

Dendrohydrologic Collections in the Jemez Mountains Region

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Activities

The goal of this project is to increase understanding of the long-term natural variability of this region by developing tree-ring based reconstructions of hydro-climatic variability for the Jemez Mountains. Our new reconstruction of cool-season (October-June) precipitation documents 1181 years of climate and drought variability that can be used to place current and 20th century wet and dry events into a long-term context. Records of past hydro-climatic variability can be used to guide expectations of future variability, aid sustainable management, provide scenarios for drought planning and as inputs for hydrologic models to test systems under a broader range of conditions than those provided by the historical climate records. The outcome of this research will furnish planners, managers, and decision-makers with the knowledge and tools necessary to employ *ex-ante* planning processes in future management of northern New Mexico water resources. In addition, this reconstruction will help to assess the associations between fire regimes and environmental factors.

Goals accomplished during the one year of this grant:

- (A) Field reconnaissance, and sampling
- (B) Building tree-ring chronologies
- (C) Preparing and analyzing the instrumental climate data
- (D) Building dendroclimatic reconstructions
- (E) Fire-climate analyses

A. Field reconnaissance, and sampling

During the period of the project (2007-2008) we sampled four sites (MEA, BCW, BCM, FEN) from the Jemez Mountains and nearby regions in northern New Mexico (Figure 1). The sites range in elevation from 2000 to 2600 m a.s.l. An additional site, EAU, was sampled by Craig Allen, updating a chronology that was originally collected in the 1980s.

B. Building tree-ring site chronologies

This study focused on developing three new chronologies and extending and enhancing one existing chronology (Fenton Lake, FEN), and updating another, (EchoAmphitheater, EAU) from the species *Pseudotsuga menziesii*, *Pinus strobiformis*, and *Pinus ponderosa*. Two of the chronologies (MEA and BCW) contain two species that were merged because visual crossdating and computer based quality control confirmed a strong common signal. We also used three chronologies that were updated by Ron Towner from the species *Pinus ponderosa* and *Pinus edulis* (Figure 1 and Table 1). These species are known to be strongly driven by climate and to have a signal for precipitation and streamflow over a broad region in the western United States. To summarize, five chronologies were developed as part of this project, and with three developed by Ron Towner, making a total of eight for the region that were used in subsequent reconstructions (Table 2).

Increment cores were taken at all sites and full cross sections were taken from selected stumps of white and ponderosa pines and Douglass fir. Samples were fine-sanded and crossdated using standard dendrochronological techniques (Stokes and Smiley 1968; Swetnam et al. 1985). The width of each annual ring on the cores and cross-sections was measured to the nearest 0.01 mm. Eight chronologies were developed from the region including the ones that were developed by Ron Towner (Table 2).

A systematic procedure was applied in chronology development. Each series of tree-ring width measurements was fit with a cubic smoothing spline with a 50% frequency response at 67% of the series length to remove non-climatic trends due to age, size, and the effects of stand dynamics (Cook and Briffa

1990). The detrended series were then prewhitened with low-order autoregressive models to remove persistence not related to climatic variations. The individual indices were combined into a single master chronology for each combination of site and species using a bi-weight robust estimate of the mean (Cook 1985).

Table 1. Site information for northern New Mexico

Site Name	Site Code	Species	Elevation (m)	Latitude	Longitude	Time Span	No. of trees	No. of Radii
Echo Amphitheater	EAU	PSME ¹	2059	36°21'N	106°31' W	1295-2007	18	19
Mesa Alta	MEA	PIST ² -PSME	2,525	36° 17'N	106° 37'W	644-2007	47	82
Alta Mesa	AMPN ⁵	PIED ³	2438	36°16'	106° 37'W	1534-2005	19	22
Bear Canyon Middle	BCM	PIST	2,597	35° 55'N	106° 40'W	1568-2007	24	45
Bear Canyon West	BCW	PIST-PSME	2561	35° 55'N	106° 41'W	1298-2007	30	56
Fenton Lake	FEN ⁶	PIPO ⁴	2,529	35° 53'N	106° 41'W	1304-2007	37	66
Upper Los Alamos	ULA ⁵	<i>Pinus ponderosa</i>	2231	35° 52'N	106° 37'W	1659-2005	21	27
Paliza campground	PCG ⁵	<i>Pinus edulis</i>	2,057	35°42'N	106°38' W	1645-2005	31	52

