WATER RESOURCES BULLETIN
VOL. 16, NO. 4 AMERICAN WATER RESOURCES ASSOCIATION AUGUST 1980

A TREE-RING RECONSTRUCTION OF DROUGHT IN SOUTHERN CALIFORNIA[1]

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ABSTRACT: Indices of annual diameter growth of trees were used to reconstruct drought in southern California back to A.D. 1700. A regional Palmer Drought Index served as predictand and tree-ring indices from eight sites as predictors in multiple linear regression analyses that yielded the prediction (reconstruction) equations. The regression explained 69 percent of the variance in Palmer Index in the period of calibration. The long-term reconstruction indicated that drought was rare in the first half of the current century relative to other discrete 50-year periods, and that based on evidence to date the last half of the 20th century may well turn out to be the most drought prone since A.D. 1700 in southern California.
(KEY TERMS: drought; tree rings; climatic change; water resources; proxy data.)

INTRODUCTION

The mid-1970's drought in the western United States dramatically pointed out how susceptible our economy and water supplies are to a long stretch of abnormally dry weather. California was particularly hard hit. Only 25 to 50 percent of normal precipitation fell from October 1, 1976, to March 1, 1977, in the northern half of the state, and 50 to 80 percent in the southern half; by the spring of 1977 storage in many reservoirs was either inadequate or projected to soon become inadequate (Harrison, 1977). Many cities and communities implemented water rationing plans, and the threat of industrial layoffs loomed because of water cutbacks (Buchanan and Gilbert, 1977).

Although the drought ended in 1978, it drew attention to the need for a better understanding of climatic fluctuations, especially prolonged dry spells. Tree rings are a useful tool in this type of problem in that they enable us to estimate drought history back beyond the period covered by instrumented weather records. Various tree-ring-based studies of drought, beginning with Kuechler's study of Texas drought (Campbell, 1949), and including among others, studies of localized drought in Oklahoma (Harper, 1961), and Nebraska (Weakly, 1943); and larger-scale studies by Fritts (1965) and Stockton and Meko (1975) have made use of the general relationship between drought and annual ring-width. A tree-ring reconstruction of drought in southern California derived from a regression analysis of a regional drought index on growth of trees recorded at eight sites is discussed in this paper.

DATA

Tree-ring indices are derived from annual ring widths, which in their raw form are generally unsatisfactory for climatic reconstruction because ring width usually decreases as a tree ages. The underlying trend of ring-width versus time commonly resembles a decreasing exponential curve. This trend is removed by fitting an appropriate curve to the time series of ring widths, and dividing each year's ring width by the value of the fitted curve for that year. The resulting stationary time series is the tree-ring index (Fritts, 1976). Tree-ring indices from several (usually more than 10) trees are averaged to form the tree-ring index for a given site.

Tree-ring indices were obtained from the date files of the Laboratory of Tree-Ring Research at the University of Arizona. The sites selected for this study are listed along with descriptive information in Table 1, and their locations are shown in Figure 1. The series ranged in length from less than 300 years to more than 1,000 years, but only the common period A.D. 1700 to A.D. 1963 covered by all series was used here.

The Palmer Drought Serverity Index (PDSI) was used as a measure of drought conditions. It is computed from monthly precipitation and temperature records by a water-balance procedure such that the contributions of low rainfall, high temperature, and antecedent soil moisture to drought are all considered (Palmer, 1965). The PDSI scale is shown below:

$+4.0 \leqslant PDSI$	extreme wetness
$+3.0 \leqslant PDSI < +4.0$	severe wetness
$+2.0 \leqslant PDSI < +3.0$	moderate wetness
$-2.0 < PDSI < +2.0$	near normal
$-3.0 < PDSI \leqslant -2.0$	moderate drought
$-4.0 < PDSI \leqslant -3.0$	severe drought
$PDSI \leqslant -4.0$	extreme drought

[1]Paper No. 80001 of the *Water Resources Bulletin.* Discussions are open until April 1, 1981.
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TABLE 1. Tree-Ring Index Series.

