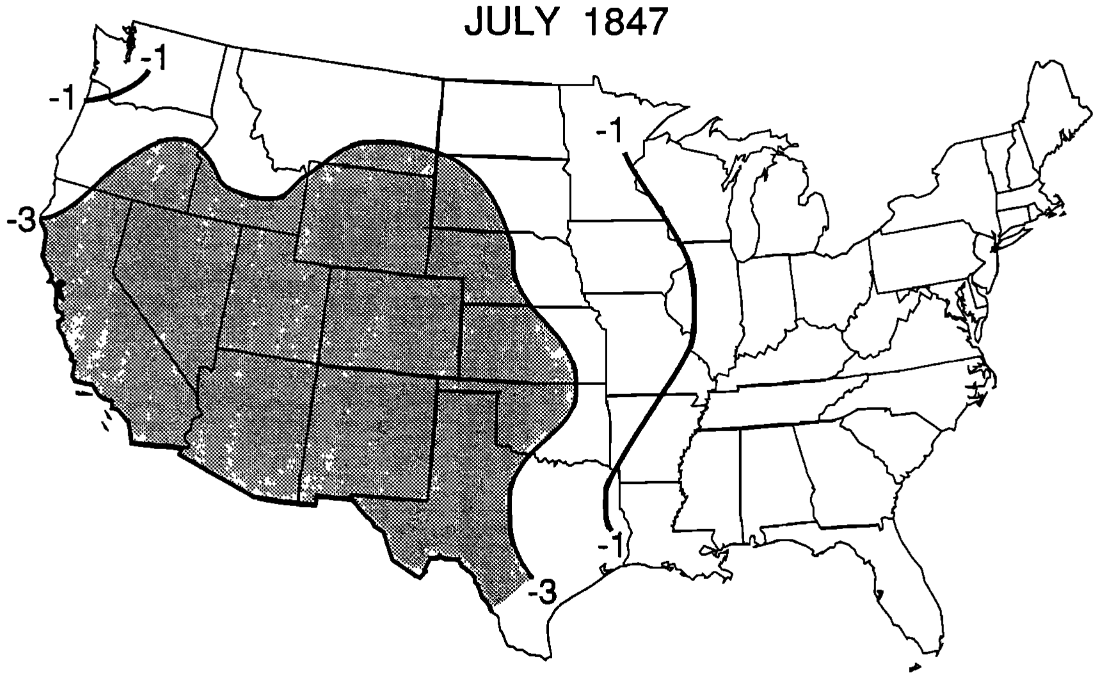


Figure 2b. Drought severity map of the western United States based on Palmer drought index for July 1847 [after *Stockton and Meko*, 1975].

Stockton and Meko [1975], shows the synchronous plot of the 1930–1970 of (observed) Palmer drought severity indices for the month of July of each year and the annual tree ring indices (a normalized time series derived from the raw tree ring width chronology, to be explained below) from a site near Kenton, Oklahoma. The approach followed in developing a reconstruction, say, for the Palmer index prior to the instrumental period beginning in 1930, is to estimate a regression equation (or transfer function) for the 1930–1979 calibration period in which the (observed) Palmer index is regressed on the tree ring index. Prior to 1930, when only the tree ring chronologies are available, the Palmer index can be predicted or "reconstructed" by applying the regression equation on the pre-1930 tree ring index data.

Two observations are warranted in regards to the data in Figure 2*a*: (1) the plotted tree ring index time series is the average of replicated individual ring widths obtained from a number of trees at the Kenton site; and (2) the Palmer drought severity index represents the spatial average over six climatological divisions in the vicinity of the Kenton site. The issue of spatial averaging is a key one in dendrohydrology. One must specify the hydroclimatic stations to be averaged prior to developing the regression equation or transfer function relating, in the context of Figure 2*a*, the averaged Palmer drought severity index to the tree ring width index. Taken in a broader context, the development of the transfer function introduces the modeling problem of selecting the suitable variables, both predicted and predictors (that are measured at numerous locations over broad regions for specified time periods), that will enter in the associated regression equation or transfer function. There are several statistical techniques available for this purpose, including stepwise regression [*Neter et al.*, 1985], principal components analysis [*Hotelling*, 1933; *Anderson*, 1984; *Sellers*, 1968], and canonical correlation analysis [*Hotelling*, 1936; *Glahn*, 1968; *Anderson*, 1984], to cite a few popular approaches. Because of their frequent use in dendrohydrology, principal components and canonical correlations will be given further analysis in the next section.

Figure 2*b*, adapted from the cited work by *Stockton and Meko* [1975], depicts a drought severity map based on the reconstructed Palmer index for the western United States for July of 1847. The map shows the areal extent of reconstructed drought, which in the period since 1770 has only been exceeded in severity in July of 1934 (the period of 1933–1937 was plagued by extreme drought and dust storms in the southern Great Plains of the United States). The map of Figure 2*b* exemplifies the applicability of tree ring analysis in the study of broad scale hydrologic phenomena over time periods not accessible with instrumental records.

There are numerous other studies of hydrologic significance based on tree ring analysis. *Stockton and Fritts* [1973] and *Brinkman* [1987, 1989] reconstructed long-term lake levels; a few other tree ring based studies have reconstructed large-scale hydroclimatic variability over North America and the eastern Pacific [*Fritts*, 1965; *La Marche and Fritts*, 1971; *Stockton and Meko*, 1983; *Blasing and Fritts*, 1976; *Fritts et al.*, 1971, 1979; *Blasing and Longfren*, 1980; *Fritts and Lough*, 1985; *Haston*, 1992; *Loaiciga et al.*, 1992]. In those studies a large number of tree ring chronologies from throughout the western United States were calibrated with precipitation, temperature, sea level pressure or runoff (or a combination of these) to reconstruct large-scale hydroclimatic patterns. Those studies illustrate that, besides the site-specific usefulness of dendrohydrological studies, larger and more general scale patterns of spatial hydroclimatic variability can be reconstructed and related to atmospheric circulation patterns. The next section discusses runoff and precipitation dendrohydrological applications illustrating the richness of hydrologic information that can be extracted from tree ring chronologies.

RUNOFF AND PRECIPITATION VARIABILITY FROM DENDROHYDROLOGICAL STUDIES

Basic Approach to Hydrological Reconstructions

The basic approach to developing a tree ring chronology is reviewed by *Stokes and Smiley* [1968], *Stockton* [1971], *Fritts* [1976], and *Cook and Kairiukstis* [1990]. The basic idea in tree ring based hydrologic studies is to use species of trees whose tree-ring growth is sensitive to hydroclimatic forcing (e.g., precipitation and temperature) to reconstruct the long-term behavior of important hydrologic variables such as runoff and precipitation. Reconstructions of precipitation and runoff for a given region can be used to derive additional components of the hydrologic water balance, such as evapotranspiration, according to well-established principles of water balancing [*Zektser and Loaiciga*, 1993; *Lvovitch*, 1972]. A general expression, or transfer function, relating the hydrologic variable of interest, Y (say, precipitation or runoff), to a set of predictor or independent variables X (typically tree ring widths but could include others such as latewood density) is of the form [*Loaiciga et al.*, 1992]

$$Y_t = \sum_{q=1}^{M} \sum_{r=1}^{N_q} \sum_{s=0}^{P_q} \alpha_{q,r,s} X_{q,r,t+s} + \xi \qquad (1)$$

in which $\alpha_{q,r,s}$ is the regression coefficient for the qth predictor variable X at the rth sampling site at time lag s; $X_{q,r,t+s}$ represents the value of the qth predictor variable sampled at the rth site at time $t + s$; ξ is a random term typically assumed to have zero mean and constant variance. In (1) the qth predictor variable X can have time lags of up to the order of P_q, implying that the current value of the dependent variable Y, say, runoff, is related to current and future (up to a time lag P_q) values of the qth predictor variable X. Some authors have included negative lags (i.e., $s < 0$) in the predictor variables X in the right-hand side of equation (1) [*Stockton and Meko*, 1983]. Equation (1) assumes that the hydrologic variable of interest, Y, is linearly related to a number (of possibly lagged) growth response predictor variables X. The lagged or autoregressive structure of the transfer equation embodied in (1) reflects the multiyear effect that hydroclimatic forcing can have on tree growth. This persistent forcing is believed to stem from the physiologic preconditioning that hydroclimatic fluctuations exert on trees, mainly affecting food storage, crown area, and root mass [*Stockton and Meko*, 1975; *Fritts*, 1976; *Cleaveland and Stahle*, 1989].

On calibration and verification. The typical procedure in dendrohydrology is to estimate the α coefficients in (1) based on contemporaneous time series of tree ring widths and instrumental records of runoff or precipitation (or some other hydroclimatic indicator, such as the Palmer index in Figure 2). The estimation of the transfer coefficients α can be approached by means of regression analysis or polynomial fitting, to cite two common estimation techniques, possibly aided by principal components or canonical correlation analysis [*Stockton and Meko*, 1975; *Fritts*, 1976; *Briffa et al.*, 1983; *Jones et al.*, 1984]. After this calibration stage, long-term tree ring chronologies predating the period of instrumental hydrologic recording are used to reconstruct annual time series of runoff and precipitation by means of the estimated equation (1). For example, in the case of only two predictor variables collected at two sampling sites with no time lags, estimation for any time period t would be carried out by the equation $\hat{Y}_t = \hat{\alpha}_1 X_{1,t} + \hat{\alpha}_2 X_{2,t}$ (where the "hat" denotes estimates).