¹PSME=*Pseudotsuga menziesii*

²PIST= *Pinus strobiformis*

³PIED=*Pinus edulis*

⁴PIPO=*Pinus ponderosa*

⁵Chronologies were update by Ron Towner

⁶FEN was updated this year

C. Preparing and analyzing the instrumental climate data and climate indices

We used monthly temperature and precipitation division data from New Mexico Climatic Division 2, 1895-2005, obtained from the National Climate Data Center (Figure 1) for our dendroclimatic analyses. Monthly flow data were also downloaded from the U.S. Geological Survey (<http://water.usgs.gov/data/>) for gage 08324000, the Jemez River near Jemez, New Mexico (Figure 1). These are gaged flows rather than natural flows, but there are no major reservoirs above the gage and the gaged record is a member of the Hydro-Climatic Data Network (Slack et al. 1988). The basin upstream of the gage has an area of 760 square miles, and the flows represent mainly runoff from the Jemez Mountains. Monthly flows are available for the period 1953-2007.

D. Climate/Tree Growth Analysis and Dendroclimatic Reconstructions

The relationships between the tree-ring chronologies and monthly and seasonal Division 2 temperature and precipitation were investigated with response function analysis (RFA) (Fritts 1976, 1991) (Figure 2).

Transfer function analysis (TFA) was then applied to estimate models to predict the seasonal climate variable identified by the RFA. The transfer function analysis is a regression of the seasonal climate series on the PCs or the regional tree-ring chronology. Regression equations of seasonal precipitation on the PCs for the calibration period 1895-2005 were developed. The validity of these equations as a transfer model was examined using the usual regression and correlation statistics, and the PRESS procedure was used for cross-validation (Weisberg, 1985; Fritts et al., 1990; Meko, 1997; Touchan et al., 1999, 2003, 2005 a and b). A split-sample procedure (Snee, 1977; Meko and Graybill, 1995; Touchan et al., 2003, 2005 a and b) that divides the full period (A.D. 1895-2005) into two subsets was also used to verify model stability. The reduction of error statistic (RE) was calculated to test for skill of reconstruction compared with that of a simple model that would use the calibration period mean of observed precipitation as the reconstruction. An RE value of greater than zero is considered positive skill (Fritts, 1976).

