Inferences from Tree Rings on Low Frequency Variations in Runoff in the Interior Western United States

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ABSTRACT: Low frequency variations in runoff, AD 1700-1964, in the interior western United States are inferred from smoothed tree-ring series averaged over north, central, and south regions. Main inferences drawn from visual comparison of smoothed curves are that: (1) observed declines in the first half of the 20th Century have been the most severe back to at least AD 1700 in all regions, (2) low-flow periods have been more synchronous from north to south than high-flow periods, and (3) longer wavelength (60-70 years) variations have been more prevalent in the north than in the central and south regions. The central regional tree-growth series was found to track reasonably well the important low frequency variations in the Colorado River, 1906-1964. Relative locations of peaks and troughs in streamflow, precipitation, temperature, and tree-ring series suggest that annual precipitation and warm season evapotranspiration variations may both be important to low frequency fluctuations in tree growth and in streamflow.

INTRODUCTION

Historical streamflow anomalies have been recognized for some time as containing useful information on climate fluctuations over the United States (Hoyt and Langbein, 1944). A common feature in adjusted annual flow records of the Colorado River at Lee Ferry and the Columbia River at The Dalles is a relatively large low frequency component, manifested primarily by steep downward trends over several decades beginning in the late 19th or early 20th Century (Meko, 1985). Given the large size of the two drainage basins, it seems reasonable to conclude that runoff summed over large areas of the interior western United States also has a large low frequency component. Existing streamflow records are too short, however, for an adequate representation of low frequency variability.

In this paper, an attempt is made to gain a long-term perspective on the regional low frequency runoff variations of the past century using tree rings. The quality of the runoff signal in tree-ring data from various parts of the interior western United States was first demonstrated by Schulman (1951) using graphical methods and simple correlations. Subsequently, modern statistical transfer/function methods have been used in streamflow reconstructions (e.g., Stockton, 1975; Smith, 1979).

The present study is closer to the graphical approach in that no quantitative reconstruction of specific streamflow records are made using transfer functions. It differs from previous studies, however, in geographical extent, density of tree-ring coverage and manner of treatment of tree-ring data, and emphasis on the low frequency component of variability. Smoothed growth series from northern, central, and southern parts of the interior western United States are examined for relative magnitude of variations in the current century and for synchrony in timing of major wet and dry anomalies.

TREE-RING DATA

Regional tree growth series were formed from 146 drought-sensitive ring-width chronologies collected and developed between 1962 and 1984 by researchers at the University of Arizona Tree-Ring Laboratory (TRL). The study area reaches from central Montana and Idaho to southern Arizona and New Mexico. Methods of sampling and development of chronologies are described in detail elsewhere (Fritts, 1976).

A method of reducing the tree-ring data was adopted that would use all available drought-sensitive chronologies, deemphasize those not co-varying with nearby chronologies, and yield regional average series that could be compared without unduly weighting variations in areas of intense tree-ring collection. The 146 sites were first grouped on considerations of natural clustering and site density into the 20 groups shown in Figure 1. Principal components analysis was then done separately on the chronologies in each group, and the amplitude series of the first principal components were defined as "group" tree-ring series. Each group series was then converted to "Z-scores" by subtracting the mean and dividing by the standard deviation. Finally, the group tree-ring series were averaged into northern, central, and southern regional tree-ring series according to the boundaries shown by the heavy dashed line in Figure 1.

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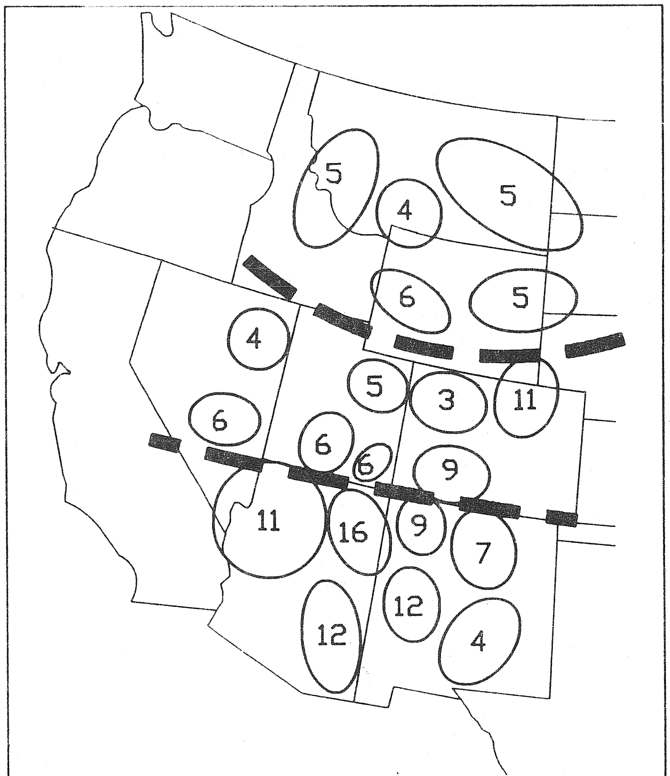

Figure 1. Locations of groups of tree-ring chronologies and number of chronologies in each group. Heavy dashed line shows division into northern, central, and southern regions.