Verification of the predictive skill of the dendrohydrological reconstructions can be assessed with a variety of goodness-of-fit statistics (correlation coefficient, adjusted correlation coefficient, reduction of error coefficient, coefficient of efficiency, t, F, and Kolmogorov-Smirnoff statistical tests [*Fritts*, 1976]). *Turner* [1992] evaluated the predictive skill of runoff reconstructions in California by examining also the *Hurst* [1951] coefficient, considered to measure the persistence, i.e., low (high) values tend to follow low (high) values, of hydrologic time series [*Landwehr and Matalas*, 1986]. *Turner* [1992] proposed that those runoff reconstructions with a Hurst coefficient significantly below *Hurst*'s [1951] empirical average of 0.73 be considered unreliable. The representativeness of the Hurst coefficient as a goodness-of-fit parameter remains controversial in hydrology [*Landwehr and Matalas*, 1986; *Feder*, 1988]. Another approach to reconstruction verification is the method of cross validation [*Mosteller and Tukey*, 1977; *Michaelsen et al.*, 1987; *Michaelsen*, 1988]. The method of cross validation differs fundamentally from the traditional verification methods in that the latter split the instrumental record into nonoverlapping periods for calibration and verification purposes. In cross validation, in contrast, the verification of reconstructions is done by resampling the data from the calibration period. Briefly, the calibration sample is resampled by removing one observation at a time from it and calculating diagnostic statistics (e.g., correlation coefficient) with the reduced sample. The removed observation is then replaced into the calibration sample, and another one is removed followed by recalculation of diagnostic statistics. This procedure is repeated as many times as there are observations in the calibration sample to yield a sample of diagnostic statistics from which average or "cross-validated" diagnostic statistics are calculated. This resampling scheme is a powerful and robust estimation method that proves valuable in exacting long-term probabilistic information from tree ring reconstructions, as will be seen below.

Averaging and standardization of tree ring chronologies. The predictor variables X that enter (1) represent averages (or medians or modes) of, say, tree ring widths belonging to many trees found at each sampling site. The core samples of tree ring widths for a given sampling site can be replicated, a situation that arises when, by sampling design, multiple cores are taking from each tree. With or without replication the value of the predictor variables X in (1) represents a measure of central location (mean, average, mode) of the growth response at a sampling site. It is a standard procedure that the raw ring width chronologies for each tree (for methodologies to develop chronologies, see *Stokes and Smiley* [1968] and *Fritts* [1976]) be detrended and standardized to dimensionless variates, the so-called tree ring indices, prior to averaging. Standardization can be achieved by dividing a given year's ring width by that width that would be expected on the basis of a normal decline of ring width with age of the tree. The latter, age-controlled ring widths define a growth trend that must be removed in order to isolate the climate-induced growth from other biologically driven growth. Techniques for fitting the age growth trend and its removal from the raw ring widths have been developed and automated in the computer program ARSTAN [*Cook*, 1985; *Holmes et al.*, 1986] and applied successfully to runoff reconstruction by *Cleaveland and Stahle* [1989]. Techniques for tree ring series standardization are described by *Cook* [1987].

Removal of the biological, age-related, growth trend necessarily filters out low-frequency (or long-period) hydroclimate-induced variability in the tree ring series. It is difficult to determine how much of the legitimate hydroclimate-related variability in the tree ring series is removed by standardization, but some empirical comparisons suggest that most of the variability on times scales shorter than 100 years is retained [*Michaelsen et al.*, 1987]. As a general rule, if adequate standardization techniques are used, the longer the tree ring chronology, the longer is the time scale of hydroclimatic variability that can be reconstructed from the average standardized chronologies (tree ring indices).

Serial and Spatial Correlation

Serial correlation. Tree ring indices typically show temporal correlation that is commonly modelled by low-order autoregressive time series [*Rose*, 1983; *Monserud*, 1986; *Haston*, 1992]. The temporal correlation exhibited by tree rings is due to a dependence of tree growth on previous seasons' growth. Prior growth preconditions the tree's response during the current growing season by affecting the level of stored carbohydrates and the number of leaf primordia [*Kozlowski*, 1971]. In regions where baseflow is a significant contributor to runoff (above 30% of runoff [*Zektser and Loaiciga*, 1993]) a slow response of the groundwater system to fluctuations in precipitation can also contribute to the interyear persistence observed in ring widths. Some authors [*Blasing et al.*, 1984; *Cook*, 1985; *Cleaveland and Stahle*, 1989] have fit autoregressive (autoregressive moving average (ARMA)) models to the tree ring index and remove the serial correlation from it (by direct subtraction of the fitted autoregressive component from the ring index time series) to prevent the masking of the hydroclimatic signal by prior persistent effects on growth. The resulting time series is called the prewhitened tree ring chronology, having undergone detrending, standardization, and removal of autoregressive components. Some authors remove, in addition, autoregressive components in runoff time series [*Cleaveland and Stahle*, 1989] prior to calibration of the transfer function (see equation (1)). The autoregressive component is latter added to the reconstructed runoff to yield the total reconstructed runoff statistically resembling the historical data. The removal of temporal or serial correlation in the ring width or hydroclimatic data is essentially a matter of choice. Model calibration, statistical estimation, and reconstruction in dendrohydrology can be implemented with the use of serially correlated data, since statistical techniques for that purpose are available [*Kmenta*, 1971; *Neter et al.*, 1985].

Further transformations can be applied to the hydroclimatic or tree ring data (e.g., taking their logarithm) to make them better approximate the normal distribution for which there exist better established statistical inference methods and tests. The types and extent of statistical manipulations effected on the tree ring and hydroclimatic data prior to calibration of the transfer function are subjective and are by no means standardized within the dendrohydrology community. They are highly dependent on the individual investigator's best judgment as to how improve the statistical accuracy of the hydrological reconstructions. Prior to giving examples of runoff and precipitation reconstructions, a popular method for coping with the spatial statistical dependence of hydroclimatic and tree ring data, principal component analysis, and its related

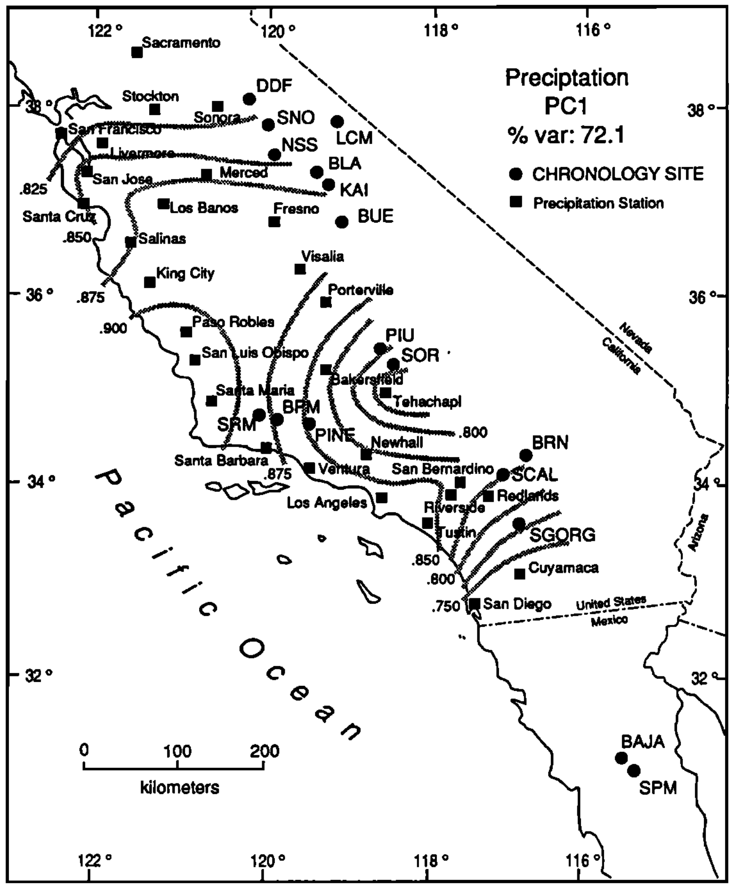


Figure 3. Map of principal component loadings of annual precipitation in California [after *Haston*, 1992].

generalization, canonical correlation analysis, are briefly reviewed.

Principal components. It is well known that hydroclimatic variables (runoff and precipitation, in particular [*Sellers*, 1968; *Cropper*, 1984] and tree ring data [*Stockton and Meko*, 1975] can have strong patterns of spatial statistical dependence. In such instances, developing regression equations between hydroclimatic variables and a number of tree ring chronologies can be difficult because of the so-called problem of multicollinearity [*Cropper*, 1984]. Briefly, because of the strong spatial correlation, dendrohydrological data at one sampling site can explain a high percentage of the variance at other sampling sites. If one includes the set of spatially correlated data collected at all sampling sites into a regression equation relating them to runoff or precipitation, the result is an ill-conditioned regression with meaningless transfer coefficients [*Neter et al.*, 1985]. There is a variety of techniques for choosing subsets of variables from the complete set of correlated variables from which multicollinearity is removed [*Weisberg*, 1980]. In dendrohydrology, principal components analysis and canonical correlation analysis, methods developed to a large extent by *Hotelling* [1933, 1936], have found fertile ground for application.

