RECONSTRUCTING THE FLOW OF THE SACRAMENTO RIVER SINCE 1560

by

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ABSTRACT

Tree-ring width time series have been shown to be useful in conjunction with regression techniques for extending instrumental records of climate variables such as precipitation, drought severity and annual streamflow. This study uses tree-ring data derived from 17 sites in northern California and eastern Oregon to develop reconstructions of annual Sacramento River streamflow for the period 1560-1980. Reconstruction methods using principal components analysis (PCA) and autoregressive (AR) modeling are tested and compared. Reconstructions based on both PCA-transformed and untransformed tree-ring data may be superior to reconstructions using only one of these two forms of data. Also, reconstructions using AR modeling of the tree-ring data are found to more accurately reproduce the time series structure of the instrumental streamflow record, but to explain less variance in the data set, than reconstructions which do not use AR modeling. The reconstructed streamflow series shows that the historical period includes the wettest (1854-1916) and driest (1928-1937) periods of the last 400 years, but that many other periods of sustained drought or high flows have also occurred. This reconstruction correlates well with a previous reconstruction of precipitation in California, and shows varying levels of agreement with tree-ring based reconstructions of climate done elsewhere in the western U.S.

INTRODUCTION

As the nation's leading agricultural state, California is uniquely dependent upon its supply of fresh water (Governor's Office of Planning and Research, 1979). It has, accordingly, developed the nation's most comprehensive water resource management system. The principal concerns of this system are the distribution of water and the variations in water supply that are associated with floods and drought (Governor's Office of Planning and Research, 1979). For instance, the drought of the 1930's produced 10 years of below-average streamflow in the Sacramento River. The lowest flows of this period were nearly repeated in the drought of 1976-77, and other periods of two or more years of low flows have also been recorded.

It would be desirable to be able to assess the potential for floods and drought of specified magnitudes and durations. This can be done, in part, by developing longer records of streamflow. Longer streamflow records can provide more accurate estimates of flow mean, variance and persistence than do shorter, instrumental records (Stockton and Fritts, 1971). They also allow better estimates of the size of needed reservoirs (Mandelbrot and Wallis, 1969). Therefore long streamflow records are useful for hydrologic modeling and design of water-supply systems.

Streamflow records can be extended to include several centuries of estimated flow by the use of tree rings as a source of proxy data (Stockton, 1975). Techniques for developing stochastic models to reconstruct climate variables using tree-rings were developed by Fritts (1976) and others (Hughes et al., 1982) and were extended to reconstructing streamflow records by Stockton (1975). These models use multiple or canonical regression techniques to calibrate a transfer function which describes a climate variable or variables as a linear function of one or more series of tree-ring width indices.

This study uses tree rings in an attempt to reconstruct over 400 years of streamflow for the Sacramento River of northern California (Figure 1). In the process, a number of matters pertaining to the procedures of dendroclimatic reconstruction are addressed:

(1) The tree-ring data used in this study include 17 site chronologies ending in 1980 or later (Figure 1). These chronologies consist of standardized ring-width indices (Fritts, 1976) representing data collected from 15 to 30 trees at each of the sites (Holmes et al., 1986a). Which of these chronologies should be used as potential predictors of streamflow in reconstruction equations?

(2) Reconstructions were produced using four distinct forms of tree-ring data as predictors of streamflow. One such form consisted of the standardized tree-ring chronologies (Fritts, 1976). The other forms included the principal components of the chronologies, the chronologies

as transformed by autoregressive models (Meko, 1981), and the principal components of the autoregressively modeled chronologies. Reconstructions using principal components as predictors may provide a record of large-scale variations in climate, while reconstructions using chronologies as predictors may accurately reflect variations at individual locations (Fritts, 1982). Therefore, the combination of more than one form of predictor data in a reconstruction may enhance the climate signal in the reconstruction and reduce the random noise component (Fritts, 1982). What are the relative merits of the four forms of tree-ring data in producing reconstructions of streamflow? Are reconstructions using both tree-ring chronologies and their principal components as predictors superior to reconstructions using only one of these forms of data as predictors?

(3) Verification is the process of comparing reconstructed to recorded flows over an independent data period which was not used to calibrate the reconstruction equation. This procedure affords an unbiased answer to the question, how well do the reconstructions perform?

(4) How accurately do the reconstructions estimate the mean, variance and persistence structure of the actual streamflow series? Study of the low- and high-pass filtered series (Fritts, 1976) of both the reconstructions and the recorded annual streamflow data makes it possible to evaluate the reconstructions over low- and high-frequency

domains. Such evaluation includes the size of the variance of the reconstructions relative to actual streamflow and the apportionment of this variance between the domains, as well as the correlations between actual and reconstructed streamflow within the two domains.

Consideration of the foregoing questions makes it possible to select what appears to be the most accurate reconstruction, which is then analyzed in the context of two additional questions:

(1) What are the periods of high and low flow as shown by the reconstructed series and its low-pass filtered transform? (2) How does the reconstruction compare with dendroclimatic reconstructions of streamflow, precipitation and drought done in the western U.S. by other workers?

