RIPARIAN DENDROCHRONOLOGY: A METHOD FOR DETERMINING FLOOD HISTORIES OF UNGAGED WATERSHEDS

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ABSTRACT

Examination of 106 crossdated tree-ring cores from the riparian zone of Pine Creek near Escalante, Utah, 10 cores from Bright Angel Creek, Grand Canyon, Arizona, 8 cores from South Taylor Creek, Zion National Park, Utah, and 5 cores from the Animas River near Silverton, Colorado, has yielded the following information:

1. Various riparian gymnosperm and angiosperm species crossdate with semi-arid site gymnosperms.

2. Tree growth is best correlated with snowpack water equivalent.

3. Flood damage to trees is manifested in growth suppression on root exposure or burial, in reaction wood on tilting, and in scarring.

4. Flood damage is very infrequent at Pine Creek from 1700 to 1880, more so from 1880 to 1909, and very frequent from 1909 to the present. (The town of Escalante was settled in 1875, and stocking of the range around Pine Creek reached a maximum shortly after 1900.)

5. Flood damage shows fairly constant frequency in the Bright Angel Creek watershed, which has seen little land use.

6. Flood damage on South Taylor Creek shows a marked increase in frequency between about 1900 and 1937 when the region was included in Zion National Monument, after which flood damage declined markedly in frequency.

Keywords: *crossdating, *tree rings, *riparian zone, *flood damage, *land use, *flood frequency, *tree growth

Riparian Dendrochronology: A Method for Determining Flood Histories of Ungaged Watersheds

I. Objectives

This project was originally conceived with the thought that growth rings of riparian trees might be used to reconstruct both the history of damaging floods and of the annual discharge in an ungaged watershed. Early attempts to achieve the second objective showed that riparian trees offer no particular advantage over semi-arid-site trees (with which they crossdate) which have already been shown by the principal investigator to provide a fairly good index of annual discharge (Stockton, 1975). Accordingly, the major efforts were devoted to the former objective.

II. Methods

A. Field Work

Two summer seasons were spent in the field, mainly at the primary study area, the Pine Creek watershed near Escalante, Utah (Fig. 1). From Pine Creek, shorter forays were made to the secondary study areas: Bright Angel Creek on the North Rim of the Grand Canyon, Arizona, Betatakin Canyon near Kayenta, Arizona, South Taylor Creek near New Harmony and Cedar City, Utah, and the Animas River north of Silverton, Colorado. Characteristics of these watersheds are given in Table 1, except for Betatakin Canyon, which yielded virtually no useful information. Sampling strategy was to look for obviously flood-damaged trees on or near streambanks, and to take cores from them with a Swedish increment borer. Especially sought were trees which had had their root systems well exposed by streambank erosion, for heavily scarred trees, and for trees that had fallen over because their underpinnings had been removed by flood flow. At first, samples were taken from both conifers and angiosperms, but it was soon found that since conifer growth rings are so much easier to work with, one could gather and process a great deal more information if angiosperms were ignored.

If the tree (conifer) was leaning, normally one core was taken from the underside to intercept any compression wood that may have formed at and subsequent to the time of tilting. If there was also significant root exposure, a core was taken from the side or top as well to examine for growth suppression, which might not be evident in the reaction wood.

Detailed notes at each site, and for each tree, were taken on the breast-height diameter, the fullness of the crown, the amount of root exposure, the direction and degree of lean, the position of the root crown with respect to the edge of the streambank (the lowest floodplain level), the depth of bank erosion, and the associated perennial plant species. These notes proved to be indispensible in evaluating the probability that a given growth anomaly actually represented a flood event.

Besides flood-damaged riparian trees, also sampled were five ponderosa pines growing on a semi-arid, gypsiferous shale ridge (Jurassic Carmel formation) on the northern boundary of the Wide Hollow drainage basin (Fig. 1), taking two cores from each tree. This was done to provide a master ring series to crossdate with the flood-damaged riparian trees, and to serve as a standard against which to compare specific rings in damaged trees to test them for abnormality.

B. Laboratory Work

Work began by using orthodox measuring and data processing techniques on the mounted and surfaced tree-ring cores as developed at the Laboratory of Tree-Ring Research. This included careful measurement and tabulation of individual ring widths and standardization of the resulting series by dividing by a negative exponential growth curve determined by an iterative curve fitting technique based on the original series. This serves to render heterogeneous ring series comparable with one another, all of them having essentially homogeneous variance about a mean value of one after standardization.

It became apparent rather quickly, however, that this standardization procedure was not appropriate to series in which the growth curve was interrupted by one or more sudden suppressions of varying lengths. Neither was a polynomial growth curve option appropriate. Accordingly, it was decided to use a measure of year-to-year variability in the ring series, and so the ring width values were converted to "half mean sensitivity" values derived from the mean sensitivity statistic in common use at the Tree-Ring Laboratory. That statistic is

$$\sum_{i=2}^{n} 2\left|x_i - x_{i-1}\right| / (x_i + x_{i-1})$$

or the absolute differences between adjacent ring widths divided by their mean values and summed over the whole series. This was simplified to $(x_i - x_{i-1})/(x_i + x_{i-1})$, which, when applied to the tree ring series, served as a high pass filter, eliminating all trends of greater than two years' duration (Fig. 2. Compare lowest plot, of ring widths, with the next plot above, of half mean sensitivity on the same series). The filtered series was considerably easier to work with in crossdating than the traditional skeleton plot method in which the narrowness of a ring relative to its neighbors is indicated on the plot by the length of a vertical line.