Suppose that there are m tree ring sampling stations for which annual ring widths are available for a period of n years. The principal components of the m-station tree ring data are linear combinations of the m tree ring widths available. Because there are m sampling sites, there will be m principal components for the tree ring data. The first principal component is the linear combination of the m site ring width measurements with the largest variance. In other words, the first principal component is the linear combination of the m ring widths that explains most of the variation in ring widths from site to site. (By a linear combination it is meant that if the ring width measurements are denoted by $x_1, x_2, \cdots, x_m$, then the sum $a_1x_1 + a_2x_2 + \cdots + a_mx_m$ is a linear combination of the ring widths, where the a_i values $i = 1, 2, \cdots, m$ are real constants or "loadings" defining the linear combination.) The second principal component has the largest variance among all linear combinations of the m site ring widths uncorrelated with the first principal component. Similarly, the ith principal component explains most of the variance among all linear combinations of the m site ring widths uncorrelated with the first, second, $\cdots$, $(i - 1)$th principal components. It follows from their definition that principal components can identify those sites or combinations of sites that explain most the variation in the tree ring time series. On the basis of principal component analysis the hydrologist can choose to work with those principal components that explain the most ring width variance. The are obvious advantages in doing this. First, the principal components are uncorrelated, which eliminates potential multicollinearity problems. Second, rather than using the *m* site vectors of *n* year tree ring data, the calibration of hydroclimatic and tree ring data involves r, $r \leq m$ principal components of the tree ring data, reducing the size of the data set that needs to be processed in the dendrohydrologic calibration. The major drawback to principal components is that it is not always clear what meaning, other than the purely statistical, one can attribute to these linear combinations.

Computational examples of principal components are given in the work by *Anderson* [1984] and *Sellers* [1968]. Figure 3 (adapted from *Haston* [1992]) shows a contour map of the spatial loadings for the first principal component of annual precipitation in California. The first principal component was found to explain 72.1% of the precipitation variance of all 29 precipitation stations. All the spatial loadings have the same sign and similar magnitude, suggesting that the first principal component of precipitation represents a state-wide average, with high and positive loadings indicating generally wetter conditions throughout the study area, and high negative loadings indicating generally drier conditions. Instead of reconstructing precipitation records for each of the 29 stations considered by *Haston* [1992], a single reconstruction of the first principal component provides a good indication of regional precipitation variability.

Canonical correlations. These statistics constitute a generalization of principal components. In this case, one seeks linear combinations of two sets of variables that have maximum correlation. For example, one could have *r* tree ring sampling stations and *m* precipitation stations in a study area. The two sets of variables (ring widths and precipitation) would normally be highly correlated posing the multicollinearity problem previously cited. The idea of canonical correlation analysis in the dendrohydrological context is to find a linear combination of the ring width data collected at *r* stations that has maximum correlation with another linear combination of precipitation data from *m* stations. The correlation between these two linear combinations of the spatial data sets is called the first canonical correlation. Next, a second linear combination of ring widths can be sought that has maximum correlation with a second linear combination of precipitation, neither one of which is correlated with the linear combinations that define the first canonical correlation. The correlation of these two second linear combinations is called the second canonical correlation. Assuming (with no loss of generality) that $m \leq r$, new linear combinations of ring widths and precipitation uncorrelated with previous linear combinations can be found that define the third, fourth, $\cdots$, *m*th order canonical correlations. The objective of canonical correlation analysis is to identify those linear combinations of stations associated with the largest canonical correlations. The result of this screening is a reduced set of transformed variables, linear combinations, that are spatially uncorrelated (i.e., the first combination is uncorrelated with the second combination, and so forth) that explain most of the mutual linear variability between the variables of interest. In practice, only a few canonical variates are of interest, simplifying the estimation of the transfer function and also eliminating the multicollinearity in the raw hydroclimatic data. Calculation examples dealing with canonical correlations are given by *Glahn* [1968], *Fritts et al.* [1971], and *Anderson* [1984].

EXAMPLES OF RUNOFF AND PRECIPITATION RECONSTRUCTIONS

Dendrohydrology: An Expanding Science

Precipitation and runoff are of interest in hydrology because they are primary determinants of surface moisture conditions. These two variables are also widely monitored, and their records are probably as good as any other type of hydroclimatic record available. Hydrologic fluctuations from median or average conditions, specifically, those events that reflect years of unusually high or low precipitation, are particularly important in hydrologic studies. Persistent and extreme hydrologic conditions impact the planning of and operation of water resources projects, and can have severe ecological and environmental effects. It is well established in dendrohydrologic studies [*Michaelsen et al.*, 1987; *Cleaveland and Stahle*, 1989] that tree ring growth is particularly sensitive to drought. Moisture stress is a fundamental growth limiting factor that can be accurately discerned from properly selected tree ring data. In years of plentiful precipitation, factors such as plant competition and soil fertility become the growth-limiting factors in trees, obscuring the hydroclimatic signal in the tree ring data for those years [*Fritts*, 1976; *Blasing et al.*, 1984]. The asymmetric growth sensitivity to extreme hydroclimatic conditions (i.e., either very wet or dry conditions) is one source of complication in using tree ring widths in dendrohydrology. Hydroclimatic conditions in any year may have a lagged forcing on growth in subsequent years with different hydroclimatic conditions. The undesirable offshoot of this is that ring widths following very dry or wet years may show slow or rapid growth forcing, respectively, that is not synchronous with current hydroclimatic conditions. Some authors have suggested that the accuracy of dendrohydrologic reconstructions following unusual hydroclimatic fluctuations (in particular, protracted drought) tend to be poorer than that observed under less variable conditions [*Stockton and Meko*, 1975]. On the other hand, when extreme conditions prevail, dry years tend to be reconstructed better than wet years [*Michaelsen et al.*, 1987].

A good body of the dendrohydrological literature deals with long-term analysis of droughts via tree ring reconstructions. Two obvious reasons for this emphasis are the drought-sensitive nature of certain species of trees and the hydrological, environmental, and economic impacts associated with drought. In a study of natural hazards around the world that included droughts, tropical cyclones, floods, earthquakes, volcanic eruptions, and, virtually, any conceivable natural hazard [*Bryant*, 1991], concluded that droughts had the greatest adverse impacts among all other surveyed hazards.

Other areas of focus in the dendrohydrological literature concern the analysis of extremely wet conditions [*Michaelsen et al.*, 1987; *Haston*, 1992], the persistence, severity, and frequency of drought [*Stockton and Meko*, 1975; *Cook and Jacoby*, 1983; *Smith and Stockton*, 1981; *Stockton and Meko*, 1983; *Cleaveland and Stahle*, 1989; *Loaiciga et al.*, 1992], streamflow and hydroclimatic variability [*Cook and Jacoby*, 1983; *Jones et al.*, 1984; *Stahle et al.*, 1985, 1988], and more recently, climatic warming thresholds and global circulation linkages to regional hydrologic variability [*Briffa et al.*, 1990; *Loaiciga*, 1992; this study]. A good deal of the dendrohydrological literature focuses on droughts in the arid western United States. The Tree Ring Laboratory of the University of Arizona has played a central role in the development of dendrohydrology. Tree ring studies related to precipitation and streamflow in other regions of the world are not equally abundant, and typically, have been carried out in temperate regions [*Holmes et al.*, 1979; *Guiot*, 1981; *Campbell*, 1982; *Guiot et al.*, 1982; *Pilcher and Hughes*, 1982; *Briffa et al.*, 1983; *Jones et al.*, 1984]. The study of *Jones et al.* [1984] was the first tree ring based runoff reconstruction in Europe. The studies of *Holmes et al.* [1979] in Argentina and *Campbell* [1982] in Tasmania represent extensions of dendrohydrological investigations to temperate regions of the southern hemisphere.

Dendrohydrological Calibrations

Calibration consists of fitting a statistical model to hydrological data. The model is then used for prediction or "reconstruction" of hydrologic events during prerecording periods. Regression analysis, principal components, canonical correlations, and (autoregressive) time series analysis have been cited previously as common approaches to dendrohydrological calibration. More complicated time series [*Box and Jenkins*, 1976] and dynamic estimation models [*Young*, 1984] have also been considered in dendrohydrologic studies.

The calibration of a predictive model for hydrologic reconstruction entails a variety of steps, not the least important of which is basic hydrologic analysis of precipitation and runoff data. Reference has already been made to statistical and modeling issues associated with tree ring sampling, growth curve removal, and filtering of tree ring indices to eliminate serial correlation. There is, however, a host of other issues of purely hydrologic nature that most be resolved in developing a properly calibrated dendrohydrologic model. One is the choice of hydrologic variable to be reconstructed, for example, precipitation or runoff (or both). Precipitation records are typically longer than those for runoff, mainly due to the ease of installation of raingage networks compared to the construction of stream gages. However, in studies of water supply, the variable of interest par excellence is runoff. It is therefore common to develop statistical relationships between recorded precipitation and streamflow and estimate streamflows by means of regression equations for those years when runoff was not measured and precipitation was recorded [*Cleaveland and Stahle*, 1989]. A more complicated approach to extend runoff records from precipitation would be to develop regional precipitation-runoff models, of which there exist many versions [*Viessman et al.*, 1989], and all of which require calibrations of their own. Once the streamflows are extended to match the length of the precipitation data, one proceeds to reconstruct streamflows in the preinstrumental period by means of the dendrohydrological methods already discussed. This latter approach was adopted in the reconstruction of Colorado river streamflows by *Michaelsen et al.* [1989] and *Loaiciga et al.* [1992]. A third possibility is to reconstruct precipitation using tree rings and then use either the statistical precipitation-runoff regressions or other empirical or conceptual precipitation-runoff models to estimate runoff in the period preceding runoff gaging.