STREAMFLOW DATA

A time series, 1906-1985, of *natural* annual flow of the Colorado River at Lee Ferry, Arizona, was obtained from the U.S. Bureau of Reclamation. The series represents flow adjusted for removal of anthropogenic influences such as withdrawals for irrigation and storage by reservoirs. Time variations in this series as they relate to streamflow variations in other parts of the West have been discussed by Meko and Stockton (1984) and Meko (1985).

CLIMATE DATA

Annual time series of **water year total precipitation** and **precipitation-weighted, warm season average temperature** averaged over the latitude/longitude range 36-40N, 106-109W, were computed using monthly station data from the F.T. Quinlan's Historical Climate Network (HCN) from the National Climatic Data Center. Both series are averages over 12 stations with records covering the period 1907-1984. Temperature was used – for lack of a better alternative – as an indicator of interannual variations in evaporation. May through October is defined as the *warm season,* and the computed temperature series is the average over those months weighted by the proportion of warm season precipitation falling in each month. This particular grouping and weighting was intended to emphasize interannual temperature variations in the warmer months of the year, when potential evapotranspiration is relatively high, and in the wetter months, when variations in potential evapotranspiration are most likely to translate into variations in actual evapotranspiration.

SMOOTHING

The tree-ring, streamflow, and climate series were each smoothed by the same low-pass filter before plotting to emphasize low frequency variations. This 11-weight, raised-cosine filter (Hamming, 1983) has a frequency response such that the amplitude of a sine wave with a period of 12 years would be reduced by half. Waves with periods less than 6 years would be eliminated entirely.

RESULTS

The single dominant feature of the smoothed tree growth plots (Figure 2) is the period of high growth about 1905-1920. The long-term anomalous nature of this period was noted previously by Fritts (1965) from spatial patterns of decadal average deviations in tree growth over the West and later by Stockton (1975) in a tree-ring reconstruction of the annual flow of Colorado River. All three regional tree-ring series in Figure 2 reached their record high levels in this period. The growth anomaly was most severe relative to previous anomalies in the central region, indicating an increase in storminess in that area relative to areas to the north and south. The north/south extent of the anomaly, at least in the early part of the 1905-1920 period, may reflect anomalous central development of storms, with precipitation increases extending north and south, or possibly a more longitudinal component rather than zonal orientation to storm tracks.

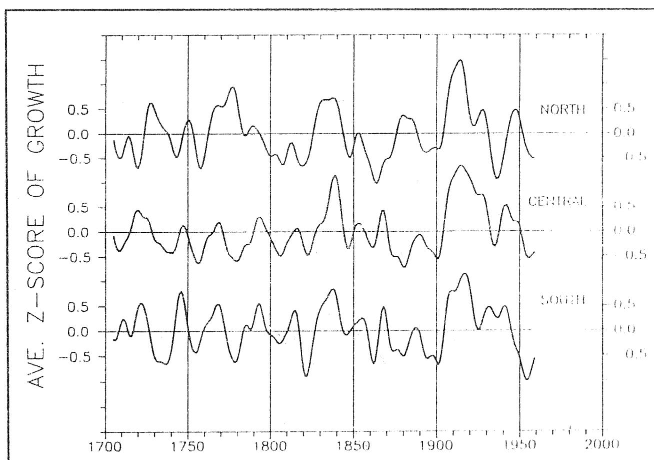

Figure 2. Smoothed annual series of regionally averaged tree growth.

Cayan and Peterson (1989) suggest that high streamflows from 1906-1910 in the northern part of the interior western United States were caused by an anomalous southern displacement of the winter storm track into the western United States associated through teleconnections with anomalously high sea level pressure (SLP) south of the Aleutian Islands. They also suggest increased activity from storms moving southward from Canada and Alaska east of the Cascades, a pattern that would be consistent with the exceptionally cold winter temperature anomalies in the interior West in the first two decades of the 20th Century (temperature curves in Bradley et al., 1982).