STATISTICAL METHODS

The chronologies were evaluated in regard to descriptive statistics that indirectly indicate the degree to which climatic variation affects tree growth at the sites represented by the chronologies (Fritts, 1976). These statistics were: (1) Common variance: This is the percent variance shared by all of the cores that are combined to produce a tree-ring chronology (Fritts, 1976). A large portion of common variance is likely to reflect the limiting effects of climate experienced by the trees at the site (Fritts, 1976). The low-frequency part of this variance may also represent nonclimatic factors which influence all of the trees at the collection site (Cook, 1985). (2) Standard deviation: High values indicate that the chronology contains a large amount of variance reflecting a high variance in common (Fritts, 1976). (3) Mean sensitivtity: This statistic measures the relative variation in the first-differenced chronology, which contains only high-frequency variance. High values indicate that the chronology contains a large proportion of this variance, which is likely to be due to climate (Fritts, 1976). (4) First-order autocorrelation: A high first order autocorrelation may indicate the presence of a high amount of nonclimatic variance (Fritts, 1976). Thus a low first order autocorrelation and high values for the variance in common, standard deviation and mean sensitivity indicate chronologies likely to contain a clear, strong climate signal.

Principal components analysis, or PCA, is a data transformation technique which takes a multivariate data set and transposes it to an orthogonal set of coordinate axes (Daultrey, 1976). The orientation of the new set of axes is expressed by a set of vectors called eigenvectors, and the transformed data are called principal components (Daultrey, 1976). The procedure is useful for two reasons. Because the eigenvectors are orthogonal, the principal components of the data are uncorrelated and so the risk of multicollinearity is reduced; and the procedure selects the principal components in order of their importance so that the first few generally explain a large fraction of the variance in the data set (Morrison, 1983). Thus fewer predictor variables are needed and degrees of freedom are conserved in the regression. In this study 10 of 17 principal components were retained, explaining 88% of the variance in the the set of tree-ring chronologies.

Autoregression is "a regression in which one value in a time series is regressed upon one or more variables which precede it in time" (Fritts, 1976, p.532). According to Meko (1981), it is desirable to perform autoregressive (AR) modeling of both tree-ring and streamflow time series because the technique can be used to produce reconstructions which display a persistence structure very similar to that seen in natural streamflow series. This is often not the case when AR modeling is not used. AR modeling techniques are presented by Box and Jenkins (1976).

Digital filters and their use in dendrochronology are described by Fritts (1976). This study used a pair of reciprocal filters; the high-pass filter passes 50% or more variance at wavelengths less than or equal to 8 years, and the low-pass filter passes 50% variance at wavelengths of 8 years or longer. These filters were applied to each reconstruction and to the instrumental record for each streamflow series to separate the high-fequency and low-frequency variance components. The ratio between high and low frequency variance seen in the instrumental data was then compared to the ratio seen in the reconstructions to determine which reconstruction models best approximated the apportionment of high and low frequency variance seen in the instrumental data.

DATA

The tree-ring data used in this study were developed by R.L. Holmes *et al.* (1986a) at the Laboratory of Tree-Ring Research, University of Arizona. The techniques used to collect and process the tree-ring samples and thereby to produce these tree-ring chronologies are summarized by Holmes *et al.* (1986b, in press). The chronologies used in this study were not in their final form, but Holmes advises that the differences between the chronologies that will soon be published and those used in this study are "extremely minimal".

The trees used in this study were sampled at a variety of sites in California and Oregon (see Figure 1). Descriptions of these sites are in Holmes *et al.* (1986b). Site and chronology names, time spans, locations, species and descriptive statistics are listed in Table 1. Four species are represented, including five western juniper (*Juniperus occidentalis*) sites, six jeffrey pine (*Pinus jeffreyi*) sites, four ponderosa pine (*Pinus ponderosa*) sites and one sugar pine (*Pinus lambertiana*) site. Site PIU is a mixed site, containing both jeffrey and ponderosa pines. All of the tree-ring sites are located either in mountainous country or on the high plateaux of eastern Oregon and northeast California. The chronologies used in this study are all at least 420 years in length, with the longest record coming from Frederick Butte, a western juniper site in eastern Oregon.

Table 1 summarizes several important chronology descriptive statistics. Standard deviation, common variance and mean sensitivity were ranked, with "1" assigned to the chronology with the highest value and "17" assigned to the chronology with the lowest value. These rank scores were summed and ordered to produce the rating given in the "Rank" column. The Frederick Butte chronology was given the highest rating, with superior statistics in all categories. The third through sixth ratings were assigned to the other western juniper chronologies. Most of the pine chronologies which lie within the Sacramento Basin were ranked eighth to thirteenth. The second and seventh ranks were assigned to sites SOR and PIU, pine sites located (Figure 1) at the southern end of the Sierra Nevada.

The streamflow data were provided by the California Department of Water Resources. They consist of monthly flow records dating from the early 1900's to 1981 for the gage stations on the Sacramento River at Bend Bridge. This station is shown in Figure 1. The data were corrected by the Department for diversions and impoundments, and consequently they represent the best available estimates of natural flow (M. Roos, pers. comm. 1985). We also received a second data set, consisting of estimates of annual streamflow for the period back to 1872-1905. We were advised (M. Roos, pers. comm., 1985) that this second data set may contain errors of up to ten percent. This second data set was not used in model development, but was reserved as truly independent data for final verification of the reconstruction models.

RECONSTRUCTION PROCEDURE

Due to the risk of multicollinearity within the predictor data sets and the desirability of maximizing degrees of freedom in the regression equation (Morrison, 1983), this study uses a variable selection procedure to reduce the number of possible predictors for each reconstruction. The method used in this study follows that of Cook and Jacoby (1983). The streamflow data were divided into two equal periods, called the calibration periods. Correlations were calculated between each streamflow series and each possible tree-ring variable for each of the calibration periods. Those variables which were significantly (95% confidence) correlated with streamflow for both calibration periods, were retained for entry into regression models. This procedure was replicated for each of the four forms of tree-ring data (i.e. chronologies, AR-modeled chronologies, and the principal components of each).