No.*	Site	Species**	Lat.	Long.	El (m)
1	San Gorgonio	LP	34°07′	116°49′	3281
2	Santa Ana	BCS	33°44′	117°33′	1214
3	Baldwin Lake	PP	34°16′	116°49′	2281
4	Santa Rosa	CIC	33°32′	116°28′	2194
5	S. California	BCS	34°03′	117°05′	1402
6	White Mountain	BCP	37°25′	118°10′	3108
7	Clark Mountain	WF	35°32′	115°35′	2194
8	San Pedro Martir	JP	31°00′	115°25′	1976

*Corresponds to number on map in Figure 1.

**LP = limber pine (*Pinus flexilus*; James)
CIC = Calif. incense cedar (*Libocedrus decurrens*; Torr.)
PP = ponderosa pine (*Pinus ponderosa*; Laws.)
BCS = big cone spruce (*Pseudotsuga macrocarpa*; Mayr.)
WF = white fir (*Abies concolor*; Gord. and Glend.)
BCP = bristlecone pine (*Pinus aristata*; Engelm)
JP = jeffrey pine (*Pinus jeffreyi*; Grev. and Balf.)

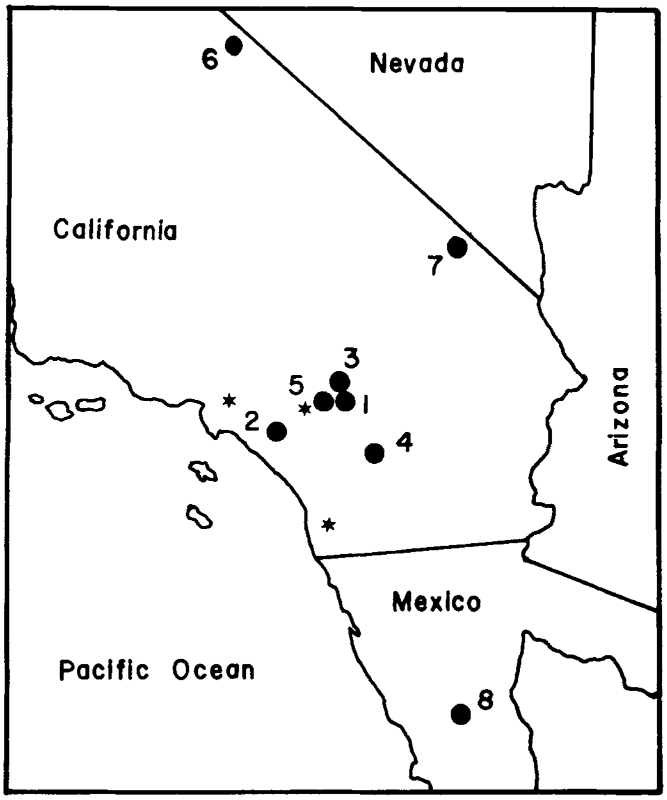

Figure 1. Map Showing Locations of Tree-Ring Sites (dots) and Weather Stations (stars). (Tree-ring sites are numbered as in Table 1: weather stations are, from north to south, Los Angeles, Riverside, and San Diego.)

PDSI maps for the entire United States are published regularly in the *Weekly Weather and Crop Bulletin* by the National Oceanic and Atmospheric Administration (NOAA). The map for July 1977, near the peak of the most recent widespread drought in the western United States, is reproduced in Figure 2.

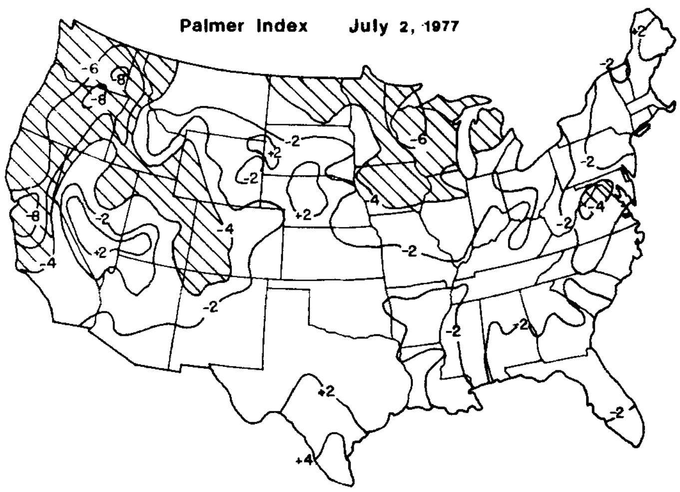

Figure 2. Map of Palmer Drought Severity Index for July 2, 1977 (redrawn from *Weekly Weather and Crop Bulletin*, 1977).