Longer wavelength fluctuations are more evident in the north than in the other two regions. An irregular periodicity of about 60-70 years is suggested by growth peaks in the north anchored near 1780, 1840, and 1915. Growth peaks near these years were also major components contributing to a significant spectral peak found previously in tree-ring data from the northwestern fringe of the Great Plains (Meko, 1982). The latter two peaks in the sequence also show up in the central and southern region plots, but the 1780 peak is conspicuously absent there. Instead, an irregular occurrence of about two peaks every 40 to 50 years is characteristic in the central and southern regions.

In spite of the obvious coincidence of the major growth peaks near 1838 and 1915 across regions, a close look at Figure 2 suggests that growth peaks generally were not synchronous from the southern to northern regions. A peak in one region was judged to coincide with a peak in another region if the year of the peak in the first region fell no more than a third of the way from a peak to the adjacent trough in the second region. Of the twelve largest peaks in the south, ten coincided with peaks in the central region, but only three coincided with peaks in the north. Low-growth anomalies were somewhat more coherent in space.

By a similar criterion as used for peaks, all of the ten identified deepest troughs in the south coincided with troughs in the central region, but only five of the ten coincided with troughs in the north. The results are consistent with meteorological data in that coherence of moisture anomalies decreases over distance, and dry periods appear to be more spatially coherent than wet (Julian, 1970).

The lack of synchrony between north and south at times deteriorated into a latitudinal contrast in sign of anomalies. Periods with a wet north and dry south are centered at 1778, 1880, and the late 1940s. Periods of marked opposite contrast – wet south and dry north – are centered at 1722, 1815, and 1868. The existence of north/south contrasts in both precipitation (Sellers, 1968) and streamflow (Langbein and Slack, 1982; Meko and Stockton, 1984) have been noted previously. Such periods of contrast may reflect unusual clustering of years with specific modes of anomalous atmospheric circulation. The wet south/dry north contrasts, for example, could be related to the El Niño phase of the Southern Oscillation (SO). The synoptic regime, as described by Cayan and Peterson (1989), is for low mid-latitude storms tapping moisture from the subtropical jet and bringing heavy precipitation to the Southwest.

Lough and Fritts (1985) list 1867, 1868, and 1869 as three of the most extreme low-index years in the period 1852-1900 by the winter SO index of Wright (1975). Interestingly, while the smoothed regional tree growth plots of Figure 2 are consistent with a low-index SO clustering at 1868, Lough and Fritts' (1985) SO tree-ring reconstruction based on a 65-station grid of pre-whitened tree-ring chronologies does not point out those years as anomalous.

Two possible explanations for the discrepancy are:

- Contamination of the SO signal at times from tree-ring sites outside the area of strongest related climate signal, and
- De-emphasis of clustering periods of SO anomalies due to the use of tree-ring series that have been pre-whitened in the reconstruction model.

The 20th Century stands out for the magnitude of the swing from high to low growth – starting at about 1915 in all regions, but ending in the 1930s in the northern region and the 1950s in the central and southern regions. Corresponding large streamflow trends in the study area in this century (Meko and Stockton, 1984) are, therefore, inferred to be at least 250-year extremes.

This conclusion cannot be generalized to include rivers with significant runoff-producing areas outside the interior western United States For example, the period of generally highest annual flows on the Columbia River at The Dalles was centered near 1896 (Meko, 1985), which from the northern region tree-ring series (Figure 2) would be inferred as a period of low runoff. The Columbia at The Dalles receives significant contributions of runoff from Canada and the U.S. Pacific Northwest. Apparently these areas and the northern region in Figure 1 were experiencing greatly contrasting runoff anomalies in the 1890s. As another example of the greater spatial coherence of dry relative to wet anomalies, however, the bottoming out of the growth curve for the north near 1940 does coincide with the record low-flow period for the Columbia at The Dalles.

How well do the regional tree-ring series reflect variations in runoff for specific watersheds? Ideal series for verification of the regional tree-ring series (actual runoff, summed regionally) simply do not exist, although it may be possible to eventually derive suitable regional runoff indices by adjusting streamflow records.

For present purposes, the natural flow series of the Colorado River at Lee Ferry was used as a preliminary attempt at rough verification for the central region growth series. Smoothed plots of Colorado River flow and central region tree growth (Figure 3, bottom) show that low frequency variations in growth generally track variations in flow. The major peaks and troughs in the tree-growth series all match up (though not in perfect timing) with similar features in annual flow. The major discrepancies are related to the early 1900s high runoff period, which is somewhat underestimated in magnitude relative to the wet period in the early 1940s. The year of peak runoff in the earlier period is also off by a few years.