One aspect that may influence the choice of approach to reconstruct streamflows is that, while annual precipitation tends to show negligible serial, or temporal, correlation, annual runoff does have a more pronounced temporal dependence in areas where lagged groundwater discharge or snow/ice melt distributes the effect of precipitation on runoff over extended periods of time. Analyses of annual precipitation and runoff worldwide have shown that the first serial correlation coefficient for precipitation is, on average, of the order of 0.050, whereas for runoff it is, on the average, 0.180 [*Salas et al.*, 1985]. Serial correlation is important in dendrohydrology, and it can be handled statistically in various ways. Some authors prefer to filter out temporal dependence in the hydrologic and tree ring series prior to model calibration, although there are statistically efficient estimation methods that have been developed for calibrating serially correlated data [*Kmenta*, 1971].

A parsimonious calibration example. Figure 4, adapted from [*Briffa et al.*, 1983] illustrates the so-called principle of parsimony in hydrologic calibration [*Amorocho and Espildora*, 1973]. Parsimonious calibration calls for the optimal set of parameters or variables to be included in a transfer function. The parameter set is optimal in the sense that the variables included explain an adequate percentage of hydrologic

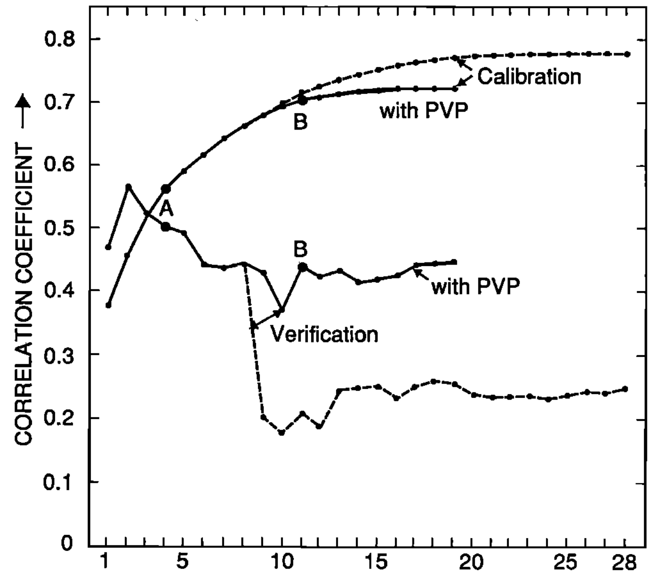


Figure 4. Verification and calibration performance as a function of the number of predictors [after *Briffa et al.*, 1983].

variability, while excluding redundant predictors that degrade the model predictive skill. It is seen in Figure 4 that calibration improves monotically as more predictor variables are included in the transfer function. This behavior holds for calibration with and without using *Guiot*'s [1981] predictor rejection, or PVP, criterion. The latter criterion uses principal component analysis to select the predictors that explain most of the variation in the hydroclimatic variable (average precipitation in England in this case). The meaning of parsimony is made apparent in Figure 4 by the verification curves. These clearly show that an indiscriminate addition of redundant predictor variables de-

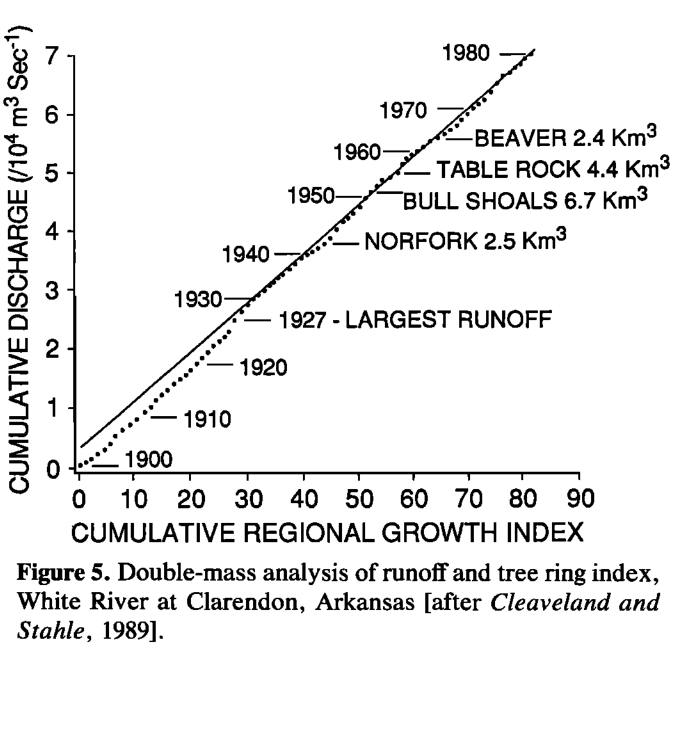


Figure 5. Double-mass analysis of runoff and tree ring index, White River at Clarendon, Arkansas [after *Cleaveland and Stahle*, 1989].

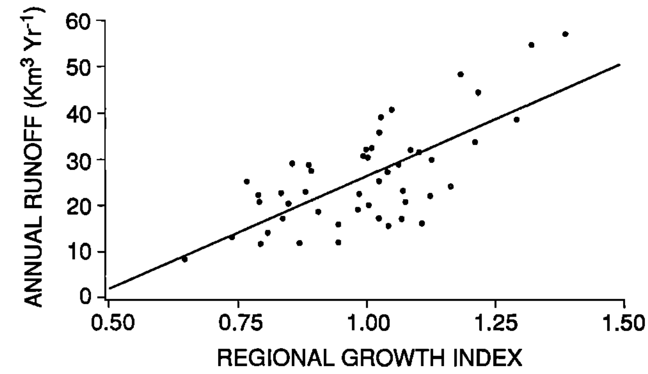


Figure 6. Scattergram of runoff reconstruction, White River at Clarendon, Arkansas, with fitted transfer function [after *Cleaveland and Stahle*, 1989].

grades the reconstruction's predictive skill, as measured by a sudden drop in the verification correlation coefficient, for $K > 9$, where K is the number of predictors. On the other hand, the predictors selected with the PVP criterion lead to a still declining but more stable predictive skill as the number of predictors increase.

An example of data homogeneity analysis and transfer function calibration. Figure 5 from *Cleaveland and Stahle* [1989] shows an example of the double-mass analysis [*Kohler*, 1949] applied to White River runoff at Clarendon, Arkansas, and regional tree ring growth index. By plotting the cumulative values of these two variables it is possible to discern a change in the discharge/ring growth index relationship, at about 1930 as evidenced by a change in the slope of the curve. This anomalous break in the slope of the double-mass curve indicates an inhomogeneity in the runoff data. Values of runoff prior to 1930 can be multiplied by the ratio of the post-1930 slope over the pre-1930 slope in the double-mass curve to make them comparable with current prevailing conditions. This example illustrates the possible use of tree ring data to detect inhomogeneities in hydroclimatic data.

For the same study by *Cleaveland and Stahle* [1989] on the White River runoff reconstruction, Figure 6 shows a scattergram of White River annual runoff and a regional average of the tree ring index with the transfer or regression equation fitted to these data, $Y_t = -23.10 + 49.54 X_t$, where Y_t is the predicted runoff (with autoregressive persistence removed) and X_t is the regional tree ring index. The autoregressive component of runoff was added a posteriori to the reconstructed runoff to obtain the total predicted values. It was stated previously that for the purpose of model calibration the autoregressive component can be removed in the tree ring index and in the hydrological variable (runoff, in this case), although this is not a statistically necessity given that there are statistical techniques to calibrate serially correlated data. The correlation coefficient, adjusted for degrees of freedom, for the calibrated transfer function of Figure 6 was 0.50, meaning that 50% of the variation in runoff is explained by the regional growth index. In dendrohydrological studies, calibrated correlation coefficients of 0.40 or larger are typically considered adequate [*Briffa et al.*, 1990]. Clearly, the adequacy of a dendrohydrological reconstruction cannot be judged on a single parameter, such as the correlation coefficient. The quality of a reconstruction can be fully assessed by how well the probability distribution (including averages, variances, higher-order moments, and extremes values), as well the recurrence properties and persistence of the hydroclimatic variable are reproduced by the reconstructions.

A goodness-of-fit statistic frequently quoted in verification or validation analyses (verification is defined as the assessment of how well a reconstruction reproduces the statistical properties of the parent hydroclimatic variable) is the reduction of error coefficient RE. The latter is defined as $RE = 1 - SSR/SSM$, where SSR is the sum of the squares of the differences between the actual data and the predicted data, and SSM is the sum of the squares of the differences of the actual (dependent) data for the verification period from the mean of the actual data used in the calibration [*Fritts*, 1976]. To calculate the reduction of error coefficient, one defines two nonoverlapping periods, one for calibration and another for verification. The predictions, made for the verification period, are based on the transfer function fitted with calibration data. Therefore the sum of squares SSR is based on values, both predicted and actual, taken from the verification period. The sum of squares SSM involves actual data from the verification period, while the mean is calculated from actual data from the calibration period. The reduction of error coefficient measures the improvement to prediction arising from the calibrated transfer function relative to predictions based on the mean value calculated during the calibration period. It is a particularly robust verification test for independent data. Its diagnostic power is hindered by the presence of serial correlation and outliers. For independent data, positive values of RE are considered to be indicative of a reconstruction's good predictive skill. In the White River study by *Cleaveland and Stahle* [1989], RE coefficients based on several different calibration periods ranged from 0.08 to 0.60, indicating an encouraging explanative power of the calibrated transfer function.