PDSI for the period 1882 to 1977 was computed for Los Angeles, Riverside, and San Diego from monthly precipitation and temperature records (U.S. Weather Bureau, ESSA, and NOAA). These PDSI series were averaged to form a three-station mean PDSI which was then used as a measure of regional drought for southern California.

METHODS

A regression equation relating regional PDSI to annual tree-ring indices was derived by stepwise multiple linear regression (Draper and Smith, 1966). A regression analyses was run for a period covered by both tree-ring indices and PDSI, and tree-ring indices for earlier years were then substituted into the resulting regression equation to reconstruct PDSI back to A.D. 1700.

The predictand series was the regional PDSI. Because of soil moisture carry-over and a built-in autocorrelation in the PDSI computation, a given month's PDSI reflects moisture conditions in several proceeding months as well as the curent month. Rather than average monthly PDSI to derive an annual drought measure, we therefore chose to calibrate tree-ring indices with a single month's PDSI. July was chosen since tree growth is largely complete by the end of that month, and it is also a critical period for agricultural crops.

Predictors were selected from a pool of 24 potential predictors – each of the eight tree-ring index series, current year

(t) and lagged forward (t+1) and backward (t−1) in time. The regression model is

$$\hat{Y}_t = \sum_{i=1}^{m} B_i X_{i,\tau} + \text{constant} + e_t$$

where:

$\hat{Y}_t$ = predicted regional PDSI in year t;

B_i, i=1, m = regression coefficient on i^{th} predictor;

m = number of predictors (tree-ring indices, current or lagged) in the equation;

$X_{i,\tau}$ = tree-ring index (i^{th} predictor) in year τ, where τ = t, t−1, or t+1; and

e_t = error or noise, the difference between predicted and actual PDSI in year t.

Initially, analyses were run for a 60-year calibration period (1903-1962) for three models, each with a different number of predictors included before the stepwise procedure was cut off. Data for the period 1882-1902 was held back for independent check of prediction. Information from this independent check as well as from regression statistics from the calibration period were then used in deciding which model to select for further study. A long-term PDSI reconstruction (to A.D. 1700) was then derived using the regression equation from the selected model. Finally the regression and reconstruction process was repeated using a similar model, but including the full 82 years (1882-1963) of available PDSI in calibration. The regression and reconstruction scheme is outlined in Figure 3.

Several standard statistics were used in evaluating the regression equations:

R^2 = the square of the multiple coefficient of correlation, a measure of percent variance of the PDSI series explained by the regression equation.

R^2_{adj} = R^2 adjusted for loss of degrees of freedom by the equation

$$R^2_{adj} = R^2 - \frac{(k-1)}{(N-k)} \times (1-R^2),$$

where k is the number of predictors and N is the number of years of data.

F_i = F-level for entry of a given predictor, X_i, tested on an F-distribution with degrees of freedom 1 and N−k−1.

Overall F = F statistic for testing regression equation as a whole, evaluated on an F distribution with degrees of freedom K and N−k−1.

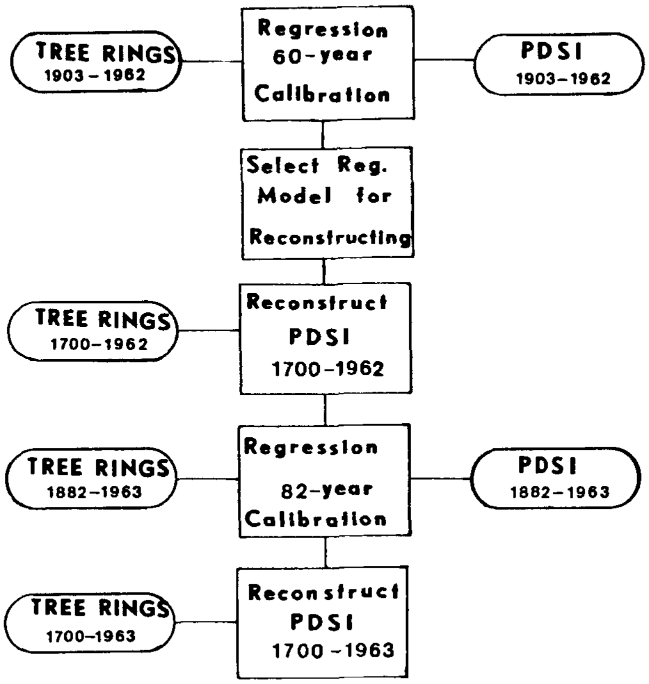

Figure 3. Sequence of Steps in Regression and Reconstruction, and Data Used at Each Step.