The associated smoothed annual precipitation and weighted warm season average temperature are plotted at the top of Figure 3. The peak in the growth curve at

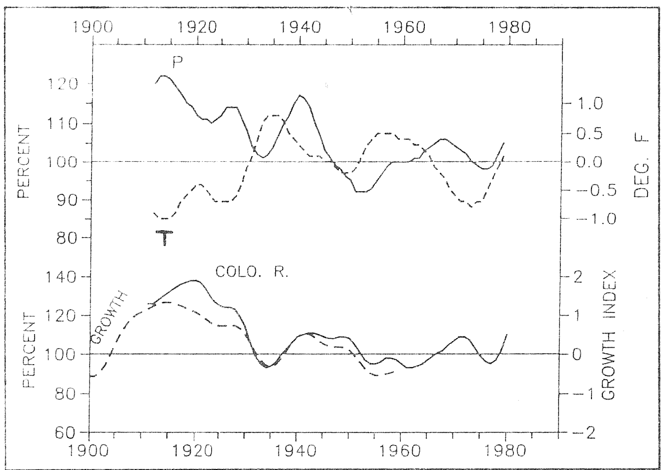

Figure 3. Comparison of selected streamflow, climate, and tree growth data for Colorado basin.
Bottom: Smoothed central region tree growth and annual virgin flow of the Colorado River at Lee Ferry, Arizona.
Top: Smoothed time series of water year total precipitation and precipitation-weighted warm season average temperature for area covering Colorado River basin. Precipitation and streamflow are given as percentages of 1951-1980 mean; temperature is given as departure from 1951-1980 mean.

about 1915 is seen to coincide with both the wettest annual and the coolest warm-season conditions in the instrumental record. From seasonal temperature and precipitation plots (Bradley et al., 1982), the period 1910-1920 was exceptionally cool and generally wetter than normal in fall, winter, and spring in Colorado and Utah. The snowpack was, therefore, probably anomalously heavy and retained unusually long into the warm season, giving ideal conditions for tree growth: gradual release of snowmelt to keep soil moisture high well into the growing season and low evaporative stress associated with cool spring and summer temperatures, probably with unusually cloudy conditions and high relative humidity.

Comparison of timing of peaks and troughs in the four series in Figure 3 suggests that low frequency variations in tree growth and runoff are associated with anomalies in annual precipitation and possibly warm season temperature. Tree growth peaks and troughs in Figure 3 are most extreme when temperature and precipitation anomalies are large and of opposite sign. Evidence of temperature (through evapotranspiration) influence comes mainly from difficulty in explaining magnitude or location of some growth peaks from precipitation alone. For example, growth minima near 1934 and 1956 both coincide with warm season temperature peaks and are deeper than growth anomalies in other periods with comparable precipitation anomalies. Support for a temperature effect on runoff is somewhat weaker: the relative severity of the streamflow minimum in 1934 appears to be greater than implied by the precipitation anomaly alone, and streamflow peaks centered at 1950 and 1972 coincide with temperature minima.

A more rigorous search for evidence of a relationship between annual runoff and temperature would require detailed examination of climate data at the seasonal resolution. A shift to a higher proportion of the annual precipitation falling in the cooler months, for example, would favor reduced net evapotranspiration and increased runoff. The increasing *winter* precipitation shown by Bradley et al. (1982) for Colorado over the period 1914-1920 is one possible explanation for the streamflow peak lagging a few years behind the annual precipitation peak at 1915 in Figure 3.

CONCLUSIONS

Recognizing that rigorous statistical tests have not been done here to establish the reliability of the runoff/tree growth signal, the following inferences are made on runoff variations in the interior western United States to AD 1700:

- Low runoff anomalies are more synchronous from north to south than high runoff anomalies.
- Longer wavelength variations (60-70 years) are more noticeable in the northern than in the central and southern regions.
- Downward trends in streamflow over the first half of the 20th Century are at least 250-year extremes.
- Periods of contrasting anomalies in the north and south are common, but exceptional periods of same-sign anomaly over a broad latitude range have occurred. The most prominent of these by far is the wet anomaly 1905-1920, which was most anomalous in the central latitudes.

Changes in seasonal distribution of annual precipitation are likely to distort the tree growth/annual runoff relationship. Fortunately for accuracy of reconstructions, development of a heavy snowpack favors both high annual flows and increased tree growth. Basins with a relatively large snowmelt component may be most amenable to accurate reconstruction of high annual flows. More research is needed on the statistical relationship of snowpack variations and tree growth.

Although low frequency variations in annual flow of the Colorado River are closely related to precipitation, interannual variations in evapotranspiration may help explain some of the details involved in the magnitude and timing of peaks and troughs.

The approach used here can be extended in time by studying subsets of longer length tree-ring series after first establishing that they retain the low frequency variations shown by the relatively dense network used in this study. Another possible extension is to concentrate field collections in areas where streamflow and climate data appear to be most sensitive to circulation indices (e.g., Southern Oscillation) to maximize the climatic value of the tree-ring data.

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