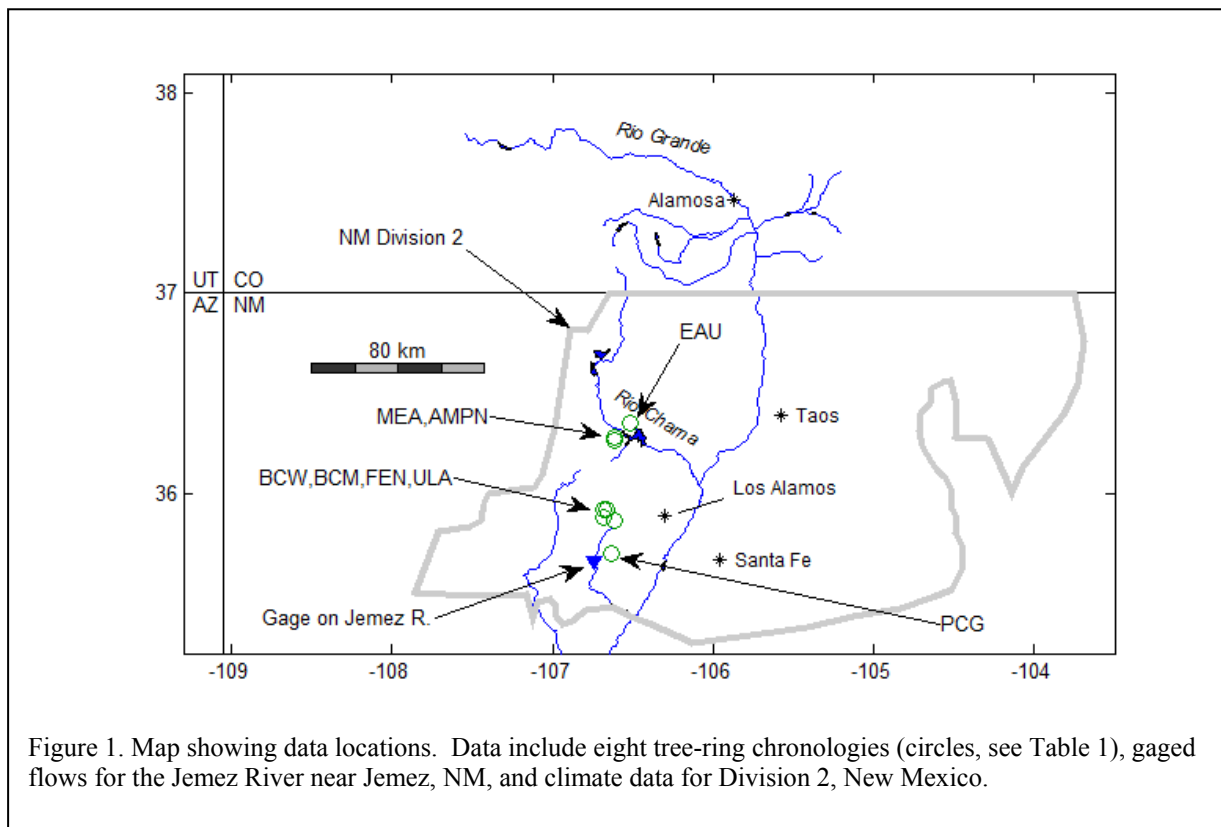
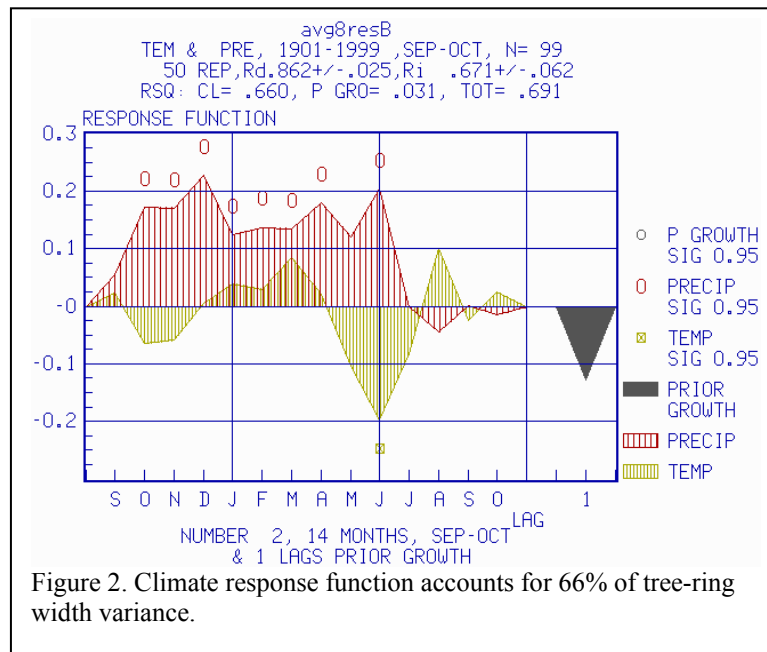


Figure 1. Map showing data locations. Data include eight tree-ring chronologies (circles, see Table 1), gaged flows for the Jemez River near Jemez, NM, and climate data for Division 2, New Mexico.



The precipitation reconstruction from this study was also re-calibrated into estimates of water-year streamflow for the Jemez River, New Mexico.