Somewhat later it was found that a rapid method used for preliminary checking was as satisfactory for crossdating as the half mean sensitivity transform. This involves simply assigning a ring a value of +2 if it's at least twice as large as the preceding ring, +1 if it's noticeably larger, 0 if it's about the same size, -1 if it's noticeably smaller, and -2 if it's at least twice as small (Fig. 2, middle plot). Use of this technique greatly sped up the processing of more than 150 cores in the collection, particularly since the need for ring measurement was eliminated.

Eight of the ten cores taken from the semi-arid site ponderosa pines at Wide Hollow were sensitive enough (high value of the mean sensitivity statistic) to use for crossdating. Sign plots for all eight of these were made and then combined into a master sign plot (Fig. 2, second from top) in which, for each year, the number of occurrences of each relative ring width change class is indicated at the appropriate level on the plot. Thus, in the year 1962, six cores showed a +1 ring, one a +2 and one a 0, so a 1 was placed in the +2 position, a 6 in the +1 position, and a 1 in the 0 position. After doing this for each year from 1783 (the earliest year common to all the cores) to 1974, a plot line was drawn connecting the modes of each vertical distribution, except where both positive and negative numbers occurred in the same year, the evidence was considered unreliable, and no line was drawn for such years, except where the mode was zero, as in 1910, with two 1's, five 0's, and one -1. Regions of unreliable data tended to cluster, and were present only after 1930, specifically: 1933-37, and 1954-55, both periods of notable drought in the Midwest. A long period of zero mode values preceded the earlier of these two unreliable regions, from 1907 to 1929 (1920 was a -1, 1921 a +1) and prior to this, the period from 1895 to 1905 showed a violent, irregular oscillation of values with all the cores behaving in very much the same way (Fig. 2). For example, the years 1896 and 1899 show a -2 for all eight cores. Prior to 1895 and after 1955, the plot lacks these kinds of distinctiveness. This master sign plot was found to crossdate excellently with a sign plot made for the Bryce Point Douglas fir tree-ring chronology (Stokes, et. al., 1973, p. 71) taken from a point about 60 miles to the west of Pine Creek (Fig. 2) and so both of these plots were used as standards for crossdating the riparian ring series. Before accepting any core for flood dating its sign plot was determined to crossdate unequivocally with at least the master sign plot and preferably with both that and the Bryce Point sign plot.

For checking the dating of cores from South Taylor Creek, Bright Angel Creek and the Animas River, master sign plots of the published tree-ring chronologies from Bryce Point, Point Imperial, and Bobcat Canyon, respectively, were used (Stokes, et. al., loc. cit. supra; Drew, ed., 1972, p. 9, and Drew, ed., 1976, p. 32). Additional checks of crossdating among the various plots were made from damaged trees in cases where a plot failed to crossdate unequivocally with the appropriate master plot.

In order to determine the environmental conditions that have affected tree growth in the Pine Creek watershed, a compilation of the binomial probability of joint occurrences of changes of sign in both annual tree growth for the Wide Hollow Ridge chronology and in specific environmental variables was made. These variables were monthly values of precipitation (1902-), snowfall (1923-), water equivalent of snowpack (1936-), Pine Creek runoff (1952-), Palmer drought index (1932-), and temperature (1902-). The results are shown in Table 2, which may be summarized by saying that the <u>maximum growth increase</u> is to be expected with low temperatures and high snowfall from November through March prior to the growing season <u>relative to the preceding year</u> (remember that this is a comparison of year-to-year changes in growth and environmental variables). Notice the tight and consistent response of growth to increased snowpack in January, February and March, with almost significant response in December and April. Increased runoff in October through December, indicative of warmer temperatures and loss of soil moisture from the watershed at that time, is unfavorable to growth, while increased runoff in April through August is indicative of increased snowpack, which, as we've already seen, correlates with increased growth. Palmer drought index is higher (moister conditions) from January through August when growth is increased. Distilling all this, it appears that snowpack water equivalent is probably the most important of all the environmental variables to ponderosa pine growth (and, by inference, to those other species which crossdate well with ponderosa pine) in the Pine Creek watershed.

Earlier, a similar analysis was done for a composite half mean sensitivity plot derived from two boxelder trees (Acer negundo L.) compared with first differences (one year's value minus the prior year's value) in precipitation, snowfall, temperature and runoff. In that analysis, the Pearson correlation coefficient was used as a measure of relationship. A significant correlation was obtained only for March precipitation (positive), January and February temperature (negative), and May runoff (positive). These results are generally consistent with the picture outlined above for ponderosa pine.

After each core was satisfactorily crossdated with the appropriate master plot, any growth anomalies present were noted on the core plot. These were basically of three kinds: growth suppressions, ring damage and reaction wood. A growth suppression is a sudden and more or less permanent reduction in the mean ring width, and with adequate field evidence for root exposure, it's the most precise means of dating a flood event, since the effect of exposure must be evidenced in the ring series between the end of one growing season and some time during the next. Thus, suppression in the 1951 ring would indicate a flood between the fall of 1950 and the summer of 1951. Ring damage is less precise, since it may be evidenced from the end of one growing season, throughout the next, and prior to the second season following. Damage to the 1951 ring would indicate a flood between the fall of 1950 and the spring of 1952. Reaction wood is, in theory, the least reliable, since it's usually associated with trees that have fallen over after stream erosion has removed sufficient soil from the root system for the force of gravity to exact its toll. The tree could stand in a metastable condition for several years and ultimately fall under the influence of a relatively minor flow, soil creep or wind. Ring damage or suppression occurring with reaction wood improves the likelihood of the time estimate being correct. In general, the adopted in this study is to assign a flood event to the time interval between summer of the year prior to the evidence and summer of the concurrent year.