Regression analyses were carried out using the Statistical Package for the Social Sciences (SPSS). Further details on statistics used may be found in the SPSS manual (1975) and in Draper and Smith (1966).

RESULTS AND DISCUSSION

Regression Analyses

Three regressions were run for the 60-year calibration: 1) the full model, in which the stepwise procedure was allowed to run its full extent, letting predictors enter as long as F-level for entry was greater than 0.01; 2) a short model, in which the stepwise procedure was cut off after only three steps; and 3) a maximum-adjusted-R^2 model, in which the procedure was cut off when R^2_{adj} was maximized. The three models, which included, respectively, 23, 3, and 11 predictors, had the following values for R^2 and adjusted R^2:

	R^2	$R^2_{adjusted}$
Full Model	0.692	0.510
Short model	0.519	0.493
Maximum-R^2_{adj} model	0.669	0.593

Plots of actual and predicted PDSI based on each model for the independent data (1882-1902) showed that the third model reconstructed wet years much more accurately than the short model, and slightly better overall than the full model (Figure 4). On this evidence the maximum-adjusted-R^2 model was selected to reconstruct PDSI back to A.D. 1700.

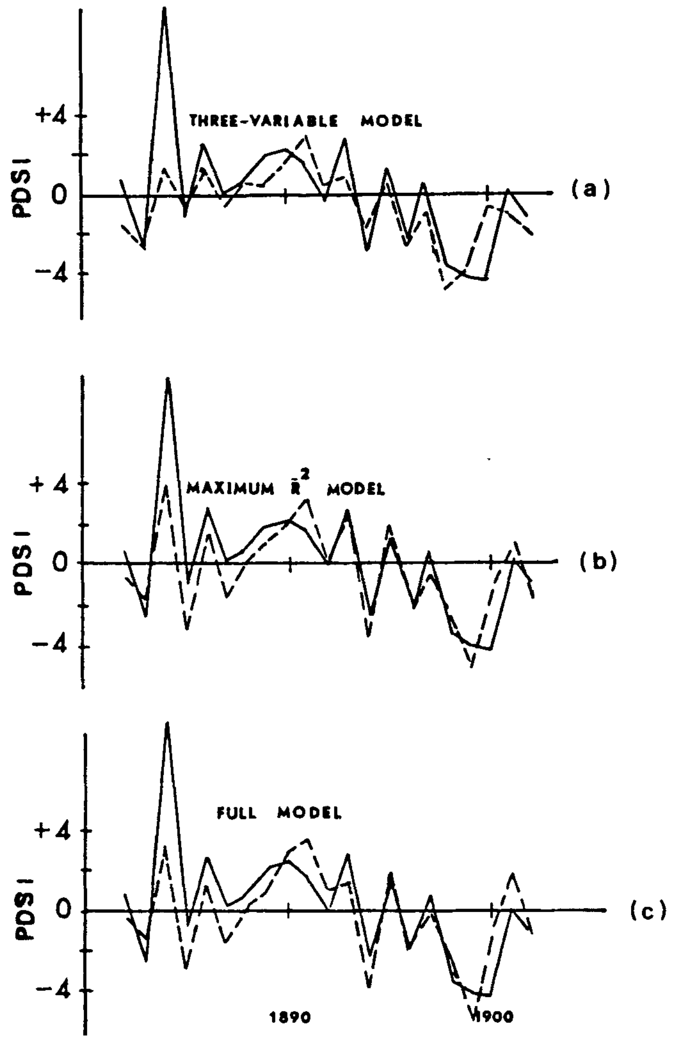

Figure 4. Reconstructed (dashed line) and Actual (solid line) July PDSI for the Independent Verification Period (1882-1902) – (a) simplest model, based on 3 predictor variables; (b) maximum-adjusted R^2 model, based on 11 predictor variables; and (c) model arrived at by letting stepwise procedure run to an F-level for variable inclusion of 0.01.