The tree-ring variables selected as a result of this correlation analysis were entered as possible predictors in backwards-selection multiple linear regressions in order to develop reconstruction models. The regression equations were calibrated using a portion of the available streamflow and tree-ring data, and were then used to reconstruct streamflow for as long a period of time as the tree-ring data allow (Fritts, 1976). Regressions were performed for each of the four forms of tree-ring data for each of the two calibration periods 1906-1942 and 1943-1979, producing a total of 8 different reconstructions.

The streamflow data that were not used to calibrate the regression equations were used as independent data to verify the reconstruction produced from the equations (Fritts, 1976). In order to obtain optimum reliability for these statistics, two verification periods were used in all cases. A 33-year verification period used data incorporated in the correlation analysis but not in development of the regression model, while a 37-year verification period represented independent data which consisted of historically-based estimates of streamflow for the period 1872-1905.

Verification statistics used to evaluate the reconstructions include the simple correlation coefficient, R; its square; R for the first-differenced series; reduction of error (RE) and its components; and chi-square tests for normality of the series. These verification statistics are described by Fritts (1976), Gordon et al. (1982) and Gordon

(1980).

R provides an estimate of the strength of the covariance between the two series at all frequencies (Gordon, 1980). R-squared indicates the variance in the streamflow series which is explained by the reconstruction for the verification period (Gordon, 1980). R for the first-differenced series estimates covariation between the series at very high frequencies (Fritts 1976, Gordon, 1980). RE is a scaled measure of the cumulative yearly errors over the verification period. An RE value of greater than zero indicates that the reconstruction produces better than random estimates of the observed data, with a value of 1.0 indicating perfect agreement between the series (Gordon, 1980). There is no lower limit on the possible values of RE. Squared errors are involved in the calculation of RE, so that only a few large errors can lead to a negative RE in what is otherwise a relatively valid reconstruction (Gordon, 1980). The last test used was a standard chi-square test for normality of the reconstruction (Gordon, 1980).

Reconstruction Evaluation

The principal criteria used to determine the relative merits of the reconstructions were: 1. High R-squared for the regression for the calibration period. 2. High R-squared for the verification periods (1906-1942 or 1943-1979, and 1872-1905); and 3. High RE for the verification periods.

Digital filters were used to compare the streamflow series to selected reconstructions, in regard to: 1. Total variance and the apportionment of variance between high and low frequency domains; and 2. Correlations between the unfiltered series and between the series at high and low frequencies.

These criteria were used to select a "best" reconstruction. The low-pass filtered series of this reconstruction was used to compare the series to other published dendroclimatic reconstructions. These other reconstructions were in the form of plots that either included a low-pass filtered series, or to which such a series was fitted by eye.

RESULTS

The first two eigenvectors produced by the principal components analysis appear to vary along a north-south gradient and so may represent patterns of variation in tree growth acting on a regional scale. The first eigenvector, which reduces 35% of the variance in the data set, assigns negative weights to all chronologies. This indicates that the most important mode of variation is one of similarly wider or narrower rings for all of the chronologies in any given year. The highest weights are assigned to chronologies developed for sites bordering the Sacramento Basin (DON, HHA, FEL) and sites in eastern Oregon (SPR to

STE). Lower weights are assigned to sites in the northern (DAL to LEM) and southern (SNO to SOR) Sierra Nevada. The second eigenvector reduces 11% of the variance in the data; it has negative weights for the chronologies developed for the northern (western juniper) sites, and it has positive weights for chronologies representing the central Sierra-southern Sacramento Basin sites DON and HHA. The weights of chronologies for other sites are near zero.

Autoregressive models were estimated for the tree-ring data using chronology data for 1906-1980, the period used to develop the reconstructions. AR coefficients were determined for this period in order that the AR model not remove persistence that may exist in earlier parts of the series and that may be climatic rather than biological in origin (Cook and Jacoby, 1983). AR modeling was attempted with the streamflow data, but was not found to be significant at lags of a year or more, and so autoregressive modeling was deemed unnecessary.

At this point it becomes necessary to introduce a nomenclature for referring to the various reconstructions. Each reconstruction will be given a code name, such as A1. This would mean:

A --- The A data set, tree-ring chronologies produced by program Arstan (Holmes et al., 1986b), is used for predictor data. The other predictor data sets are P, the principal components of chronologies; W, chronologies fitted with AR or "whitening" models; and WP, principal components of the W data.

1 --- The reconstruction is calibrated over the first period of flow data, 1906-1942, and verified over the second period, 1943-1979. "2" indicates calibration over the 1943-1979 period and verification over the 1906-1942 period.

Simple correlations were calculated between the streamflow series and each of the 17 chronologies or 10 principal components in each of the four data sets, for both calibration periods (1906-1942 and 1943-1979), at lags of from -1 to 3 years. The highest correlations were about 0.7, indicating that these variables can explain as much as 50% of the variance in streamflow. Three chronologies in the A data set showed variables with significant (95% confidence) correlations with streamflow in both time periods. Four chronologies showed such correlations in the W data set, Six principal components showed them in the P data set, and one principal component in the WP data set. These correlations all involved lags of 0 or -1 years. The tree-ring variables which showed significant correlations with streamflow were input to the regression models. Certain consistencies emerge concerning the predictor variables that were selected by these regressions.

The reconstructions using the A or W data set chose only the Frederick Butte chronology (FRE) as a predictor.

While the Frederick Butte site is outside of the Sacramento basin in eastern Oregon, the site chronology ranks highest in terms of chronology statistics. The correlation analysis indicates that the site chronology is consistently positively correlated with flow.

