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DROUGHTS IN RIVER BASINS OF THE WESTERN UNITED STATES

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Abstract. Tree-ring reconstructions of centuries-long streamflows in four river basins of western United States were used to assess the severity, frequency and distribution of duration of droughts in the basins, and the probability of extreme drought in well-populated areas of California and Arizona. Our results show (i) greater long-drought threat than that inferred from historical streamflow records; (ii) weak statistical dependence of streamflows across the river basins; and (iii) significant probability of droughts in individual river basins.

Introduction

The use of tree-ring chronologies has proven to be very valuable in the analysis of long-term hydroclimatic phenomena [e.g., Stockton and Meko, 1975; Fritts, 1976; Michaelsen et al, 1987; Briffa et al, 1990]. The basic idea in tree-ring based hydrologic studies is to use the growth of tree rings in species of trees that are sensitive to key hydroclimatic variables (e.g., precipitation and temperature) to reconstruct the long-term behavior of important hydrologic variables such as streamflow [Stockton, 1971]. A general expression relating the hydrologic variable of interest, Y (in our case streamflow), and the tree response variable, X (typically tree-ring widths, but could include others such latewood density), is of the form:

$$Y_t = \sum_{q=1}^{M} \sum_{r=1}^{N_q} \sum_{s=0}^{P_q} \alpha_{q,r,s}\, X_{q,r,t+s} + \xi \qquad (1)$$

in which $\alpha_{q,r,s}$ is the regression coefficient for the q–th response variable at the r–th sampling site at time lag s; $X_{q,r,t+s}$ represents the value of the q–th response variable sampled at the r–th site at time t+s; the q–th response variable can have time lags of up to order P_q, implying that the current value of, say, streamflow, is related to current and future (up to a time lag of P_q) values of the q–th response variable (see, for an example of lagged dependence [Briffa et al, 1990]; ξ is a random term of zero mean and constant variance. The typical approach in tree-ring hydrology is to estimate the α coefficients based on contemporaneus time series of tree-ring widths and instrumental records of streamflow (the hydrologic variable par excellence). After this calibration stage, long-term tree-ring chronologies are used to reconstruct (annual) streamflow for periods predating the instrumental record by means of equation 1. Verification of the predictive skill of the reconstruction equation 1 is most accurately assessed by the method of cross-validation, discussed at length in Michaelsen (1988).

In this study, tree-ring based reconstructions of annual streamflow in the Sacramento basin (includes the American, Feather, Sacramento and Yuba rivers of California, Earle and Fritts, 1986, and extends from 1560 to 1980), the Southern California basin (from the Ventura to the Tijuana rivers of California, Michaelsen et al, 1990, and extends from 1460-1966), the Upper Colorado river draining at Lees Ferry, Arizona (just above the Grand Canyon, Michaelsen et al, 1990, from 1568-1962), and the Lower Colorado river draining at the confluence with the Gila river (Michaelsen et al, 1990, from 1575 to 1962), were used to ascertain the likelihood of simultaneous drought occurring in the aforementioned basins. (The time series of reconstructed annual streamflows are published in Michaelsen et al, 1990). The occurrence of such droughts will pose the most critical stress on the vast water supply systems of the arid West, including the Central Valley and State Water projects of California and the Central Arizona project [Loaiciga and Marino, 1985]. Figure 1 shows a map of the study areas, that extend over seven states of the arid western United States.

Tree-ring Hydrology and Droughts

Droughts are a distinct type of natural disaster. Unlike floods, earthquakes, wildfires, tornadoes, earthslides, tsunamis and volcanic eruptions (to cite some notorious examples), droughts are protracted. They can last from a few years to several decades (an example is the 1276-1300 drought that might have caused the abandonment of Mesa Verde cliff dwellings in southwestern Colorado). The ecologic and economic impact of droughts exceeds in many instances the combined effects of other natural hazards in a region. For example, the current California drought, now in its sixth year, has taken a toll of close to $20 billion in decreased economic output [Loaiciga et al, 1991)].

In spite of their significance as a natural disaster, droughts remain one of the least studied and understood phenomena. Precipitation and streamflow records in the arid western United States do not exceed 150 years in duration. Major streams such as the Colorado and Sacramento rivers have stream gage records starting in the early 1900's. These instrumental records are too short to provide a reliable description of the nature of drought recurrence. To illustrate, the Sacramento river basin of California has had two runs of below-median annual streamflow lasting five or more years, the first from 1928 to 1937, and the second started in water year 1986-87 and is still ongoing. If one were to infer from the instrumental streamflow record the average recurrence time elapsing between such droughts, we would have a sample size of one, with the only interarrival time being 49 years. If the average recurrence time of below-median streamflow droughts that last at least five years were, say, 50 years, a time series of at least 500 years would be needed to be able to make useful inferences about such type of droughts.