E. Fire-Climate Analyses

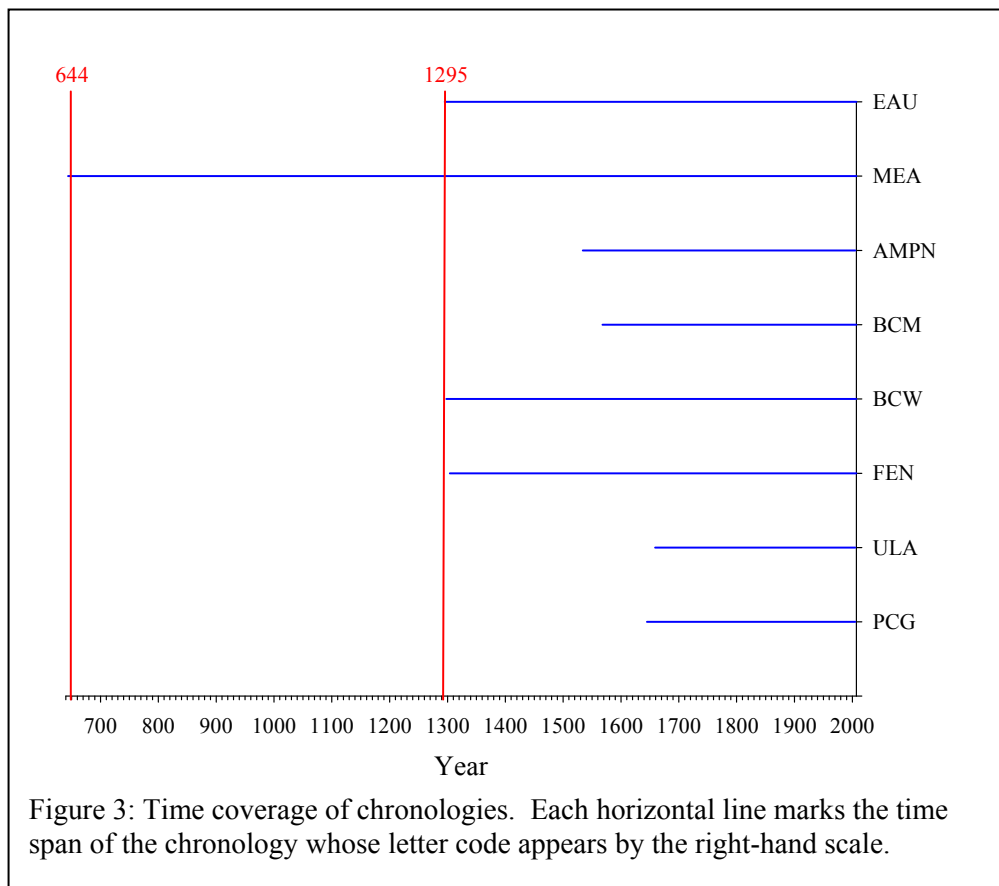
Superposed-epoch analyses (Baisan and Swetnam 1990; Swetnam 1993; Touchan and Swetnam 1995; Touchan et al., 1996) was applied to compute the mean climate conditions before, during, and after sets of fire years in both the ponderosa pine and mixed-conifer forests. In this analysis, fire years were "superposed" on the independent tree-ring nested reconstructed October-June precipitation for the period 824 to 2005. Mean precipitation values (expressed as departures from the long term mean) were computed for the set of fire years and lagged years and then plotted. We conducted 1,000 Monte Carlo simulations of the same number of randomly selected dates to estimate confidence intervals for the mean departures of the fire dates at the 95% and 99% probability levels based on the normal approximation and percentile-rank methods (Mooney and Duval 1993).

Discussion of Findings

A. Development and analysis of regional chronologies

We developed five ring-width chronologies from the region, and combined them with three chronologies developed by Ron Towner for a regional analysis (Figure 1). The length of the eight chronologies ranges from 344 (ULA) to 1362 years (MEA) (Table 1 and Figure 3). Statistical analyses of each chronology are summarized in Table 2. The mean correlation among individual radii at each site represents the strength of their common signal and ranges from 0.56 to 0.74. The highest correlation is for MEA and the lowest are for the chronologies developed from BCM and BCW. The mean sample segment length (MSSL) of the eight chronologies ranges from 222 to 319 years. All of the chronologies have MSSL greater than 200 years and many have several samples exceeding 300 years. Therefore, the chronologies are suitable for investigating low-frequency climate variability.

Principal component analysis (PCA) applied to chronologies showed a strong common statistical growth signal. PC1 accounts for 76% of the tree-ring variance.



B. Dendroclimatological analysis and reconstructions

The response function analysis identified October to June total precipitation as the most appropriate seasonal predictand for reconstruction (Figure 2) based on consistent patterns of monthly series with significant response function elements of the same sign and PC1 resulting from the eight chronologies. The reconstruction was calibrated on the mean October-June Division 2 precipitation.