The reconstructions using the P data set chose the four most important principal components, 1, 2, 3, and 4, as well as 8 and 9 as predictors. The reconstructions using the WP data set chose only the first principal component (explaining 35% of the variance in the data set), as this is the only one which could be entered as a possible predictor based on the correlation analysis.

Table 2 summarizes the variance (R-squared) in actual streamflow explained by each reconstruction for the verification period. Values range from 10.7% to 37.5%, with 5 of 8 values above 25%.

The reduction of error statistic is listed in Table 3 for each reconstruction, for both the standard (1906-1942 or 1943-1979) and early (1972-1905) verification periods. RE values greater than zero, indicating that the reconstructions are better than simply random estimates of streamflow, were found for 7 of the 8 reconstructions for the standard verification period.

For the early verification period, 5 of the 8 reconstructions show RE values of less than zero. This poor result could be explained by the fact that the streamflow data are estimates which may contain errors of up to 10% from the actual flows, or it may also be attributable to inferior reconstructions.

Reconstructions W1 and W2 failed to pass the chi-square test for normality for the 1943-1979 data period. They did pass this test for the 1872-1905 and 1906-1942 data periods.

The reconstructions were ranked from high to low according to calibrated variance, variance explained and RE for the verification period, and RE for the 1872-1905 verification period. These results are summarized in Table 4.

The reconstructions using the A data set received the highest ranks, with intermediate ranks for reconstructions using the P and W data sets and lowest ranks for reconstructions using the WP data set.

Two selected reconstructions were combined by averaging the estimated flows to obtain a "composite" reconstruction. One of the selected reconstructions was the highest ranking model using the A or W data set, and the other was the highest ranking model using the P or WP data set. Thus the composite combined the best reconstruction using single station data with the best using principal components. This reconstruction, A1P2, was verified over the 1872-1905 data period; it shows an RE of 0.09, intermediate between the RE values of its component reconstructions (.14 and -.06). The composite reconstruction was examined for its similarity to the instrumental data in regard to the proportions of variance allocated to the low- and high-frequency domains. Results of this analysis are summarized in Table 5.

In the Actual (recorded streamflows) series, the ratio of high-pass to low-pass variance is 2.4:1. The proportions for reconstructions based on A, P and Composite predictors are 1.6:1, 0.5:1, and 0.8:1. The reconstruction based on the A data set most nearly reproduces the ratio of high-pass to low-pass variance that is observed in the streamflow series, but the reconstruction based on the P data set has a total variance that is closer to that of the actual streamflow (60%). The Composite reconstruction is intermediate in both respects.

Table 6 summarizes the correlations between streamflow, and the composite reconstruction and its component reconstructions for the series and their low- and high-pass filtered transforms.

Correlations are highest for the low-pass series and lowest for the high-pass series, but do not differ appreciably between the three reconstructions.

On the basis of the verification results, apportionment of variance between low- and high-pass filtered series and the correlation study just mentioned, A1P2 was chosen as the "best" reconstruction for the Sacramento River. This reconstruction is plotted in Figure 2.

DISCUSSION

Study Limitations

The tree-ring data are limited to 17 chronologies. Only two of these (FRE and LEM) are chosen by more than one reconstruction model, and one (FRE) is chosen by every reconstruction model that uses tree-ring chronologies as predictors.

The use of correlation and regression between tree-ring data and streamflow presumes linearity in the relationship between those variables. Such linearity was not explicitly tested, but was not apparent in scattergrams comparing the tree-ring and streamflow data. The regression procedure also assumes that the model residuals are not correlated. Only the first-order autocorrelation in the residuals was tested, and it was not significant at the 95% confidence level as determined by the Durbin-Watson statistic (Morrison, 1983). Computing correlations for both calibration periods and using only those variables that are significantly correlated with flow for both periods, prevented the verification tests on the 1906-1980 data from being completely independent. However, the 1872-1905 streamflow data can be considered truly independent.

All statistical tests involving a degrees-of-freedom calculation assume that there is no autocorrelation in the data. This assumption is untrue in cases involving the A or P data set, or reconstructions using those data for predictors. Thus, the confidence intervals are likely to be underestimated is such tests as the significance of simple correlations or of the predictors in a regression equation.

Reconstruction Accuracy

These reconstructions of streamflow contain the same limitations in regard to accuracy that apply to tree-ring reconstructions of past climate in general. Two of these limitations are direct consequences of the use of linear regression to develop the reconstructions: 1. Flows close to the mean will tend to be accurately estimated, whereas high or low flows will be estimated less accurately (Draper and Smith, 1981). 2. The reconstructions display lower variance than the instrumental records of streamflow because the variance of the instrumental records is equal to the variance of the reconstruction plus the variance of the model residuals (Ezekiel and Fox, 1959). This simply means that high flows will tend to be underestimated by the reconstructions, and low flows will tend to be overestimated. A third limitation on the accuracy of the reconstructions is that low-frequency variations in flow are more accurately reconstructed than are high-frequency variations. This point is demonstrated by the correlations in Table 6, which indicate that the low-pass filtered reconstructions are all more strongly correlated with observed streamflow than are the high-pass filtered reconstructions.

Interpretation of the Reconstructions

Figure 2 is a plot of the Sacramento River reconstruction A1P2 for the period 1560-1980. The plot includes both the reconstructed flows and their low-pass filtered transform. The reconstruction indicates that throughout the record there have been short-period, large-magnitude fluctuations in the streamflow, with reconstructed low flows of four to five million acre-feet (maf) and high flows of eleven to twelve maf.