III. Research Results

Tabulation of the various growth anomalies assumed to be flood-related in the Pine Creek study area revealed a high frequency of such anomalies beginning in 1909-10 and continuing to the present (Table 3 and Fig. 3, top). Prior to about 1880, and back to 1700 (the early limit of the study) anomalies are very infrequent, and in the transitional period between 1880 and 1910, they increase in frequency. The number of tree-ring cores available for study also increases with time from 6 in 1705 to 106 since 1958. To allow for this, the number of growth anomalies identified in each year was expressed as a percentage of the number of cores available for the same year (Fig. 3, middle plot). This served to increase the importance of the earlier anomalies, but obviously not their frequency. To approach the latter problem, note was made of the increase in the number of growth anomalies in time relative to the increase in available cores (time-cumulated anomalies divided by time-cumulated cores). The results show that anomalies have increased markedly over cores since 1909-10 (Table 3 and Fig. 3, bottom). The flood of August 31, 1909 on Pine Creek is documented in U. S. Geological Survey Water Supply Paper #269, p. 183. A gaging station on the Escalante River just below the mouth of Pine Creek "was washed out by a severe flood, August 31, which scoured out the bed of the creek about 3 feet and changed the location of the channel..." Monthly Weather Review, Vol. XXXVII, 1909, p. 505, documents the abnormally intense and excessive rainfall of the month of August. This weather condition was related to a meridional atmospheric circulation pattern prevalent at the turn of the century and since replaced (until the late 1960's) by more zonal flow, as discussed below.

Late summer cloudbursts seem to be frequent associates of flood events in the Pine Creek watershed as suggested by Table 4, in which most principal flood years (indicated by dots at the top of Fig. 3) are matched with storm rainfall amounts recorded at Escalante.

Figure 4 shows evidence of the change in atmospheric circulation type from meridional to zonal and back again in the precipitation record of Tucson, Arizona. At this station, there is a fairly clear separation of the annual precipitation into summer and winter regimes as shown by Figure 4A. This figure shows the median monthly precipitation for the period of record (1896-1972, solid bars). Medians were used instead of means because while July and August precipitation are normally distributed, other months are not, and September appears to be trimodal. Furthermore, a histogram of means for the same data shows a very irregular top curve as opposed to the simple, two-humped curve in Figure 4A. The higher, sharper hump from June to October represents the monsoon-dominated regime of summer in which moist air from the Gulf of Mexico flows northwestward into the American Southwest along the southwest edge of the Bermuda High, reaching its maximum development and westward extent in the summer months. The lower, broader hump from November to May represents the frontal, winter regime in which cyclones entrained in the prevailing westerlies occasionally extend far enough south to bring precipitation to southern Arizona.

Figure 4B is a plot of the measured annual precipitation at Tucson between 1896 and 1972 inclusive. Figure 4C is a half mean sensitivity transform of the same data indicating year-to-year variability. This plot shows quite clearly two constrasting modes of behavior in the annual precipitation. One, extending from 1909 to 1965, exhibits a random pattern of change, while the other, characterizing the two intervals, 1900-1908 and 1966-1972, shows high-amplitude, high-frequency oscillation with a two year periodicity. Equivalent plots for the two seasons (not shown) reveal that this pattern is characteristic only of the frontal, winter regime, the summer precipitation pattern appearing to be random (except for the interval 1917-1926 when high-amplitude, high-frequency (HAF) oscillations in the winter regime from 1920 to 1925, and they combine to form a random pattern in the annual plot).

Comparing the sign of the change for individual years within the two modes of behavior between the summer and winter plots, it was found that for the HAF intervals the sign of the change was the same (wet summer follows wet winter, or dry summer follows dry winter) in 11 years out of 16 while the sign was opposite in 2 (one sign was zero in 3 years out of 16). For the random interval, the sign of the change was the same in 15 years out of 61, and opposite in 34 (one sign was zero in 12 years out of 61). A test on these data yielded a chi square value of 12.40 with a significance probability of chance occurrence of less than .005, which leaves little doubt that direct correlation of summer and winter precipitation is characteristic of the HAF periods, and inverse correlation is characteristic of the random periods.

A further chi square test was made to see whether any monthly precipitation anomalies might be associated with periods of positive and negative correlation between summer and winter season precipitation regimes. For this analysis, the monthly precipitation values were divided into three equal classes for each month for the period of record, and called the upper third abnormally high, the middle third normal and the lower third abnormally low. (The white bars in Fig. 4A represent a measure of variability equivalent in function to the coefficient of variation, and defined by the difference between the upper and lower limits of the central third of the precipitation values divided by the median. In general, this figure indicates that variability is inversely proportional to median precipitation, March and June deviating somewhat from this trend.)

The chi square analysis showed that when winter is positively correlated with the following summer, March shows fewer wet anomalies and more normal values (near the median) and May shows more wet and fewer dry anomalies. When the seasons are negatively correlated, March shows more wet anomalies, and May shows fewer wet and more dry anomalies. The chi square probabilities for these relationships are less than .005 for March and between .05 and .10 for May (the latter is altered to between .01 and .025 if the zero correlation category is eliminated).