Table 2 lists the predictors in the order they entered along with their corresponding regression coefficients and standard errors. The first six predictors to enter were from sites nearest the weather stations whose records were used to compute the mean PDSI series (see Figure 1). The regression accounted for 67 percent of the variance of PDSI in the calibration period and 70 percent of the variance in the 21-years of independent data. Independent data verification (Figure 4b) shows excellent agreement both in droughts and in wet years. The most substantial discrepancies between actual and reconstructed PDSI were in 1885, 1887, and 1900 on the dry side, and 1884 on the wet side. In 1884 heavy rains drenched southern California throughout the normally dry spring, leading to a very high July Palmer Index (PDSI = +9.5). Although the tree rings reconstructed 1884 as the wettest year of the independent data, the magnitude (PDSI = +4.0) was appreciably in error. A possible explanation for the discrepancy is that diameter growth of trees does not respond to additional moisture beyond an optimal amount. The statistical relationship between PDSI and tree-ring index may consequently be linear up to a certain level of PDSI, and nonlinear at higher PDSI, possibly leading to substantial errors in reconstructing extremely wet years.

TABLE 2. Summary of Regression Equation (60-year calibration).

Step	Site	Lag	B*	Standard Error B	F**	α**
1	Southern California	t	3.244	1.000	10.5	0.002
2	Santa Ana	t–1	–3.315	0.966	11.8	0.001
3	San Gorgonio	t	5.514	1.743	10.0	0.003
4	Baldwin Lake	t–1	–1.696	0.952	3.2	0.081
5	Santa Rosa	t+1	1.183	1.184	1.0	0.323
6	Santa Ana	t	2.338	1.181	3.9	0.054
7	White Mountains	t+1	–1.566	0.872	3.2	0.079
8	San Pedro Martir	t+1	3.528	1.429	6.1	0.017
9	San Gorgonio	t+1	–3.408	1.833	3.5	0.069
10	Santa Rosa	t–1	1.858	1.151	2.6	0.113
11	San Pedro Martir	t	–1.447	1.251	1.3	0.253
	Constant		–6.283	1.401	20.1	0.000

R^2 = 0.669, coefficient of determination.
Adjusted R^2 = 0.594.
F = 8.83 overall F level for equation, significant at 0.999 level.

*Unstandardized regression coefficients.
**F-levels for inclusion of predictors and corresponding α for significance of F, where $1-\alpha$ = significance level.

The agreement between actual and reconstructed PDSI is summarized in the contingency tables of Figure 5. Figure 5a, which is based on the data both in the calibration period and in the independent data period, shows that accuracy is especially good in the most extreme drought category: 8 of 11 are correctly classified and the remaining three are one class off. The problem of reconstructing extremely wet years shows in the lack of accuracy (only 6 of 11 correct or nearly so) in the wettest class. This again is probably an indication of departure from linearity in the tree response under very wet conditions. Figure 5b, based only on data outside the calibration period, also shows good agreement between actual and reconstructed. Again, the entries are clustered along the diagonal and none of the 21 entries were in error by more than one class.

A similar regression was run using the full 82-year (1882-1963) of PDSI calibration, again using a Maximum-R^2 model. This regression, which is summarized in Table 3, served two purposes: 1) it allowed us to evaluate the effect of varying period of calibration on the order of importance of individual predictors, and 2) it yielded regression coefficients for use in long-term reconstruction. We felt that the most accurate long-term reconstruction was likely to result from regression equations calibrated on as long a period as possible.

MEASURED PDSI

RECONSTRUCTED PDSI	< -3	-1 to -3	-1 to +1	+1 to +3	> +3
< -3	8	2	1		
-1 to -3	3	11	5		
-1 to +1		7	10	3	
+1 to +3			7	10	7
> +3				3	3

(a)

MEASURED PDSI

RECONSTRUCTED PDSI	< -3	-1 to -3	-1 to +1	+1 to +3	> +3
< -3	2	2			
-1 to -3	1	3	1		
-1 to +1			4		
+1 to +3			1	5	
> +3				1	1

(b)

Figure 5. Contingency Tables Showing Number of Years Reconstructed in and Actually in Various PDSI Ranges – (a) based on 82 years from 1882 to 1963 and (b) based on only 21 years of data from 1881 to 1902 prior to the calibration period.