Figure 3 is a plot of reconstructed dry years as the number of standard deviations below the mean of each year's flow, calculated as standardized scores of the low-pass filtered data. The large peak centered during the 1930's comprises the single longest period of reduced flows in the entire reconstruction, a period in which filtered flows remained below average for 34 years. Other notable periods of low flow occurred in 1577-1583, 1592-1595, 1618-1630, 1678-1681, 1719-1723, 1777-1779 and 1843-1850. Several conspicuous wet periods are also seen, in Figure 2. Flows remained above average for more than a decade in 1597-1613, 1641-1657, 1664-1675, 1725-1735, 1741-1754, 1798-1821, 1854-1869, 1874-1887, 1891-1916 and 1962-1973. The last four of these periods fall within the time of modern man's activities in northern California, indicating that the historical period is generally wet in the context of the last 400 years, although it also contains the worst drought of the record.

Comparison with Other Dendroclimatic Reconstructions

Table 7 compares the major low flow events in the low-pass filtered Sacramento River reconstruction with conditions for those years as reconstructed by six dendroclimatic studies performed in the eastern and western U.S. The table suggests that there is little agreement between the timing of drought or low flow events on the Sacramento River and in the eastern United States. However, the Sacramento River record largely agrees with a reconstruction of statewide California precipitation (Fritts and Gordon, 1982). Intermediate agreement exists with a reconstruction of Pasco Basin, Washington precipitation (Cropper and Fritts, 1984), and a reconstruction of Upper Colorado River Basin streamflow (Stockton and Jacoby, 1976). Poor agreement exists with a reconstruction of Salt River, Arizona streamflow (Smith and Stockton, 1981).

CONCLUSIONS

(1) Although it is not within the Sacramento Basin, the chronology that is ranked highest in terms of chronology statistics, Frederick Butte, was the predictor variable most consistently selected by the reconstructions. Other chronologies representing sites within the Sacramento Basin were also found to be significantly correlated with

streamflow.

(2) The composite reconstruction displays time series properties and verification statistics that are intermediate between its component reconstructions.

(3) Reconstructions using AR-modeled data showed poorer verification statistics than models which did not use AR modeling. However, these models more accurately reproduced the time series structure of the recorded streamflow data than did models which did not use AR modeling.

(4) The verification statistics based on instrumental data indicate that the composite reconstruction is providing better than random estimates of past streamflow. This finding is supported by verification statistics based on the historical estimates of flow for the 1872 to 1905 period.

(5) The reconstruction indicates that the mean and variance of streamflow in the last 420 years has varied relative to the mean and variance for the 1906-1981 period of instrumental data. The reconstruction contains about 38% as much variance as the instrumental data, with 49% as much variance for the low-frequency component.

(6) The reconstruction indicates that the instrumental data include the periods with the highest and lowest flows of the last 420 years, but that many other episodes of prolonged high or low flow have occurred in the past.

(7) A comparison of the Sacramento River reconstruction with other dendroclimatic reconstructions for the West indicates that the Sacramento River reconstruction agrees strongly with reconstructed precipitation in nearby areas such as California (Fritts and Gordon, 1982) and less strongly with reconstructions of more distant areas such as the upper Colorado River basin (Stockton and Jacoby, 1976) and the Pasco Basin (Cropper and Fritts, 1984).

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Table 1

Summary of essential information on the 17 selected tree-ring chronologies.

Site Name	Species Code	Latitude deg, min	Longitude deg,min	Elevation (meters)	Chronology length (years)	AR var. expl	Std. Dev.	Com. var.	Mean sens	Rank
Spring Canyon	JUOC	44 54	118 56	1341-1390	578	.28	.329	47%	0.30	3
Frederick Butte	JUOC	43 35	120 27	1433-1554	886	.29	.432	61%	0.46	1
Calamity Creek	JUOC	43 59	118 48	1433-1494	587	.17	.274	53%	0.28	4
Steens Mountain	JUOC	42 40	118 55	1625-1686	482	.20	.245	51%	0.25	5
Hager Basin Res.	JUOC	41 46	120 45	1518-1530	671	.30	.245	49%	0.23	6
Dalton Reservoir	PIPO	41 39	120 58	1463-1524	624	.59	.283	40%	0.21	8
Antelope Lake	PIJE	40 09	120 36	1366-1561	508	.67	.222	29%	0.15	13
Antelope Lake	PIPO	40 09	120 36	1366-1561	497	.58	.227	36%	0.18	10
Lemon Canyon	PIJE	39 34	120 15	1707-2012	566	.43	.222	43%	0.20	9
Donner Summit	PIJE	39 19	120 21	2201-2329	471	.52	.218	44%	0.17	11
Hell's Half Acre	PIJE	39 36	122 57	1890-1954	484	.33	.168	34%	0.15	15
Felkner Ridge	PILA	39 30	122 40	1433-1555	438	.45	.173	36%	0.14	14
Saint John Mtn.	PIPO	39 26	122 41	1427-1939	481	.18	.167	29%	0.17	15
Snow White Ridge	PIPO	38 08	120 03	1696-1743	424	.31	.202	39%	0.19	12
Devil's Dance Floor	PIJE	37 45	119 45	1951-2084	539	.32	.166	28%	0.15	17
Piute Mountains	PI	35 32	118 26	1951-2012	454	.62	.286	44%	0.21	7
Sorrel Peak	PIJE	35 26	118 17	1975-2256	477	.38	.304	61%	0.29	2

Notes: See text for an explanation of the statistics. Statistics are for the Arstan chronology. Results are from first runs of Program ARSTAN and may differ very slightly from final results, in Holmes *et al.*(1986a). "Rank" is relative to Standard Deviation, Common variance and Mean Sensitivity, with high values assigned low ranks. In "species code": JUOC = *Juniperus occidentalis*, western juniper. PIPO = *Pinus ponderosa*, ponderosa pine. PIJE = *Pinus jeffreyi*, jeffrey pine. PI = mixed *Pinus ponderosa* and *Pinus jeffreyi*.