Thus, a wet May is characteristic of years in which both winter and the following summer are either abnormally wet or abnormally dry, while a wet March and a dry May are characteristic of years in which a wet summer follows a dry winter or the reverse.

In order to try to relate these behavior characteristics of the Tucson precipitation to the general circulation of the atmosphere, use was made of the series of winter and summer types developed by Blasing and Fritts (in press) by map-pattern correlation for the period 1900-1966. Their winter includes December, January and February, and their summer includes July and August, both periods falling within the defined winter and summer seasons of November through May and June through October.

Chi square analyses of the joint occurrence of climatic types with periods show that their type 4 summers are strongly associate (P between .01 and .025) with the HAF period 1900-1908 (the more recent HAF period is beyond the range of the typing analysis) and perhaps type 3 winters.

Type 4 summers are characterized by a low pressure anomaly from Siberia to the Gulf of Alaska which feeds moisture and low temperatures across the entire United States. Hence, it appears that during the HAF periods the influence of the polar front may extend throughout the year in the Tucson area, which would account at least in part for the tendency of winter and summer precipitation to be directly correlated during these periods. It would also explain wet Mays, in that May is central to the dry time of year when the influence of the polar front normally is replaced by that of the Bermuda High in the Tucson area. If this shift fails to occur, and the polar front continues to influence the region, then May would be expected to be wetter than usual.

Type 3 winters show a strong positive pressure anomaly in the same general region where type 4 summers show a strong negative one. Polar trough formation off the west coast of the United States is indicated by a negative pressure anomaly in this region. In general, both the type 3 winter and the type 4 summer are consistent with a mean annual southward displacement of the polar front, and of the subtropical belt of high pressure. Dzerdzeevskii (1962, p334) citing Bezrukove, notes the inverse relationship between zonal and meridional circulation types and between solar activity (number and total area of sunspots) and meridional circulation. Solar activity has increased from a low value at the beginning of the 20th century, and meridional circulation has declined correspondingly as zonal circulation has increased. Both type 3 winters and type 4 summers occur most frequently during times designated by Dzerdzeevskii as being dominated by meridional circulation. In the 1900-1908 interval, both winter and summer had meridional flow, a condition not reoccurring subsequently except for the two year period, 1916-17. An interesting fact is that from 1917 to 1924 winters had zonal flow while summers had meridional, dominated by the almost exclusive occurrence of type 2 summers. This was going on at the same time that two sets of HAF fluctuations were occurring out of phase in a period of inverse correlation, and thus interfering destructively, in the two seasons, as noted above. In contrast, for the 1900-1908 interval, when both seasons had meridional flow, they were directly correlated, and the HAF fluctuations were interfering constructively. This lends further strength to the idea that the intervals of direct correlation are so correlated because of the year-round continuous dominance of the polar front.

The foregoing results suggest that the HAF periods in the Tucson November to October annual precipitation are associated with meridional circulation occurring in both winter and summer, and that the source of most of the moisture is the northern Pacific Ocean. The reason for the pronounced alternation of wet and dry years may have to do with biennial fluctuations in sea surface temperature (Douglas, 1974 and Pyke, 1972) which would affect the amount of precipitable water available to storms entering the United States.

As noted above, the year 1909 dramatically opened a long-persistent epoch of flash-flood erosion in the Four Corners region with the appalling late August storm which tore watersheds apart and lowered streambeds by tens of feet in places. The results of the analyses presented in this paper may shed some light on this remarkable change in erosion, which took place at the earlier period of HAF oscillations. What is proposed, tentatively, in this regard is that the presence of such oscillations, if they occurred generally throughout the Southwest and not just in the Tucson area, would have constituted a stress upon the ecology of watershed systems. Stenotypic species, especially shrubs, would have been adversely affected by the rapid alternation between wet and dry periods, and probably by the colder temperatures implied by the climate types as well, with the likely result that the herbaceous and shrubby vegetative cover would be severely reduced, thus rendering watersheds more vulnerable to flood erosion.

That meridional circulation was not the sole cause of the increased flood activity of the 20th century on Pine Creek is suggested by the analysis of the set of 10 cores from Bright Angel Creek (Table 3). Here, the cumulative increase in flood-related growth anomalies is closely matched by the cumulative increase in cores, and no increase in flood frequency is evident. The main difference between the Pine Creek and Bright Angel Creek watersheds is that the former has been subjected to intensive grazing and lumbering since the settlement of the Escalante area in 1875, while the latter has been relatively free of such activity. Sheep were removed from the Pine Creek range in 1955, at which time the range was rated as being in poor to fair condition (Dan Baird and Charles Birkemeyer, U. S. Forest Service, Escalante, personal communication). Note the decrease in flood activity indicated by Figure 3 for the period since 1955.

The research results favor the interpretation that the Pine Creek watershed, having been subjected to heavy land use, was rendered more susceptible to damage under a climatic change than the better protected Bright Angel watershed. If this is true, it suggests that the flood-rating of watersheds may not be representative of their long-term flood behavior prior to the inception of grazing and lumbering.

The data from the Animas River (Table 3) are too scant to allow the kind of analysis performed for Pine Creek and Bright Angel Creek, and Betatakin Canyon yielded so little useful information that it was decided that they were not worth analyzing, but the South Taylor Creek data (Table 3) proved to be of considerable interest. South Taylor Creek is in a section of Zion National Park that wasn't annexed until 1937, and hence was subject to unrestricted land use until that time. The record shows a considerable increase in flood frequency from 1900 to 1937, and then a sudden decrease in frequency thereafter. This further strengthens the idea that land use may be a--or the--major factor in the frequency of damaging floods in some western watersheds.