TABLE 3. Summary of Regression Equation (82-year calibration).

Step	Site	Lag	B*	Standard Error B	F**	α**
1	Southern California	t	1.329	1.097	53.9	0.000
2	Southern California	t–1	–0.158	0.926	14.2	0.000
3	Santa Rosa	t+1	1.674	0.979	5.0	0.028
4	San Gorgonio	t+1	–4.893	1.306	5.1	0.026
5	Santa Ana	t	4.027	0.957	6.4	0.013
7	San Pedro Martir	t+1	3.026	1.025	3.0	0.085
8	San Gorgonio	t	4.100	1.247	5.3	0.024
9	Santa Ana	t–1	–2.821	0.946	6.7	0.012
10	Santa Rosa	t–1	–1.768	0.910	2.3	0.134
11	San Gorgonio	t–1	–2.104	1.238	2.7	0.105
12	White Mountains	t+1	–0.868	0.701	1.5	0.220
	Constant		–5.544	1.249	14.9	0.000

$R^2 = 0.708$, coefficient of determination.
Adjusted $R^2 = 0.654$.
F = 14.9, overall F level for equation, significant at 0.999 level.

*Unstandardized regression coefficients.
**F-levels for inclusion of predictors and corresponding α for significance of F, where $1-\alpha$ = significance level.

Comparison of results of the 82-year model with those of the 60-year model yields several points. First, in both analyses the sites that entered in the first five steps were those nearest the climatic stations, reflecting that drought tended to be localized such that the more remote sites were often under substantially different drought conditions than the climatic stations, or that by chance trees on the sites most remote from the climatic stations happened to be less sensitive to drought.

Second, the order in which predictors entered, and the magnitude of the regression coefficient on any particular predictor changed substantially in going to the longer calibration period. This result is not surprising considering that the tree-ring series are intercorrelated with one another, and appreciably correlated in time (first-order autocorrelation coefficients ranging from 0.24 to 0.61). The information added by any one predictor therefore is not independent of that added by other predictors, making the physical interpretation of any individual regression coefficients speculative at best.

Finally, the adjusted R^2 in the 82-year calibration (R^2_{adj} = 0.65) was higher than the 60-year calibration (R^2_{adj} = 0.59), suggesting that the longer period should definitely be used in deriving a long-term reconstruction. The following section describes that reconstruction. A long-term reconstruction was also derived using the 60-year calibration; the conclusions based that reconstruction, however, did not differ appreciably from those based on the 82-year reconstruction, and they are not discussed.

Reconstruction

A long-term reconstruction of PDSI from A.D. 1700 to A.D. 1963 based on the 82-year calibration model (Table 3) is shown in Figure 6. The two driest single years were 1857,

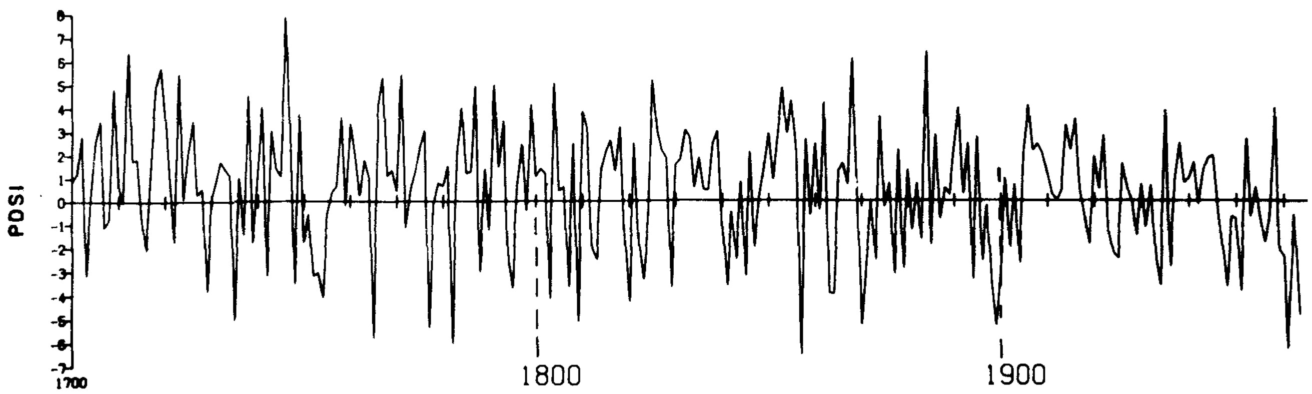

Figure 6. Reconstructed Palmer Drought Severity Index (PDSI) for 1700-1963 Based on 82-Year Calibration Period.