Dendrohydrology and Hydroclimatic Reconstructions

Hydroclimatic periodicity from tree ring reconstructions. One of the most interesting aspects of dendrohydrologic reconstructions is their long-term approximation of past hydrologic variability. Centuries-long reconstructions permit the assessment of hydrologic fluctuations with multidecadal periods, as well as the occurrence of extreme (very dry or very wet) events. Fluctuations with secular or longer periods are more difficult to discern from tree ring reconstructions because the standardization, or removal of the growth curve, from tree ring widths eliminates most of the low-frequency (or long-period) components in the data. In spite of this latter limitation, tree ring reconstructions provide the most accurate approximation to long-term past hydroclimatic variability. There are, in general, two ways of identifying periodicities in hydroclimatic data. The first is to fit the hydrologic data with time series models. Temporal trends and correlations are examined in search of patterns of cyclic repeatability. The other approach to studying hydroclimatic periodicity is to transform the data to the frequency demain using the Fourier transform of the covariance function [*Jenkins and Watts*, 1968] to yield the power spectrum or spectral density function. The spectral density function provides a distribution of the variability of a hydroclimatic variable as a function of frequency. Statistically significant frequency components are detectable from the spectral density function, thus revealing the presence of phenomena, such as drought, that repeat themselves with average regularity. Time domain and frequency domain (spectral) examples are given next.

Moving windows. Figure 7 adapted from *Loaiciga* [1992] shows (1) the number of years N of below-median annual streamflow (solid line); and (2) the standard deviation σ (dashed line) of streamflow, both calculated in a moving window, 41-years wide, in the Sacramento river basin of California. (Units of streamflow are in thousands of acre feet, where 1 acre foot equals 1233 cm^3.) The streamflow data were obtained from a streamflow reconstruction by *Earle and Fritts* [1986]. Each N in Figure 7 is assigned to the (moving) window's central year. N is stable about a relatively constant level, that is equal to the statistical median, or 21, for the chosen window width, although there are pronounced oscillations in N from approximately 1775 to 1925. The long-term streamflow reconstruction, in excess of 400 years, shows that the incidence of below-median streamflow, typically associated with hydrologic droughts [*Loaiciga et al.*, 1992], has intermittent variability but an overall stable behavior about a long-term median count of 21.

The plot of the streamflow standard deviation σ in Figure 7 (dashed line) indicates a slightly declining trend up to the late 1800s, when it returns to levels typical of the first half of the 17th century. There is a somewhat cyclic pattern of σ, with peaks appearing early in the 17th, 18th, 19th, and 20th centuries. No particular pattern of correlative behavior seems to exist between N and σ, other than a larger N is observed during some periods of decline in σ (this happens at around 1650, 1720, 1850, and 1930). There is no apparent explanation for this coincidental pattern of

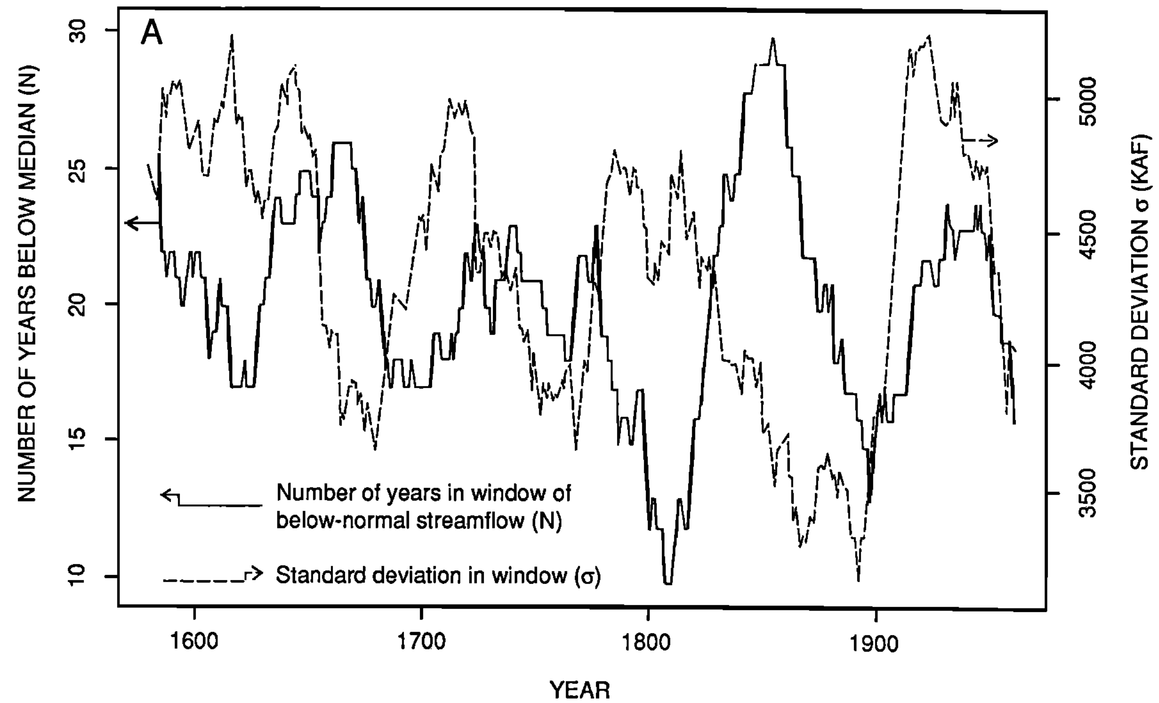


Figure 7. Number of years (*N*) of below-median streamflow and standard deviation (σ) of streamflow, Sacramento basin, California, in a 41-year moving window [after *Loaiciga*, 1992].

low-flow and streamflow variance, and, in fact, the opposite effect is noted at approximately 1770. (It will be seen below that it is sometimes possible to establish linkages of regional long-term hydrologic variability with global climatic processes and atmospheric circulation based on streamflow reconstructions.) The data presented in Figure 7 clearly depict the high variability of the first and second moments of runoff in the Sacramento basin.

Spectral analysis. Figure 8 [from *Smith and Stockton*, 1981] displays the spectral density function for the October–April discharge of the Salt River near Roosevelt, Arizona, with the lower 90% confidence level plotted for two of the frequencies. The white noise line in Figure 8 corresponds to the spectral density of an independent Gaussian random variable. From Figure 8 it was established that the 22.2-year periodicity (equivalent to a frequency of 0.045 cycles/year) is significant at the 90% confidence level. The noteworthy hydrologic implication here is that low-flow periods are to be expected, on the average, approximately every 22 years in the Salt River at Roosevelt, Arizona, according to *Smith and Stockton* [1981]. Those authors note the importance for water supply planning that this low-flow return period has. They point to previous investigations on the periodicity of droughts in the United States and cite past hypotheses linking drought to astronomical cycles. In particular, previous studies have attempted to link drought and flood phenomena to astronomical cycles such as the 22-year Hale solar magnetic cycle and the 18.6 lunar cycle [*Bryant*, 1991]. *Currie* [1984] has shown using statistical analysis of rainfall worldwide that only the 18.6-year lunar cycle and the 11-year sunspot cycle are statistically significant in explaining the variance of flood and drought in many regions of the world. It appears that the lunar tide, with a 18.6-year cycle, influences patterns of general circulation that include the path of the westerly jet stream. Throughout a band influenced by this path, and exclusively within this band, lunar and 11-year sunspots signals have been found in ocean level, air pressure, and temperature data [*Bryant*, 1991].

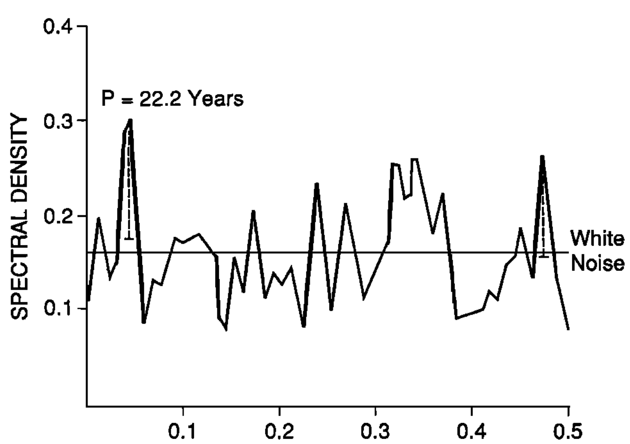


Figure 8. Spectral density function of October–April runoff, Salt River near Roosevelt, Arizona [after *Smith and Stockton*, 1981].