Perhaps the most interesting discovery of the Taylor Creek study was in connection with two large rockfall dams in the drainage, one breached dam where the road first crosses South Taylor Creek about three miles up the canyon from its intersection with Interstate 15, and another, larger, unbreached dam about a mile farther up in the drainage. Permanent growth suppression in a Douglas fir (#TC1-PM-1NE) growing on the interface between a steep bedrock apron of mid-Mesozoic aeolian orthoquartzite (Navajo sandstone) and valley fill on the south side of South Taylor Creek canyon gives a date of 1740 A.D. for the breaching of the lower dam, allowing the creek to incise its channel in the valley fill and exposing the root system of the tree.

The time of formation of the upper rockfall dam is indicated by an extreme growth suppression from 1469 to 1478 A.D. in a very old ponderosa pine (the inside ring is 1386 A.D.). This tree was partially buried by debris from the rockfall which forms a steep embankment rising from gentler ground beyond the base of the tree.

Alluvium and colluvium have nearly filled the valley behind the dam, and there is a small, probably intermittent pond terminating this apparently internal drainage. No outlet could be found over the dam, so evidently flood runoff that caused erosion downstream recorded in tree rings must have been contributed from areas of the watershed below the dam. A dense forest of boxelder (Acer negundo), bigtooth or Wasatch maple (Acer grandidentatum) and occasional white fir (Abies concolor), all more or less buried in alluvium, extends from the dam eastward to the head of the drainage. It seems likely that this dam will be breached as soon as the valley fill rises high enough behind it to permit flow over the dam, or an unusually heavy storm produces enough runoff to fill the reservoir beyond capacity. Certainly, it merits consideration as a prime geologic hazard to the valley and the piedmont alluvial plain below, and efforts to construct some sort of stable overflow channel would undoubtedly be well spent.

IV. Conclusions

The methods of riparian dendrochronology as outlined in the foregoing discussion appear to be useful in deciphering the history of destructive flood occurrence in ungaged watersheds, particularly where large samples can be taken. The 106 cores from Pine Creek seem to have been quite adequate in reconstructing flood occurrence in that drainage, and while the eight and ten cores from Taylor Creek and Bright Angel Creek, respectively, yielded valuable information, larger samples would undoubtedly have given a clearer picture. In the former case, not much more material was available for sampling, and in the latter, collecting was curtailed by a short time schedule.

Perhaps the most cogent inferences to be drawn from this study are that human land use may be far more significant than generally allowed in its impact upon the flood behavior of western watersheds, and that land use effects, in combination with the kinds of climatic change discussed above, may cast doubt on the validity of traditional approaches to flood frequency analysis in gaged watersheds, in which stationarity of the time series is presupposed. Further studies of this type would serve to substantiate or refute these inferences.

V. References

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Table 1. Characteristics of Watersheds Studied

	Pine Creek	Bright Angel Creek	South Taylor Creek	Animas River
Location of outlet	37°46'30"N 111°34'19"W	36°05'57"N 112°05'33"W	37°27'46"N 113°11'41"W	37°48'32"N 107°39'34"W
Elevation of outlet	5650'	2400'	5450'	9305'
Maximum relief	5087'	(6800')	2585'	4555'
Approximate area, mi^2	95	120	1.25	75
Lithology	Mesozoic sandstones and shales, Oligocene basalt	Archaean schists, Paleozoic sandstones, shales and limestones	Mid-Mesozoic sandstones	Miocene volcanics
Basin order (Strahler)	4th	4th	1st	4th
Vegetation (order of frequency)	Pp,Js,RF, PM,So,Bo, Ppg,Pt,Paf	Aco,PM,Hd, Rsp,Pp,Rn, QG,So	Ag,An,QG, Aco,PM,Pp, So	Peg,Ssp, Pfr,Li

Species

Pp	ponderosa pine.	Hd	mountainspray
Js	Rocky Mt. juniper	Rsp	currant species
RF	Fendler rose	Rn	New Mexican locust
PM	Douglas fir	QG	Gambel's oak
So	mountain snowberry	Ag	Wasatch (bigtooth) maple
Bo	western birch	An	boxelder
Ppg	blue spruce	Peg	Engelmann spruce
Pt	aspen	Ssp	Willow species
Paf	narrowleaf cottonwood	Pfr	shrubby cinquefoil
Aco	white fir	Li	black-berried honeysuckle

Table 2. Environmental conditions for maximum growth increase in ponderosa pine at Pine Creek, near Ecalante, Utah. A plus indicates an increase in the variable relative to the preceding year, a minus indicates a decrease. A circle indicates beyond the 95% confidence limit. Otherwise beyond the 90% limit.

					Prior growing season												Current growing season			
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A
Precipitation				⊕								⊕	⊕	+						
Snowfall	−										⊕	+	⊕		+					
Wat. Eq. Sno.	−	⊖	⊖									+	⊕	⊕	⊕	+				
Temperature		⊕		⊖							⊖	⊖		−	⊖				⊖	+
Pal. Dr. I.		⊖											+	+	⊕	⊕	⊕	⊕	⊕	⊕
Runoff								−		⊖	⊖	⊖				⊕		⊕	⊕	⊕

Wat. Eq. Sno. = Water equivalent of snowpack
Pal. Dr. I. = Palmer drought index

Table 4. Rainfall amounts at Escalante, Utah, which may correspond with principal flood events in Pine Creek watershed.