PDSI = –6.57; and 1961, PDSI = –6.48; followed by 1782, PDSI = –6.04; 1965, PDSI = –5.84; and 1777, PDSI = –5.35.

Comparison of reconstructed with actual PDSI indicated that actual levels of PDSI of –4.0, –3.0, and –2.0 had about the same exceedence probability in the 82-year calibration period as reconstructed PDSI levels of –3.5, –2.6, and –1.5, respectively. Thus the latter figures were used as cut off values to indicate "extreme, severe, and moderate" drought categories for the reconstructed PDSI's. The number of years reconstructed at these drought levels for discrete 50-year intervals back to A.D. 1700, and for the period 1950-1963 are listed below:

Period	PDSI ⩽ –3.5	PDSI ⩽ –2.6	PDSI ⩽ –1.5
	Number of Years		
1700-1749	4	5	8
1750-1799	5	7	10
1800-1849	6	8	14
1850-1899	6	8	14
1900-1949	2	4	11
1950-1963	3	3	6

Droughts at all three levels were most frequent in the two periods making up the 19th century. Extreme droughts (PDSI ⩽ –3.5) were relatively rare in the first half of the twentieth century but have become more frequent since 1950. In three years during 1950-1963 reconstructed PDSI was below –3.5, and actual PDSI was below –4.0 again in 1970 and 1972. Evidence so far therefore suggests that the current half-century may well turn out to be the driest such period since A.D. 1700.

An important problem to water resource planners and others is the likelihood of droughts lasting several years. Only in 1863-64 and in 1898-99 were years reconstructed back-to-back in extreme drought (PDSI ⩽ –3.5). Table 4 summarizes the occurrences of 2-year and 3-year runs for PDSI –2.6 and PDSI –1.5. Droughts lasting three years were evidently rare over the study period, with no three-year droughts at the extreme (PDSI ⩽ –3.5) level, only one at the severe (PDSI ⩽ –2.6) level, and three at the moderate (PDSI ⩽ –1.5) level. The last 3-year drought occurred at the end of the reconstruction period in 1959-1960-1961. Since 1963, the actual PDSI record (San Diego-Riverside-Los Angeles mean) shows a severe (actual PDSI ⩽ –3.0) 3-year drought in 1970-1971-1972 and a severe 2-year drought in 1963-64. These results suggest that droughts lasting several years have become more frequent in the past 20 years than in the previous 250 years, and that extreme drought (Reconstructed PDSI ⩽ –3.5, actual PDSI ⩽ –4.0) has become especially more frequent in the past 20 years relative to the first half of this century.

TABLE 4. Runs of Two or Three Consecutive Years of Drought.

Runs* PDSI ⩽ –1.5			Runs PDSI ⩽ –2.6	
2-year**		3-year	2-year	3-year
1752	1870	1752	1752	1752
1794	1898	1898	1863	
1812	1924	1959	1898	
1819	1933			
1822	1947			
1863	1959			

*Entry is first year of run.
**Only nonoverlapping 2-year runs are listed.

The practical significance of a given level of PDSI to many water users will of course depend somewhat on water demand. In areas where demand for water for domestic consumption, industry, and irrigated agriculture is increasing, a static value (e.g., PDSI = –3.00) cannot in general be interpreted as the same severity of drought from year to year. The areas of the West where oil shale is expected to be mined and processed, for example, would probably feel the strain of a 1977 magnitude drought more acutely 15 or 20 years from now than they did in 1977. On the other hand, alternative sources like ground water mining and interbasin transfers of water may mitigate the effects of drought in some areas. Results from a study and as this one are therefore most useful to water resource planning when supplemented by information on other aspects of water supply and demand.

ACKNOWLEDGMENTS

This material is based upon work supported by the Division of Atmospheric Sciences, National Science Foundation Under Grant ATM 77-26189.

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