Table 2

Variance explained for calibration and verification periods

Reconstruction	Calibrated Adj. R^2	Verification R^2
A1	47.9%	30.8%
A2	28.8%	28.8%
P1	54.2%	13.1%
P2	46.8%	37.5%
W1	40.0%	25.4%
W2	26.5%	25.4%
WP1	25.0%	11.7%
WP2	9.2%	10.7%

Table 3

Reduction of error for the reconstructions for both verification periods

Recon.	1943-1979 RE	1872-1905 RE	Recon.	1906-1942 RE	1872-1905 RE
A1	.28	.14	A2	.31	.05
P1	.02	-.08	P2	.04	-.06
W1	.20	-.17	W2	.25	.05
WP1	.12	-.18	WP2	.12	-.18

Table 4
Ranking of selected reconstructions by verification statistics and calibrated variance

Recon	RANKS				
	Cal var	Ver var	RE	Early-period RE	Rank
A1	2	2	2	1	1
A2	5	3	1	2	2
P1	1	6	8	5	6
P2	3	1	7	4	3
W1	4	4	4	6	5
W2	6	4	3	2	3
WP1	7	7	5	7	7
WP2	8	8	5	7	8

Recon = Reconstruction. Cal Var = Calibrated variance. Ver Var = Variance in streamflow explained for verification period. 1st diff sign = First difference sign test for verification period.

Table 5

Variance of recorded streamflow series, selected reconstructions, and their high- and low-pass transforms

	Total	Hi-Pass	Lo-Pass
Actual (%)	12.50	7.91(63)	3.19(26)
Arstan (%)	3.98(32)	2.10(53)	1.32(33)
PC (%)	7.56(60)	2.43(32)	4.45(59)
Composite (%)	4.77(38)	1.92(40)	2.36(49)

This Table summarizes variance for the standard and high- and low-pass filtered series for selected reconstructions of Sacramento River streamflow. This is determined for the period 1877-1974, the longest possible common period for all series. Values are in trillions of acre-feet, squared. Percentages in the "Total" column are in respect to actual (recorded flows) variance; percentages in the other columns are relative to the variance in the "Total" column of each row.

Table 6

Correlations for standard series and high- and low-pass transforms between streamflow series and selected reconstructions.

Standard		Low-Pass		High-Pass	
A1	.5002	A1	.7024	A1	.4156
P2	.4761	P2	.6976	P2	.3597
A1P2	.4098	A1P2	.7410	A1P2	.4195

This Table summarizes correlations between recorded streamflow and composite and component reconstructions of the Sacramento river. Correlations are expressed between the reconstructed and actual streamflow series for the series themselves ("Standard") and for their high- and low-pass filtered transforms. Correlations were calculated for the period 1877-1974, the longest possible common period for all series. All values are significant at .001%.

Table 7

Drought events on the Sacramento River compared to other dendroclimatic reconstructions for the U.S.

Drought:	Potomac	Hudson	Calif	Salt	Colo	Pasco
1577-83				*	+	
1592-95				*	+	
1618-21			+	*	-	-
1627-30			+	*	+	+
1678-81			*	*	-	+
1719-23	*		+	-	-	*
1777-79	+	-	+	+	+	*
1794-95	-	*	+	+	*	*
1830	+	-	+	*	+	*
1843-50	-	*	*	+	+	+
1918-20	*	*	+	*	*	+
1924-40	*	*	+	*	*	+
Agreements	2/7	0/6	8/10	3/12	6/12	5/10
Ratio	.29	.00	.80	.25	.50	.50

+ indicates agreement, - indicates a wet period, * indicates near-average conditions. "Drought" is defined as a period of flows at least 0.5 standard deviations below the mean, with mean and standard deviation calculated for the low-pass reconstruction of Sacramento River flows. "Hudson" refers to a reconstruction of Hudson Valley, New York PDSI done by Cook and Jacoby (1977). "Potomac" refers to a reconstruction of Potomac River summer streamflows done by Cook and Jacoby (1983). "Calif" refers to a reconstruction of statewide California precipitation by Fritts and Gordon (1982). "Salt" refers to a reconstruction of annual Salt River, Arizona streamflow (Smith and Stockton 1981). "Colo." refers to the reconstruction of upper Colorado River annual streamflow done by Stockton and Jacoby (1976). "Pasco" refers to a reconstruction of annual precipitation for the Pasco Basin, eastern Washington (Cropper and Fritts 1984).

Figure 1. Map showing location of the Sacramento River and the streamflow gage station and tree-ring site collections used. The map symbols are as follows: S, gage station on Sacramento River at Bend Bridge. 1, Spring Canyon site. 2, Frederick Butte site. 3, Calamity Creek site. 4, Steens Mountain site. 5, Hager Basin Reservoir site. 6, Dalton Reservoir site. 7, Antelope Lake sites. 8, Lemon Canyon site. 9, Donner Summit site. 10, Hells Half Acre site. 11, Felkner Ridge site. 12, Saint John Mountain site. 13, Snow White Ridge site. 14, Devils Dance Floor site. 15, Piute Mountains site. 16, Sorrel Peak site.