A nested reconstruction was developed to accommodate the varying chronology lengths while exploiting the potential to accurately capture the long-term extreme events history of the region (Touchan 2008). The individual chronologies were used as the potential predictors to develop a set of nested multivariate stepwise regression models (Meko 1997; Cook et al. 2002) to estimate the mean October through June precipitation over the study region. In this procedure, an estimate of past precipitation values was calculated from the stepwise regression model for the period covered by all the individual site chronologies (1662 to 2005). Additional statistical models were subsequently developed for progressively longer periods back in time, with their span corresponding to significant changes in the availability of the underlying predictor tree-ring series. The individual reconstructions in this manner are

Table 2. Summary statistics for the seven chronologies for the ARSTAN program

Site Code	Total Chronology				Common Interval			
	MSSL ^a	Std ^b	SK ^c	KU ^d	1 st Year EPS ^e >0.85	Time Span	MCAR ^f	EV ^g PC1(%)
EAU	294	0.35	0.03	0.01	1367	1713-2002	0.73	77
MEA	243	0.43	0.41	0.27	824	1798-2007	0.74	75
AMPN	319	0.29	-0.63	0.45	1553	1727-1998	0.66	68
BCM	228	0.23	0.09	1.12	1667	1834-2007	0.56	58
BCW	222	0.24	0.33	2.00	1655	1805-2007	0.56	58
FEN	262	0.31	-0.16	0.33	1535	1764-1980	0.59	61
ULA	234	0.37	-0.23	-0.17	1675	1838-2005	0.63	66
PCG	259	0.39	-0.50	-0.16	1671	1737-1972	0.66	67

^aMSSL is Mean Sample Segment Length^bStd is Standard Deviation^cSK is skewness^dKU is Kurtosis^eEPS is Expressed Population Statistic (Wigley et al., 1984)^fMCAR is Mean Correlation Among Radii^gEV is Explained Variance

scaled to have the standard deviation of the one that cover all the chronologies (1662 to 2005), and joined into a single long reconstruction such that each time period is represented by the corresponding regression model with the greatest available data. This procedure permits the skill of the precipitation reconstruction to be estimated as a function of the changing set of available predictor data (Table 3 and 4).

Table 3. Results of the statistical calibration between October-June precipitation and tree growth for four reconstructions for the Jemez Mountains in northern New Mexico.

Reconstruction Period	Calibration Period	Verification Period	Adjusted- R ² Calibration	r ² - Verification	Reduction of Error, RE
1662-2005	1896-1950	1951-2005	0.60	0.58	0.58
1569-2005			0.58	0.55	0.54
1304-2005			0.63	0.53	0.53
824-2005			0.58	0.54	0.54
1662-2005	1951-2005	1896-2005	0.57	0.61	0.60
1569-2005			0.54	0.59	0.58
1304-2005			0.52	0.64	0.63
824-2005			0.53	0.59	0.58

Split-sample calibration/validation shows that the nested reconstructions are skillful as a function of time and the underlying tree-ring data (Table 3 and 4), and account for a significant portion of the observed variance (50%) irrespective of which period is used to develop or verify the regression model (Table 4). The split-sample validation also supports our use of the reconstructions based on the full period of reliable observational data (1896-2005) in the following discussions (Figure 4). None of the regression models showed any trend or first-order autocorrelation in the residuals.

The October-June reconstruction time series is plotted in Figure 5. Dry and wet years are arbitrarily defined as reconstructed precipitation below the 30th or above the 70th percentile based on the 1896-2005 instrumental period ($PPT \leq 7.7$ in and ≥ 10.47 in respectively). The long term reconstruction contained 237 drought events. One hundred sixty-seven events have a duration of one year, thirty-two events have a duration of two year, one event has a duration of three year (AD 1097-1099), and one event has a duration of four year (AD 951-954). The driest single year over the full length of the reconstruction is 1996 (4.1 in) while the driest year in the instrumental data is 2002 (4.32 in). The second driest year is 1748 (4.2 in) which Ellis (1974) reported that tree-ring data showed as possibly the driest year in the century. Swetnam and Betancourt (1990,) indicated that the frequency of wildfires was substantially above normal in 1748.

The long term reconstruction contains 288 wet events. One hundred fifty-three events have a duration of one year, thirty-eight events have a duration of two years, thirteen events have a duration of three years, and five events have a duration of four years (AD 1015-1018, 1170-1173, 1512-1515, 1594-1597, and 1985-1988). The wettest single year over the full length of the reconstruction is 1325 (15.45 in).

Table 4. Results of the statistical calibration and cross-validation between October-June precipitation and tree growth for four reconstructions for the Jemez Mountains in northern New Mexico.