YEAR	DATE		RAINFALL (")	% OF CORES HAVING ANOMALIES
1909m	8/30-9/1	1909	3.80	31
1914m				5
1916m	10/6	1916	3.39	7
1917	----			5
1919m	2/1	1919	1.50	5
1920m				6
1933	11/29-30	1933	1.91	7
1937	8/27-30	1937	1.88	5
1939	9/4-6	1939	2.92	5
	9/10-12	"	1.65	
1940	9/16-17	1940	1.62	12
1941m	10/2-3	1941	1.69	8
	10/20-23	"	2.62	
1945m	8/11-12	1945	1.30	5
1949m				8
1950	7/7-8	1950	?	7
1952m	9/20-21	1952	1.32	8
1954m				5
1969	----			7

Data from U.S. Weather Bureau
m = some missing data

Table 3. Flood events recorded by tree rings in 4 watersheds. E = events, C = available cores, I = cumulated events divided by cumulated cores, AR = Animas River, PC = Pine Creek, TC = South Taylor Creek, BA = Bright Angel Creek.

	AR	PC			TC			BA		
	E	E	C	I	E	C	I	E	C	I
1705		1	6	0.17		1				
10						2				
15										
20						3				
25										
30										
35					1					
40			7	0.14	2		1.00			
45										
50			8	0.13						
55										
60									1	
65			9	0.11				1		1.00
70		3		0.44	3		2.00			
75										
80										
85			10	0.40						
90			11	0.36				1		2.00
95										
1800										
05		1		0.45						
10			12	0.42					2	
15		1		0.50						
20										
25		2		0.67	1		2.33	2		2.00
30									3	
35		1	16	0.56						
40		1	18	0.56						
45		1	19	0.58				1		1.67
50			20	0.55						
55		1		0.60		4		1		2.00
60		1	22	0.59	1	5	1.60			
65			25	0.52						
70		1		0.56	1	6	1.50	1		2.33
75		1	27	0.56				2		3.00
80		2	31	0.55				1		3.33
85		4	34	0.62	1		1.67	2	5	2.40
90		5	40	0.65		8		2		2.80
95		1	43	0.63						
1900		3	51	0.59	1		1.38			
05		20	55	0.91	2		1.63		6	
10		7	59	0.97	1		1.75	1	7	2.14
15		11	64	1.06	1		1.88			
20		9	70	1.10	3		2.25	1	9	1.78
25	1	10	77	1.13	2		2.50	4		2.22
30		12	88	1.13	1		2.63	1		2.33
35		21	95	1.26	5		3.25		10	
40	1	20	03	1.36				1		2.20
45	1	18		1.53				4		2.60
50	3	21		1.74	1		3.38			
55		8	106	1.76						
60	2	8		1.84	2		3.63	2		2.80
65		9		1.92	1		3.75	1		2.90
70	1	1		1.93				3		3.20