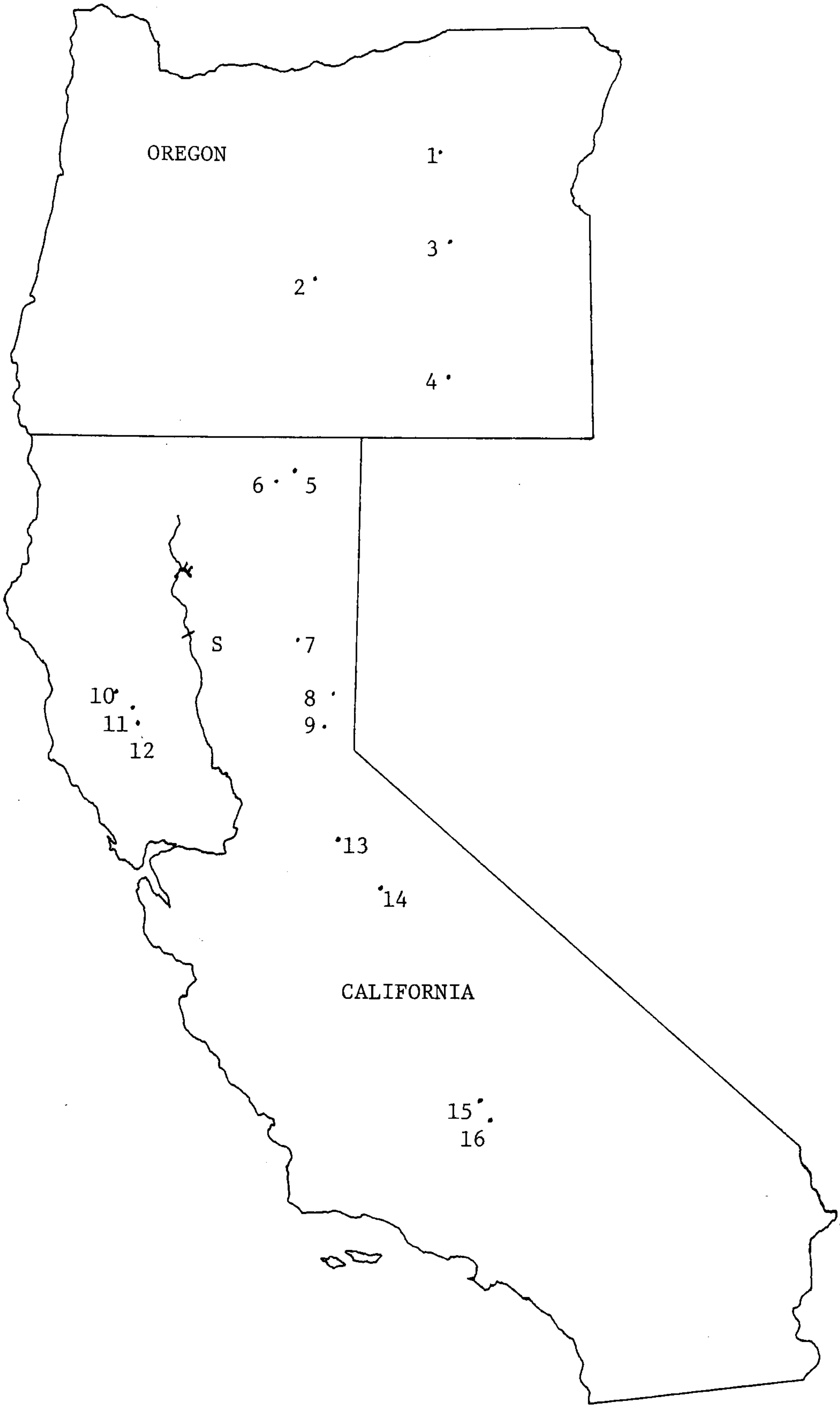

OREGON
1
3
2
4
6
5
S
7
10
11
12
8
9
13
14
CALIFORNIA
15
16

Figure 2. Reconstructed and recorded flows for the Sacramento River at Bend Bridge, showing mean of both series for the 1906-1980 calibration period. Reconstruction includes 8-year low-pass filtered flows.