Reconstructions	Calibration Period 1932-2002	Variable	Coefficient	Adjusted- R ² Calibration	PRESS	No. of Chronologies
1662-2005		Constant	9.23	0.59	0.58	7
		PC1	0.72			
1569-2005		Constant	9.27	0.56	0.55	6
		PC1	0.80			
1304-2005		Constant	9.24	0.58	0.56	4
		PC1	1.04			
824-2005		Constant	4.67	0.56	0.55	1
		MEA	4.60			

This reconstruction is significantly correlated with a previous July to current July reconstruction developed by Grissino-Mayer (1996) ($r=0.60$, $n=1169$, $p \leq 0.0001$).

The October-June 10-year moving average precipitation reconstruction indicates multi-year and decadal variation in the reconstructed precipitation. The driest ten years in the reconstruction is AD 1131-1140 (7.78 in). The second driest ten years is AD 1950-1959 (7.85 in) which coincide with Manthey, (1977) and Tuan et al., (1973) reported that an extended drought, the most severe since the inception of scientific recording of weather data, impacted the region's agricultural and industries. Thomas (1963) reported that this drought severely affected the amount of available surface water, and the use of ground water sources increased over normal usage.

To facilitate hydrologic interpretation of the tree-ring record, the precipitation reconstruction was recalibrated statistically into unit of water-year-average flow (cfs) for the Jemez River near Jemez New Mexico. The precipitation reconstruction has a curvilinear relationship with flow for the common period 1954-2005, and scatter increases toward high flows (Figure 6A). The relationship becomes more linear and scatter more uniform with log-10 transformed flow (Figure 6B). The R² values annotated on the plots indicate that the time series of reconstructed precipitation can explain 42 percent of the variance of water-

year flows and 57 percent of the variance of the log-transformed flows. The R^2 of reconstructed precipitation with log-10 flow is comparable with the R^2 of the precipitation models (Table 4).

The linear relationship between log-10 flow and reconstructed precipitation (Figure 6B) was used to recalibrate the full-length precipitation reconstruction into estimates of log-10 flow, and those were then transformed back into cfs flows units. The recalibration was made with the regression equation

$$\hat{q}^* = 1.0022 + 0.08849 \hat{p}$$

where $\hat{p}$ is the reconstructed precipitation (inches) and $\hat{q}^*$ is the reconstructed log-10 flow in log10 cfs.

The transformation back to cfs units was then made by

$$\hat{q} = \exp(\log(10)\hat{q}^*)$$

That flow reconstruction, or time series of $\hat{q}$, for years 824-2005 is listed in file jemezrecon.txt. The flow reconstruction gives no “new” information on drought history beyond that in the October-June precipitation reconstruction, and so is not subjected here to a drought tabulation. Such a tabulation would be redundant, as the rank from driest to wettest reconstructed years is identical for the precipitation and flow reconstructions. The flow values may however be of use to water managers and hydrologist. It should be emphasized that the flow reconstruction has a much larger error for high flows than for low flows. Statistically this derives from the use of log-10 flows as a predictand. Physically, the amplified error relates to difficulty in capturing high-flow events in small semi-arid watersheds with tree rings. Also note that a standard model validation procedure was not undertaken for this flow reconstruction.

C. Fire-Climate Analyses

The superposed epoch analysis revealed that in both the mixed-conifer and the ponderosa pine forests the mean precipitation departure during fire years was significantly negative (i.e., droughts) (Figure 7). For example, in the ponderosa pine forest the mean precipitation departure during fire years was -0.12 inches; in the mixed conifer forest the mean precipitation departure during fire years was -0.22 inches. In the ponderosa pine forest, precipitation in all three years prior to the fire was above normal. The second and third year prior to the fire year was significantly wet at the 95% confidence level (0.04 inches). However,