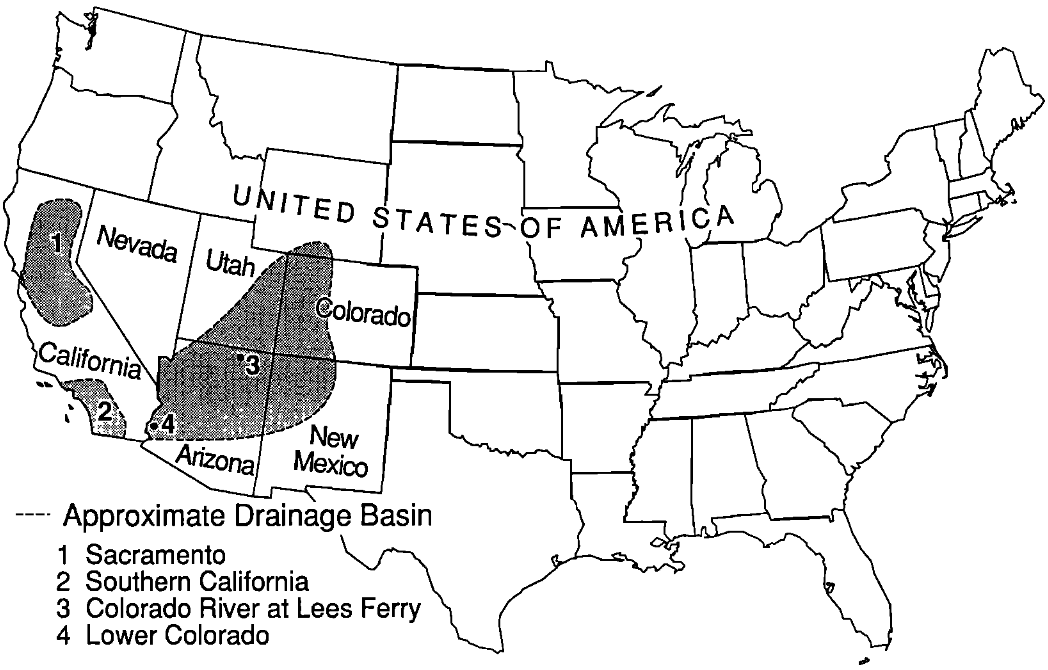


Figure 9. Sacramento, Southern California, and Colorado river basins [after *Loaiciga et al.*, 1992].

In a subsequent study, *Stockton and Meko* [1983] expanded their drought recurrence study to the Great Plains of the United States based on tree ring reconstructions of precipitation. In that instance, they found a more complex pattern of drought periodicity, with periods ranging from 16 to 60 years across regions in the study area. It is important to keep in perspective that even though dendrohydrologic reconstructions might suggest statistically significant associations or "teleconnections" between droughts, floods, and global transport processes, the processes by which these teleconnections are established remain scientific puzzles.

Probabilistic Dendrohydrologic Analysis of Runoff and Precipitation

Stochastic analysis. It has been stated that some species of trees register hydroclimatic forcing rather well in their tree rings. With a proper tree ring sampling protocol and core analysis it is possible to develop tree ring chronologies extending several centuries and, in some cases, several millenia. What makes dendroclimatic reconstructions so unique for studying long-term hydrologic variability is their unusual length and annual resolution. In the case of annual runoff and precipitation reconstructions, these long time series permit a thorough probabilistic characterization. This includes inference of (1) the probability distribution of annual series; (2) analysis of extrema; (3) distribution of the duration, severity and recurrence of dry and wet sequences; (4) conditional probability analysis and serial dependence; and (5) statistical association with other natural phenomena (joint probability analysis). Tree ring reconstructions are particularly apt for drought analysis because tree growth is sensitive to moisture stress.

Figure 9, from *Loaiciga et al.* [1992] shows several river basins of the western United States, namely, (1) the Sacramento, (2) the Southern California, and (3) the Colorado river basin, with gages at Lees Ferry, Arizona, and at (4) the junction with the Gila river. *Loaiciga et al.* [1992] studied the joint behavior of drought incidence across these river basins, that are of foremost importance for the economic and ecologic vitality of areas depending on their runoff. Droughts were defined by at least 3 years of below-median annual streamflow in all or any subset of the basins. This particular definition of drought fits well with the water supply/demand situation in the study areas and with the hydrologic perspective of the study [*Loaiciga*, 1989]. Various other definitions of drought have been used with peculiarities depending on the meteorologic, climatic, ecologic, or economic emphasis given to drought phenomena. Figure 10 displays the conceptual representation of drought as a stochastic process introduced by *Loaiciga et al.* [1992]. The duration of drought is a random variable D; the time elapsing between the end of a drought and the initiation of the next one is denoted by τ; the sum of D plus τ is R, the total time elapsing between the initiation of consecutive droughts; $N(t)$ is the number of droughts in a time period t. The representation of Figure 10 applies equally well to the recurrence of droughts in one basin or their simultaneous occurrence in two or more basins. The latter case refers to below-median annual streamflow conditions in two or more basins simultaneously for at least 3 years. Figure 11 [from

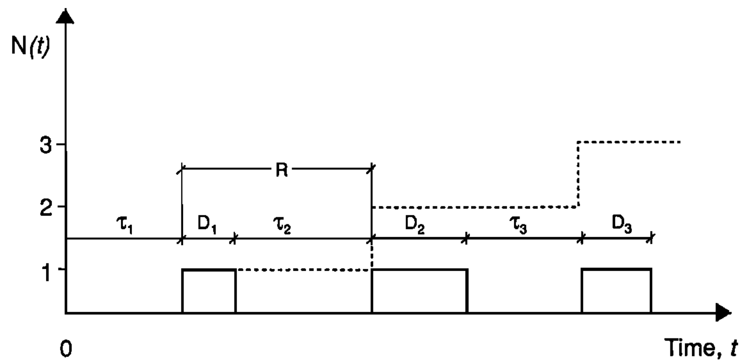


Figure 10. Conceptual representation of drought as a stochastic process [after *Loaiciga et al.*, 1992].

Loaiciga, 1992] shows the histogram of durations of below-median, above-median (this is the interoccurrence time in between below-median events), and critical runs (i.e., sequences of years in which streamflow is 50% of the median) of annual streamflow in the Sacramento basin. It can be seen the geometriclike decay in the distributions of duration of dry runs and interarrival times. Because of the independence of drought duration D and elapsed time τ, the occurrence of below-median droughts in the study areas constitutes a renewal process [*Parzen*, 1964], a result of utmost importance in the analysis of drought recurrence.

In order to assess the average interoccurrence of below-median droughts in the study areas, a fundamental result of renewal theory is very useful. This states that the number of events (in our context, droughts) in a period of time t, $N(t)$, divided by t converges to μ^{-1} when the time interval t is sufficiently large, where μ denotes the expected value of the renewal time (i.e., $\mu = E(R)$). On the basis of this result the average times elapsing between below-median droughts lasting 3 or more years in individual basins or in two or more basins simultaneously were calculated and are given in Table 1. It can be seen in Table 1 that there were no simultaneous droughts in all four basins, registered by the tree ring reconstructed streamflows, so it was not possible to estimate their average recurrence times. For three basins the average recurrence time is approximately equal to or in excess of 100 years. These long average recurrence times can be misleading, however, in assessing drought threat because drought occurrence in single basins that are critically important, such as the Sacramento and Upper Colorado, represent a significant threat on their own right. The estimates in Table 1 indicate that, on the average, one can expect below-median droughts lasting at least 3 years once every 18 and once every 15 years in the Sacramento and Upper Colorado basins, respectively. For two basins at a time it follows from Table 1 that simultaneous drought in the two California basins is to be expected once every 45 years. Interestingly, the historical record of 87 years contains two such droughts for an estimated average recurrence of about 44 years. As a caveat to the previous discussion on astronomical effects, there does not seem to be any pattern of association between drought average recurrence and astronomical cycles, other than the, perhaps fortuitous, closeness of some of the one-basin recurrence times to the lunar cycle.

Another aspect of the work by *Loaiciga et al.* [1992] is their analysis of the probability distribution of drought duration in their interregional study of droughts. For this purpose, the empirical frequency F_D, defined as the proportion of times that streamflows were simultaneously below median for D consecutive years in one or more basins, proves very useful. It is calculated by dividing the number of below-median runs that lasted D years by the total number of m of below-median runs (including durations of 1, 2, 3, $\cdots$,

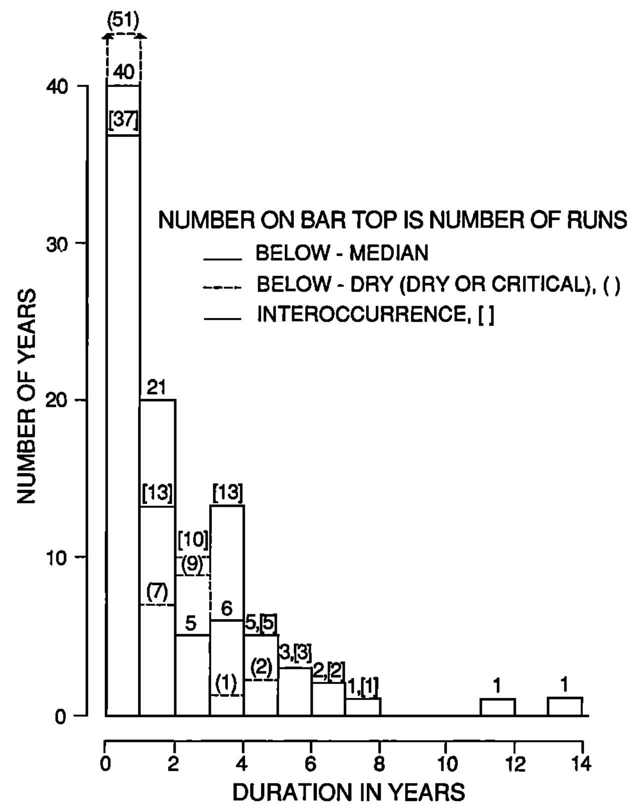


Figure 11. Histograms of durations of below-median, above-median, and critical runs of annual runoff in the Sacramento basin, California [after *Loaiciga*, 1992].

years). The 95% confidence intervals for the probability that a D year run of below-median annual streamflows occurs simultaneously in one or more basins were calculated by *Loaiciga et al.* [1992], and the midpoints of the probability confidence intervals are presented in Table 2 for the special case of droughts lasting at least 3 years. For one basin the probabilities are in all cases larger than 25%. For two and three basins they range between 4–10% and 2–4%, respectively. For the four basins considered simultaneously the estimated probability of joint drought was zero, since no such event was recorded in the streamflow reconstructions. Had the reconstructions been much longer, unquestionably the four-basin probability would have had a finite, nonzero value.