FIGURE 1

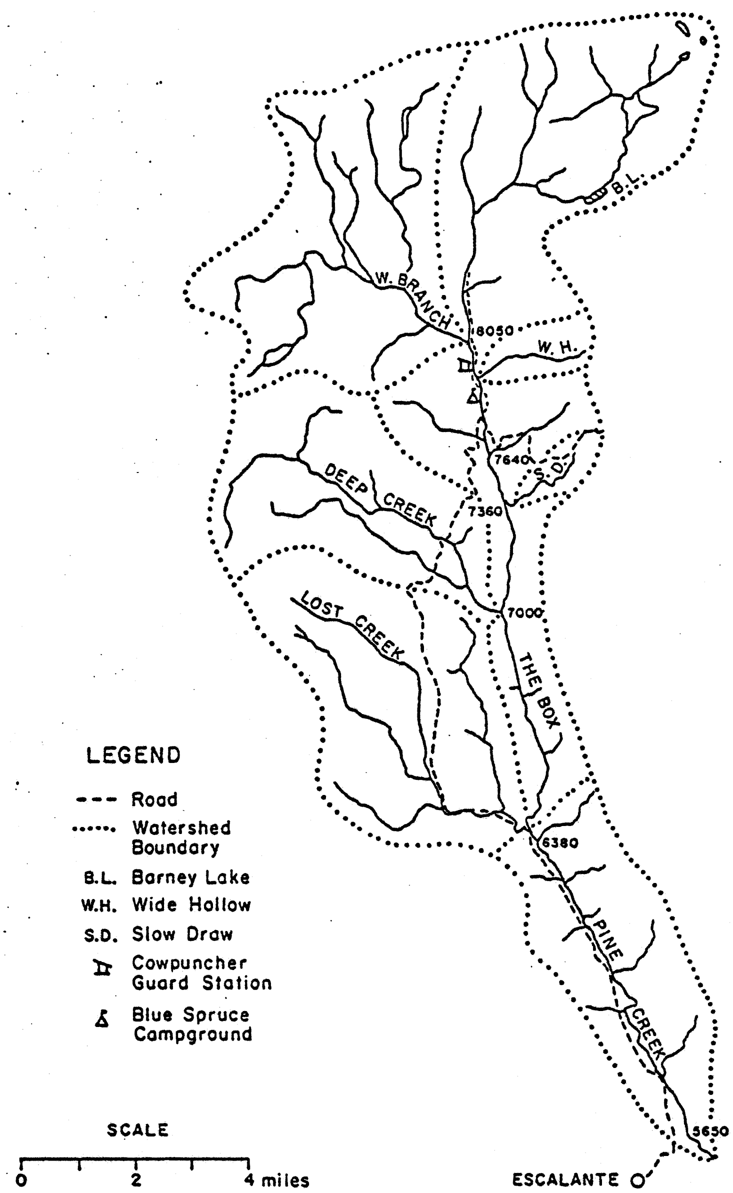

Figure 1. Pine Creek watershed at Escalante, Utah. Elevations in feet are shown along the trunk stream. Collecting sites are distributed along Pine Creek and the lower reaches of Lost Creek, Deep Creek, West Branch, Wide Hollow and Slow Draw between 6290 and 8500 feet elevation. Between 6380' and 7640' elevation, Pine Creek flows through a deep, narrow canyon (The Box) in the Jurrassic Navajo sandstone where the stream has been superposed on the steep west flank of the northwest-trending Escalante anticline.

FIGURE 2

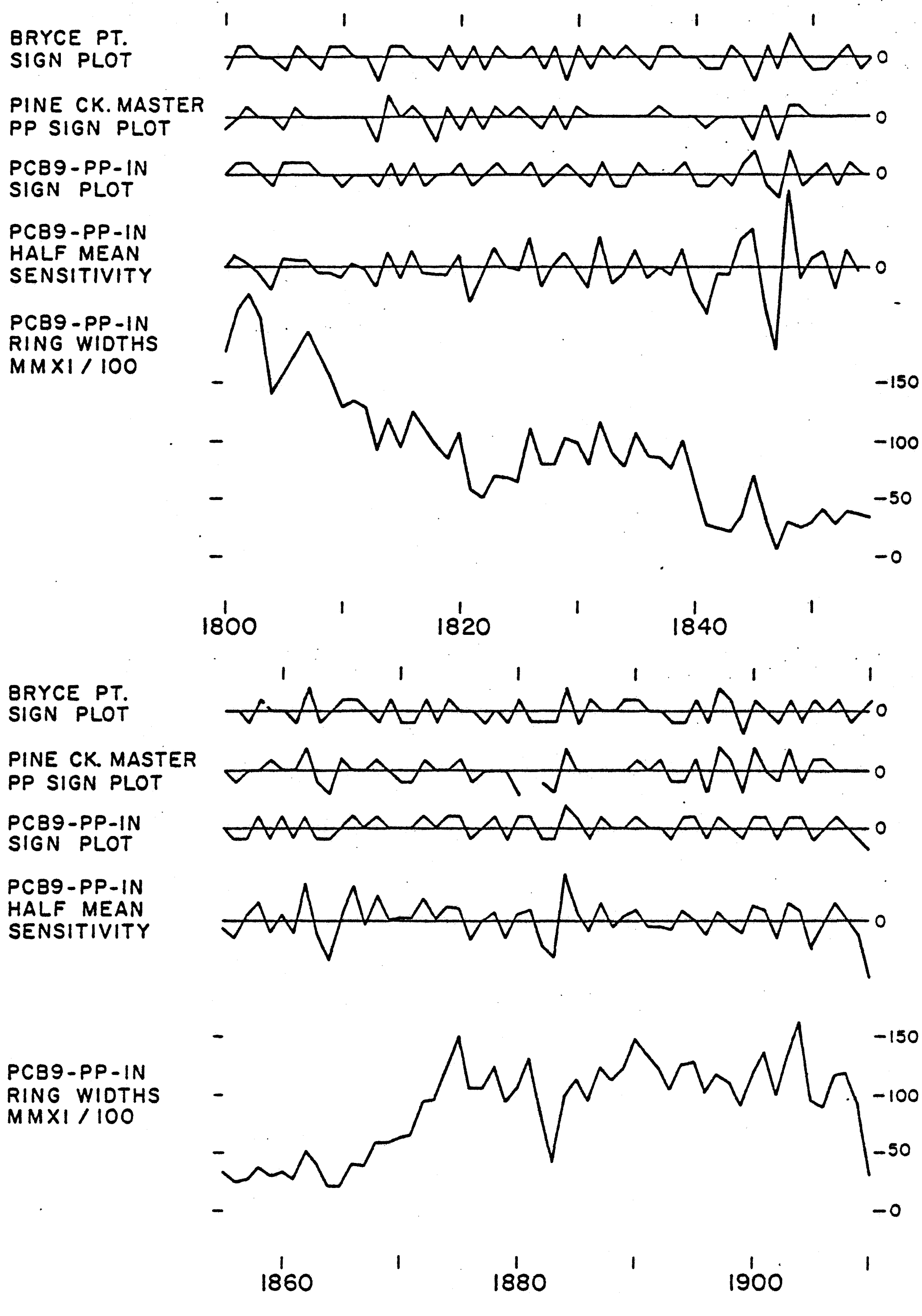

Figure 2. Crossdating and anomaly spotting. The lowest plot of measured rings (Hundredths of a mm) from a flood-damaged ponderosa pine growing in the lower end of the Box (Fig. 1) about a mile up Pine Creek from its confluence with Deep Creek. This plot shows severe and semi-permanent growth suppressions in 1841 and 1910, which are interpreted as being flood-related. The tree was suspended on steep sandstone ledge with its root crown about 9 feet above the present stream bed, indicating that much scour in the flood of 1909. Above this plot is a half mean sensitivity transform of the same series (see Text). Next above is a sign plot of the same series. (Note the close correspondence between these two). Second from top is a composite sign plot of eight cores from semi-arid site ponderosa pines near Pine Creek, and at the top is a sing plot of the Bryce Point Douglas fir tree-ring chronology. Note the excellent crossdating among the upper four series, placing the two growth suppressions exactly in time. Since ten rings were missing from the young end of the core from PCB9-PP-1N, a simple ring count would have given erroneous dates for these suppressions and the floods they represent.