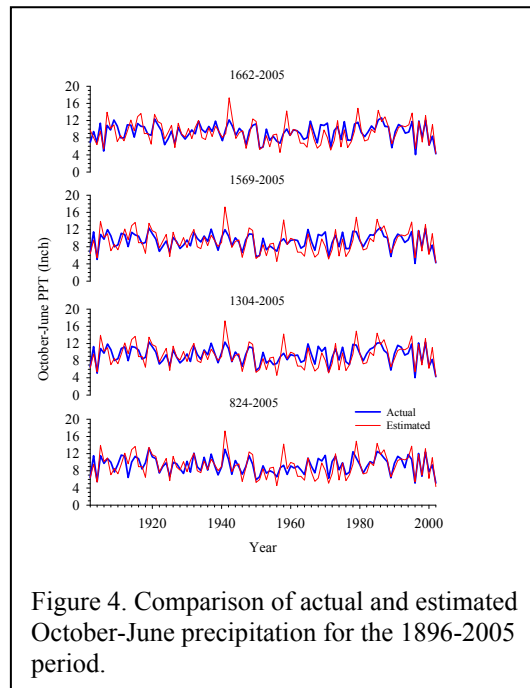
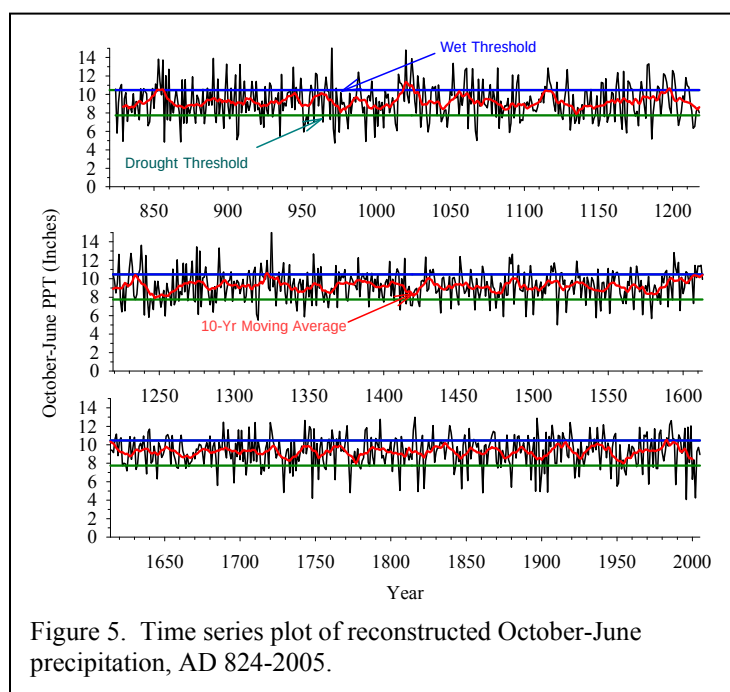


Figure 4. Comparison of actual and estimated October-June precipitation for the 1896-2005 period.

in the mixed-conifer forest, the second and third years prior to the fire year had above normal precipitation, but not statistically significant at the 95% level ($p>0.05$).

The regional fire activity in the Southwest is more likely to occur during years of below-average moisture. The superposed epoch analysis showed that the year of the fire was significantly drier than normal in both the ponderosa pine and mixed-conifer forests (Figure 7). We observed that the more intense the drought, the more widespread and/or intense was the fire (Touchan and Swetnam 1995; Touchan et al., 1996). The same relationship was demonstrated in studies of the mixed-conifer forest of the Pinaleño Mountains in southeastern Arizona by Grissino *et al.* (1994), and the ponderosa pine and mixed-conifer forests of southeastern Arizona by Baisan and Swetnam (1990). The superposed epoch analysis also showed that in the ponderosa pine forest, all three years prior to the fire were wet years, but



only the second and the third year prior to the fire was significantly wetter than average. This suggests that the build-up of fine fuels, such as herbaceous vegetation, during wet years is an important factor in the spread of fire in local ponderosa pine forests. This hypothesis was previously applied to the ponderosa pine and mixed-conifer forest of southwestern Arizona by Baisan and Swetnam (1990). They concluded that two unusually wet years prior to fire occurrence increased fine fuel production and enhanced the probability of the spread of fire in both the ponderosa pine and mixed-conifer forests. A consequence of the normally mesic conditions on north-facing slopes is that fuel is always available in the mixed-conifer forests. Our analysis of climatic variations for the mixed-conifer forests in the Jemez Mountains suggests that the only significant year is the fire year, which is drier than normal. Therefore, we believe that *fuel moisture* is the critical factor for fire occurrence in these mesic forests. If fine fuels are dry enough, then there is a high probability of the spread of fire in these mesic forests.