Besides the important results concerning return intervals and probabilities of duration of simultaneous droughts, streamflow reconstructions facilitate fitting theoretical probability models to variables such as the renewal time R of drought recurrence (see Figure 10). For example, when the drought duration D and the interarrival time τ in Figure 10 are independent and geometrically distributed [*Loaiciga and Marino*, 1991] with parameters p_1 and p_2, respectively (and without loss of generality, $p_1 > p_2$), the distribution of the renewal time R is given by

$$P(R = n) = \frac{(1 - p_1)(1 - p_2)}{p_1 - p_2} [p_1^{n-1} - p_2^{n-1}] \qquad (2)$$

TABLE 1. Average Recurrence Times of Below-Median Droughts Lasting at Least 3 Years

	Average Recurrence Time, years
One basin	
Sacramento	18
Southern California	14
Upper Colorado	15
Lower Colorado	16
Two basins	
Sacramento/Southern California	45
Sacramento/Upper Colorado	44
Sacramento/Lower Colorado	65
Southern California/Upper Colorado	23
Southern California/Lower Colorado	65
Upper Colorado/Lower Colorado	30
Three basins	
Sacramento/Southern California/ Upper Colorado	99
Sacramento/Southern California/ Lower Colorado	196
Sacramento/Upper Colorado/ Lower Colorado	196
Southern California/Upper Colorado/Lower Colorado	196
Four basins	undetermined

Upper Colorado refers to Colorado at Lees Ferry. Lower Colorado refers to Colorado at the Gila river.

TABLE 2. Probability of Below-Median Droughts Lasting at Least 3 Years

	Midpoint Probabilities, %
One basin	
Sacramento	28
Southern California	29
Upper Colorado	42
Lower Colorado	26
Two basins	
Sacramento/Southern California	6.0
Sacramento/Upper Colorado	7.0
Sacramento/Lower Colorado	4.7
Southern California/Upper Colorado	9.7
Southern California/Lower Colorado	4.4
Upper Colorado/Lower Colorado	8.6
Three basins	
Sacramento/Southern California/ Upper Colorado	4.0
Sacramento/Southern California/ Lower Colorado	2.6
Sacramento/Upper Colorado/Lower Colorado	2.4
Southern California/Upper Colorado/Lower Colorado	2.0
Four basins	undetermined

Midpoint probabilities are for the 95% confidence intervals. Upper Colorado refers to Colorado at Lees Ferry. Lower Colorado refers to Colorado at the Gila river.

where $n = 2, 3, \cdots$. When we have the probability of the interarrival time R in (2), it is possible from the theory of characteristic functions [*Lukacs*, 1960] to derive the probability of the total time to the nth arrival (i.e., nth drought occurrence), $S_n = \sum R$, where the sum is from 1 to n. S_n is the sum of n independent and identically distributed variables. From the distribution of the time to the nth arrival, several parameters of paramount importance in risk analysis of droughts follow rather easily: (1) the expected number of droughts in a time interval t, $E[N(t)] = \sum P[S_n \leq t]$, $n = 1, 2, 3, \cdots$; (2) the probability of observing n droughts in a time interval t is $P[N(t) = n] = P[S_n \leq t] - P[S_{n+1} \leq t]$; and (3) the risk of drought is given by $P[N(t) \geq 1] = P[R \leq t]$. The previous example of probabilistic analysis of droughts points out to the richness of issues that can be addressed once long and accurate reconstructions are available. In the next example it is shown that the probabilistic analysis can be extended to the important subject of conditional probabilities.

Conditional probabilities. *Michaelsen et al.* [1987] introduced conditional analysis in the interpretation of reconstructed precipitation data. Conditional probabilities are very important in the study of drought persistence. Questions concerning the probability of continued dry or wet hydrologic conditions given that so many years of drought or flooding have already occurred are of significant interest in hydrologic and

TABLE 3. Conditional Probabilities of Droughts for Single Basins

Event*	Basin† 1	2	3	4
3/2	0.25	0.70	0.60	0.38
4/3	1.0	0.37	0.78	0.67
5/4	0.83	0.71	0.57	0.67
6/5	0.60	0.20	0.50	1.0
7/6	0.67	1.0	0.0	0.25

*Here 3/2 indicates the probability of a third year of drought given that two dry years have already occurred. All conditional events have analogous meaning.

†Basins 1, 2, 3, and 4 refer to Sacramento, Southern California, Colorado at Lees Ferry, and Colorado at the Gila river as shown in Figure 8.

water resources studies. The basic equation for conditional probability analysis is given by the expression of the conditional probability of event X given event Z, $P(X|Z) = P(X; Z)/P(Z)$ in which $P(X; Z)$ denotes the joint probability of events X and Z, and $P(Z)$ is the unconditional probability of event Z. As an example, consider the probability of having one more year of drought (event D) given that exactly two previous years of drought (event DD) have occurred. This conditional probability is $P(D|DD) = P(DDD)/P(DD)$, since the probability $P(D; DD)$ is clearly equal to the probability of a 3-year run, $P(DDD)$. For estimation purposes the aforementioned conditional probability, $P(D|DD)$, is estimable by dividing the empirical frequencies of 3-year droughts and 2-year droughts. These frequencies are available from the histogram of drought duration (from Figure 11, for example, the empirical frequency of a 4-year drought, F_4, equals 6/85).

Conditional probabilities were estimated by *Loaiciga et al.* [1992] from the reconstructed annual streamflow in the four basins of Figure 9 and are summarized in Tables 3 and 4. Table 3 contains the conditional probabilities, for each of the four basins, of getting exactly one additional year of drought given that exactly r years of drought have occurred, where r ranges from 2 to 6. For example, $P(3|2)$ is the probability of a third year of drought given that there have been 2 years of drought. Notice in Table 3 that (1) the conditional probabilities are not monotonically decreasing with the duration of drought, and, for example, for the Southern California basin (basin 2), $P(5|4) > P(4|3)$; (2) sometimes the conditional probability estimate is equal to 1 (see, for example, $P(4|3)$ in the Sacramento basin or basin 1); this occurs when droughts of longer durations have occurred more frequently than droughts of shorter durations (e.g., durations of 4 and 3 years in Figure 11); and (3) the conditional probability estimate can be zero (see $P(7|6)$ for the Colorado river at Lees Ferry or basin 3) in which case no events of an additional dry year were observed beyond a specified number of dry years in the data set.

TABLE 4. Probability of a Third Year of Drought in Two Basins

Basin	Basin* 1	2	3	4
1	0.25	0.35	0.23	0.24
2	0.35	0.70	0.44	0.27
3	0.23	0.44	0.60	0.77
4	0.24	0.27	0.77	0.38

*Basins 1, 2, 3, 4 refer to Sacramento, Southern California, Colorado at Lees Ferry, and Colorado at the Gila river as shown in Figure 8.

TABLE 5. Bootstrapped Conditional Probabilities for Extreme Events

Event	Probability $P(yy)$	$P(y|y)$	$P(yyy)$	$P(y|yy)$
Dry	0.1293	0.3922	0.0435	0.3725
Wet	0.1207	0.3746	0.0522	0.4656
Extremely dry	0.0259	0.1681	0	0
Extremely wet	0.0172	0.1834	0.0087	0.5043

Table 4 presents joint conditional probability estimates for the event 3|2, i.e., the probability of a third dry year given two previous dry years, occurring simultaneously in two basins. Recall that this is the threshold adopted by *Loaiciga et al.* [1992] in defining the initiation of hydrologic drought in a study area. From Table 4 it is seen that there is a surprisingly high conditional probability, over 20% in all cases, that a third dry year will occur given two previous dry years in any one of the two-basin combinations.

Probabilistic inference and the bootstrap method. *Michaelsen et al.* [1987] estimated extreme precipitation conditional probabilities with the bootstrap method [*Efron*, 1982]. In this method a large number of samples (e.g., 1000) of equal length (e.g., 100 years) are drawn at random from the reconstructed time series. Conditional probabilities are estimated from the empirical frequencies (as in the previous example) based on each random sample. This procedure is repeated for as many times as random samples are generated, to yield bootstrap estimates of the conditional probabilities in question. Confidence intervals for the conditional probabilities can then be calculated. "Bootstrapping" is a robust method for probabilistic and statistical inference. Table 5 (adapted from *Michaelsen et al.* [1987]) presents the conditional probability estimates $P(Y|YY)$ and $P(Y|Y)$, where Y denotes an event, i.e., dry, wet, extremely dry, or extremely wet conditions measured in terms of annual, reconstructed, precipitation in Central California, as well as the unconditional probabilities $P(YY)$ and $P(YYY)$. It can be seen in Table 5 that the conditional probabilities of having an additional event when the event has occurred either the previous year or the two previous years are larger (or at least as large) than the corresponding unconditional probabilities of either two or three events in a row (e.g., $P(Y|Y) > P(YY)$ and $P(Y|YY) > P(YYY)$). For example, for extremely wet conditions, the probability of a 3-year run is less than 1% while the conditional probability of having a third extremely wet year, given two previous extremely wet years, is slightly over 50%.