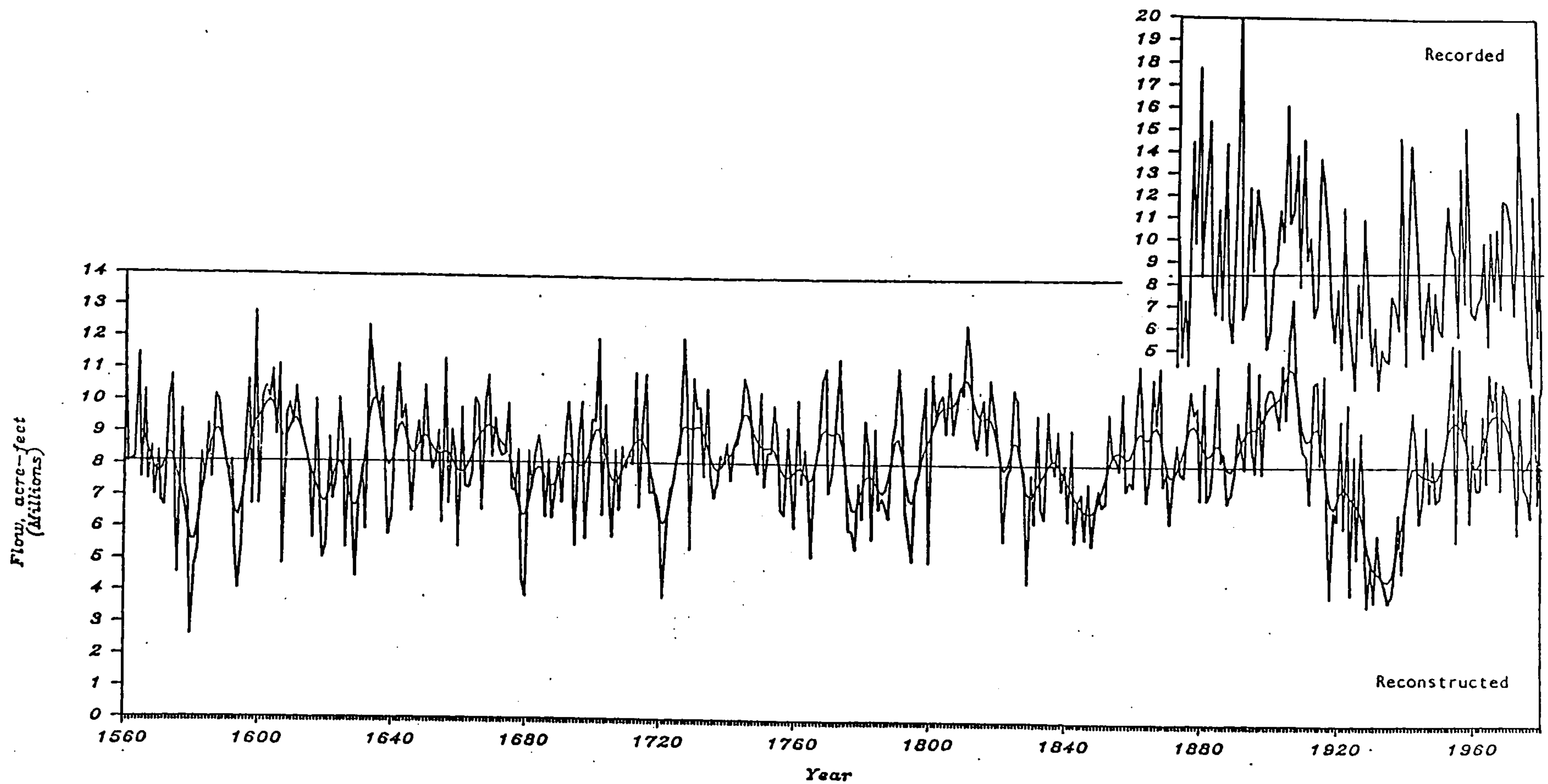
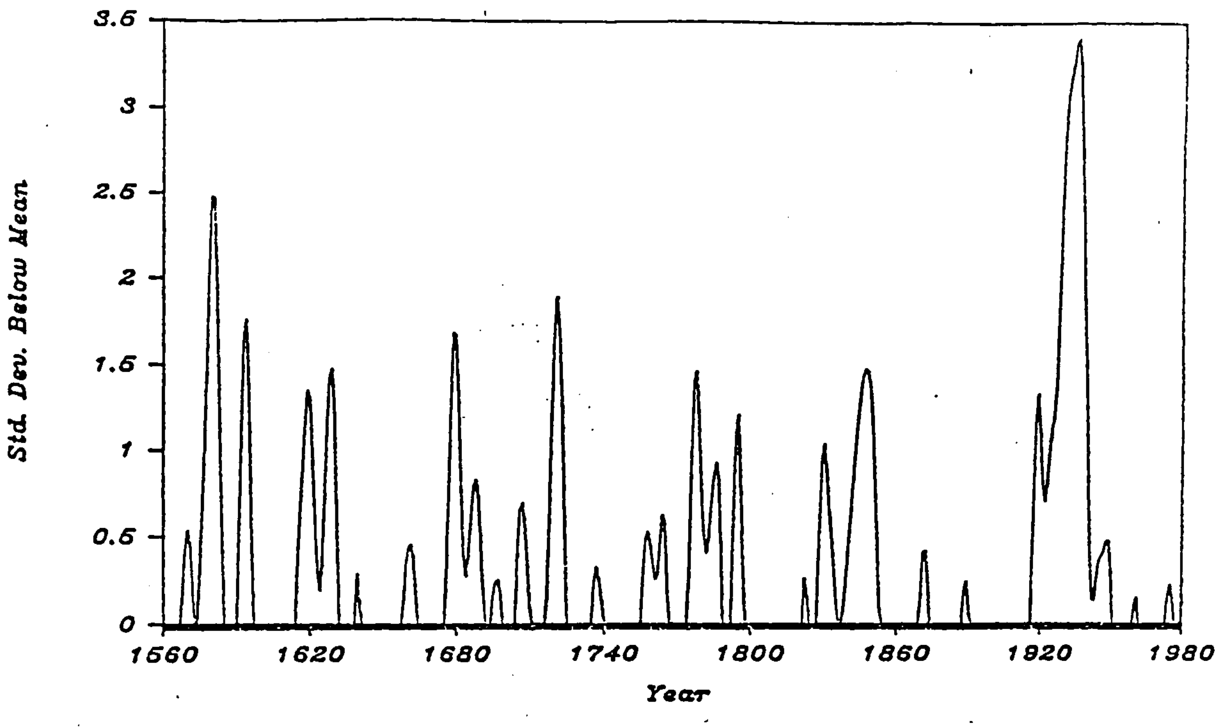

Recorded
Reconstructed
Flow, acre-feet (Millions)
Year

Figure 3. Reconstructed Sacramento River low flows, calculated as number of standard deviations below 1560-1980 mean using the low-pass filtered reconstruction.



3.6
3
2.5
2
1.5
1
0.5
0
Std. Dev. Below Mean
1560
1620
1680
1740
1800
1860
1920
1980
Year