D. Deliverables

Accompanying this final report are the following computer files:

- 1) 8chronologies.xls – the tree-ring chronologies developed under the project
- 2) Nmrecon.txt – the reconstructed time series of October-June precipitation (inches)
- 3) Jemez_flow.txt – the reconstructed time series of water-year flow, Jemez River near Jemez, New Mexico (cfs).

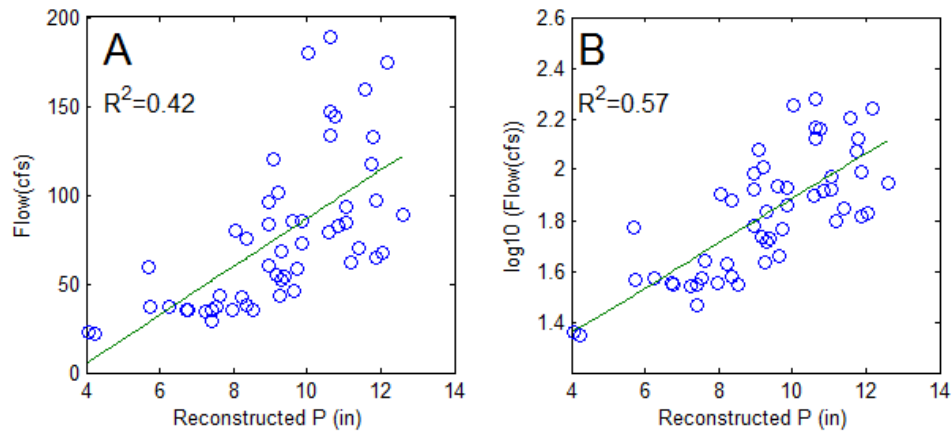
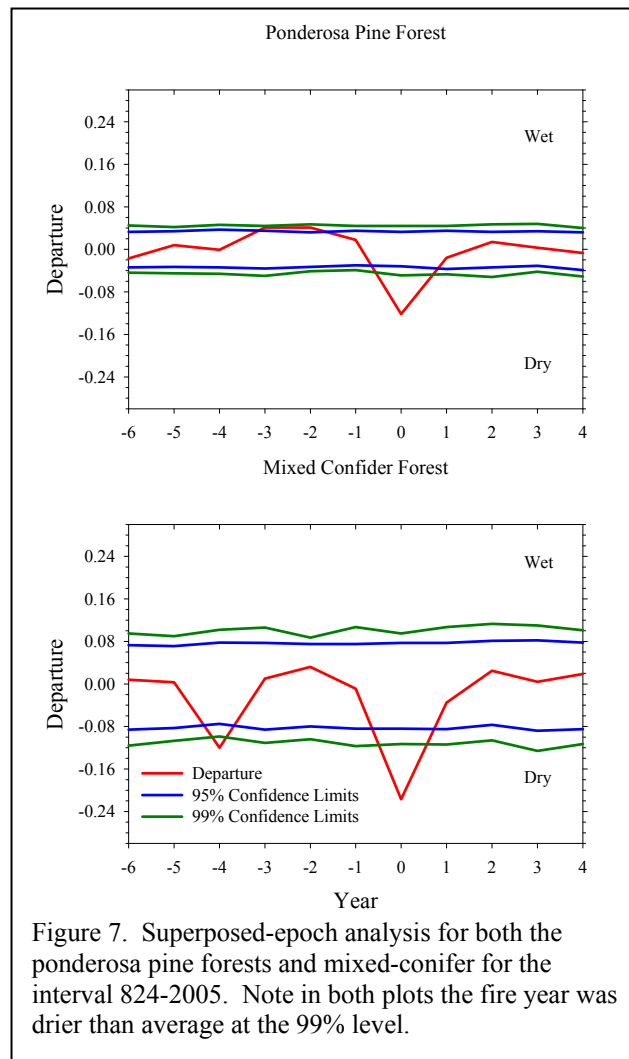


Figure 6. Relationship of annual flows of Jemez River to reconstructed divisional precipitation. (A) Flows in units of cfs. (B) Flows transformed to log10 flow. Analysis period is 1954-2005. Flow is total for water year, gage 08324, Jemez River near Jemez, New Mexico. Reconstructed precipitation is for New Mexico Division 2, as described in text. Annotated are the regression R^2 values associated with the fitted straight lines. Note the amplified scatter toward high flows.



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