The previous examples illustrate some of the most important types of statistical and probabilistic inferences that can be accurately made based on long dendrohydrological reconstructions. Beyond the descriptive value of these estimates, they are instrumental in formulating explanative hypotheses about the possible processes or reasons behind otherwise inscrutable phenomena. The following section delves into this matter further.

Linkages Between Regional Hydrology and Atmospheric Circulation

Testing statistical association between El Niño and regional hydrology. Some of the reviewed dendrohydrologic studies have demonstrated the feasibility of reconstructing past patterns of spatial and temporal hydrologic variability over broad regions [*Stockton and Meko*, 1975]. In most cases, patterns of drought/flood incidence or probabilities of simultaneous dry or wet periods across vast areas can be associated with known patterns of atmospheric transport. For example, *Loaiciga et al.* [1992] found weak correlation of hydrologic conditions between the California river basins and the Colorado river basin, as well as between basins within California (see Table 2). Those authors argued that this situation arises from complex climatic systems that govern atmospheric transport and surface moisture in the form of snow and rainfall in the California and Colorado river basins. The major sources of

TABLE 6. Test of Proportions for El Niño Runoff Association in the Colorado River at Lees Ferry

Streamflow Category	*Number of El Niño Years*	*Number of Non-El Niño Years*	*Number of Both Years*
Below median	26 (46.4%)*	23 (59.0%)	49 (51.6%)
Above median	30 (53.6%)	16 (41.0%)	46 (48.4%)
Total	56 (100.0%)	39 (100.0%)	95 (100.0%)

The *P* value in the tests of equality of proportions for below-median and above-median conditions is approximately 0.22 in both cases.

*The numbers in parentheses are the proportions of years in each streamflow category.

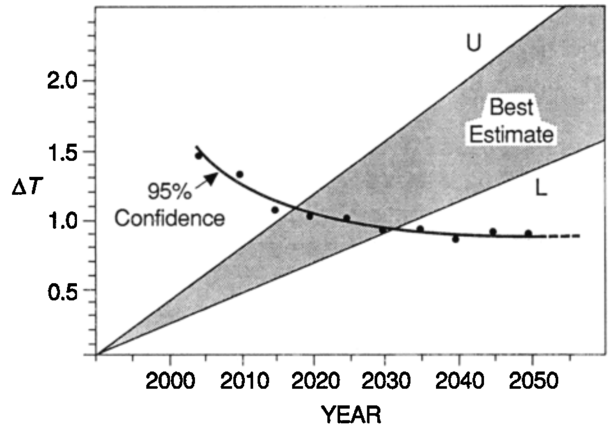


Figure 12. Range (stipled area) of northern Fennoscandian summer temperature increases (ΔT) due to increased greenhouse concentrations, and minimum temperature threshold (curve line) needed to detect greenhouse warming signal [after *Briffa et al.*, 1990].

precipitation in those basins are mid-latitude winter storms whose track and area of influence are affected by pressure blocking ridges in the westerlies. Given the large areas included in the river basins, it is unlikely that persistent blocking ridges will occur simultaneously across the basins. This, compounded by convective and subtropical flow into the Colorado basin and southern California, makes the occurrence of simultaneous drought across the study areas rather unlikely.

Dendrohydrologic studies can go one step further in testing the degree of possible association between global climatic phenomena and regional hydrology. One of the most interesting scientific problems in this context concerns the role that El Niño has in the incidence of droughts and floods in various parts of the world. Most of the evidence accumulated to study the possible linkage between El Niño and regional hydrologic variability around the world comes from modern instrumental records of precipitation and ocean temperatures [*Philander*, 1990; *Bryant*, 1991; *Redmond and Koch*, 1991]. From a climatological viewpoint, one must look to the modifications brought about by El Niño on large-scale transport systems, such as the jet streams, to discern possible associations between El Niño phenomena and regional droughts or floods. From a hydrologic perspective, one is interested in the likelihood that El Niño events will either enhance or reduce regional surface moisture. This latter problem can be assailed statistically using synchronous tree ring reconstructions of precipitation (or runoff) and other independent long-term reconstructions of El Niño events [*Quinn et al.*, 1987]. *Loaiciga* [1992] proposed this latter approach to test the possible association between runoff in the Sacramento river basin of California and in the Colorado river (at Lees Ferry, Arizona) and El Niño events. Tree ring reconstructions of runoff were pooled with historical runoff data and related to a pooled sample of reconstructed and instrumental El Niño events (the reconstructed data goes back some 400-odd years while the instrumental El Niño data began in 1933 [*Quinn et al.*, 1987]). Runoff in strong El Niño years was compared to runoff during weak and non-El Niño years. Two tests of statistical association between hydrologic conditions and El Niño events were carried out: (1) a *t* test for the equality of mean annual runoff in El Niño and non-El Niño years and (2) a test of proportions to test whether the proportion of years with below-median (or above-median) runoff during El Niño years equals the proportion of years with below-median (or above-median) runoff during non-El Niño years. The tests results suggest that there is no statistically significant association between median annual runoff and El Niño occurrences in either the Sacramento basin or the Colorado river (at Lees Ferry). Table 6 shows the results for the test of proportions for the Colorado river at Lees Ferry. The *P* value [*Anderson and Sclove*, 1978] for this test was approximately 0.22, indicating the plausibility of the null hypothesis (i.e., the equality of proportions as defined previously).

Forecasts on greenhouse warming. This is, by and large, a very new perspective on the usefulness of tree ring reconstructions. One study is exemplary of the kinds of predictions that can be constructed from dendrohydrologic studies. Figure 12 from *Briffa et al.* [1990] shows an estimate of the range (stipled area in Figure 12) of northern Fennoscandian summer temperature increases (ΔT) due to increased greenhouse concentrations. The curved line can be considered a minimum threshold over which future summer temperature trends must pass before a greenhouse signal can be distinguished from natural regional climatic variability. The threshold was drawn through a series of points each of which is the upper 95% percentile of the distribution of trends of length up to that point on the horizontal scale. For example, the point plotted at 2030 (40 years after 1990, the year in which the previous study was published) comes from the distribution of 40-year trends in a 1400-year reconstruction of summer temperatures for Fennoscandia. The authors draw the interesting conclusion that depending on whether the climate sensitivity (embodied in ΔT) is at the upper limit (*U*) or the lower limit (*L*) in Figure 12, one would not be able to identify the greenhouse warming signal until 2020 or 2030, respectively.

Future efforts in dendrohydrology will most likely attempt to develop tree ring data bases for various parts of the world with different climatic regimes. From this chronologies, and through the types of analyses reviewed previously, it can be expected significant discoveries of past hydrologic variability at continental and global scales. Possible clues as to how future environmental forcing (e.g., greenhouse warming) might effect the hydrologic cycle might stem from these tree-ring data bases of large temporal and spatial coverage.

SUMMARY AND CONCLUSIONS

Dendrohydrological methods provide one of the most reliable ways to study long-term hydrological variability. Previous studies have revealed temporal and spatial patterns of droughts and floods over broad regions. Accurate tree ring reconstructions of precipitation, runoff, temperature and climatic indices have enabled hydrologists to discern the distribution, frequency, severity, and duration of hydroclimatic phenomena (droughts, floods) with a degree of accuracy not attainable with other hydrologic methods based on instrumental hydrologic records.

A good portion of the existing dendrohydrologic studies have been carried out in semiarid areas of the northern hemisphere, and, in particular, in the arid west and the Great Plains of the United States. Temperature, precipitation, and streamflow (tree-based) reconstructions have also been conducted in South America, Europe and the Australian continent. As the accuracy of tree ring reconstruction methodologies and statistical analysis improves, it is expected a greater reliance on dendrohydrological studies for long-term hydrologic analysis. Ongoing studies include areas as far apart as the Sierra Nevada in Spain, tropical forests of Costa Rica and temperate regions of China. The realization that ring-widths in climate-sensitive trees can be reliable indicators of past hydroclimatic conditions over centuries and even millenia, has made dendrohydrology a leading scientific discipline for long-term, regional, hydrologic analysis.

Recent interest in disruptions of regional hydrologic regimes by greenhouse warming, and general scientific interest in the role of atmospheric teleconnections in shaping regional hydrologic cycles, have spurred interest in dendrohydrologic reconstructions. Examples in the literature include predictions on threshold times needed to identify the greenhouse-induced signal in regional temperature trends, and the analysis of the statistical association between El Niño and regional droughts.

The limitations for dendrohydrology becoming a routine tool of the practicing hydrologist are found primarily in (1) the lack of long-living, climate-sensitive, trees in many parts of the world; (2) the elaborate process of field sampling, laboratory sample analysis, and statistical methodology required to develop ring width series; and (3) limited exposure of mainstream hydrologists to dendrohydrologic methods, that have been predominantly mastered by researchers in specialized fields. This review paper demonstrates that, in spite of inherent limitations, dendrohydrologists have produced a wealth of long-term, regional-scale, hydrologic information on natural hazards of utmost importance, such as droughts and floods, and on the pattern of precipitation, runoff, and temperature for many areas of the planet.

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