FIGURE 3

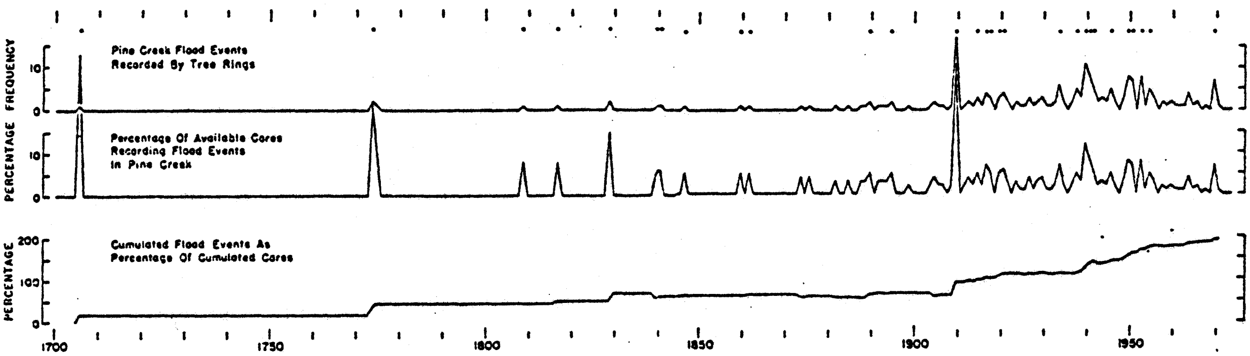

Figure 3. Frequency of destructive flooding in the Pine Creek watershed near Escalante, Utah. See text for explanation. Dots above the upper plot correspond with values of 5% or above on the second plot.

FIGURE 4

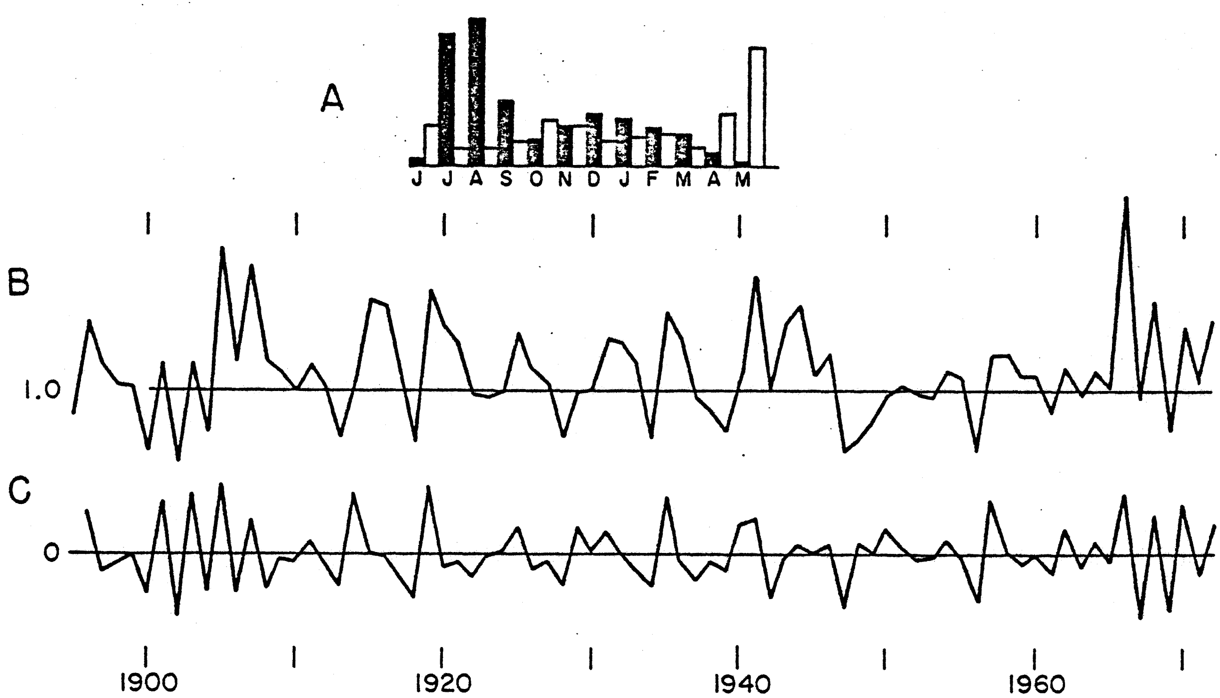

Figure 4. Analysis of the 1896-1972 precipitation record at Tucson, Arizona. 4A shows median values of precipitation for each month (black bars) and variability (white bars, see text). 4B is a plot of the total annual precipitation from November through October. 4C is a half mean sensitivity transform (see text) of the same annual series showing year-to-year variability. Note the random pattern between 1909 and 1965 contrasting with the regular, high amplitude, high frequency pattern between 1900 and 1908 and since 1966.