It is clear from the previous example that the instrumental records are not sufficiently long for the study of droughts. Tree-ring reconstructions of streamflow spanning several centuries become essential for the analysis of hydrologic drought. In this study, and based on previous work by [Loaiciga, 1989] a hydrologic drought is defined as a condition where annual streamflow falls below median level for three or more years in a row. In most circumstances in the agricultural and urban lands of the desert

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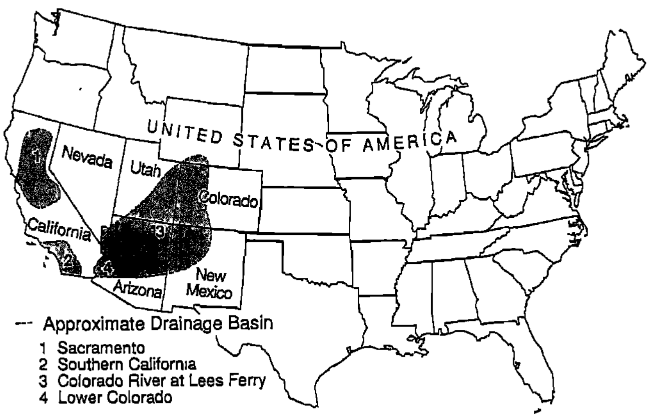

Fig. 1. Location of study areas

southwest of the United States, this condition of low surface moisture begins to exert measurable economic and ecologic impact. The available reconstructed annual streamflow time series for the study areas shown in Figure 1 range from approximately 400 to 500 years, an adequate range of length for the probabilistic characterization of droughts as defined herein. Critical droughts, defined by streamflow falling below 50% of the annual median for two or more years in a row, such as the 1976-77 California drought, are of interest but their rare occurrence (only one event since the start of streamflow measuring in California in the early 1900's) requires very long streamflow reconstructions for reliable probabilistic assessment to be attainable. Such lengthy time series are not available for the study areas at this time.

Tree-ring reconstructions of precipitation and streamflow have been previously used for the purpose of drought analysis in the western United States [Schulman, 1947; Stockton and Meko, 1975; Stockton and Jacoby, 1976; Meko et al, 1980; Smith and Stockton, 1981; Stockton and Meko, 1983; Earle and Fritts, 1986; Graumlich, 1987; Michaelsen et al, 1987; Loaiciga et al 1991; Haston, 1992]. The results presented in this work are innovative relative to previous drought studies in two respects: (i) the analysis and results concern the joint or simultaneous occurrence of drought across river basins; and (2) theoretical results are provided on the probabilistic structure of simultaneous drought. Our study emphasis the multiple random nature of droughts, where their level (or severity, as measured, say, by below-median streamflow conditions), duration, and recurrence must be taken into account in order to properly characterize drought behavior.

Droughts as a Renewal Process

Figure 2 shows our conceptual representation of drought incidence as a stochastic process. The duration of drought is a random variable D; the time elapsing between the end of a drought and the initiation of the next one is denoted by τ; the sum of D plus τ is R, the total time elapsing between the initiation of consecutive droughts; $N(t)$ is the number of droughts in a time period t. The representation of Figure 2 applies equally well to the recurrence of droughts in one basin or to the their simultaneous occurrence in two or more basins. The latter case refers to below-median annual streamflow conditions in two or more basins simultaneously for at least three years (the median annual streamflows are 17,495, 747, 13,757 and 17,457 KAF for the Sacramento, Southern California, Colorado river at Lees Ferry and Lower Colorado streamflows, respectively, where a KAF - one thousand acre-feet- equals $1{,}233.5 \times 10^3\ m^3$). Figure 3 shows the

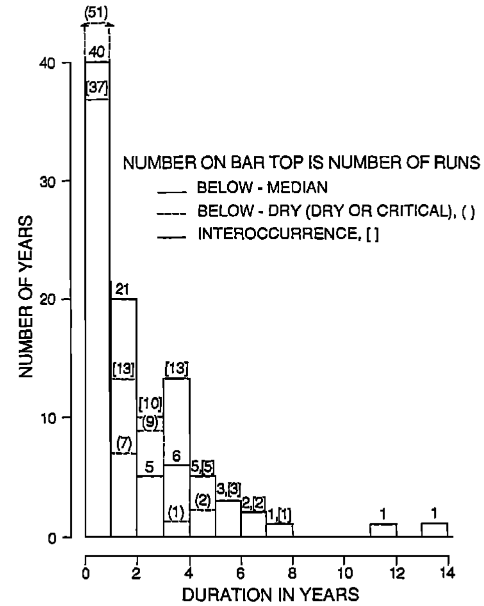

Fig. 2. Drought recurrence as a renewal process

histogram of below-median, above-median (this is the interocurrence time in between below-median events) as well as critical (i.e., 50% of median) runs of annual streamflow in the Sacramento basin. It can be seen the geometric-like decay in the distributions of duration of dry runs and interarrival times. Loaiciga et al (1991) have established the independence of drought duration D and elapsed time τ, and, therefore, the occurrence of below-median droughts in the study areas constitutes a renewal process [Parzen, 1964], a result of utmost importance in the analysis of drought recurrence.

In order to assess the average interoccurrence of below-median droughts in the study areas one can use a fundamental result of renewal theory (see, e.g., Ross, 1985) that states that the number of events (in our context, droughts) in a period t, $N(t)$, divided by t converges to μ^{-1} when the time interval t is sufficiently large, where μ denotes the expected value of the renewal time (i.e., $\mu = E(R)$), or

$$\frac{N(t)}{t} \to \mu^{-1}, \qquad t \ \mathit{large} \tag{2}$$

Result 2 was used in estimating the average time elapsing between below-median droughts lasting three or more years in individual basins as well as in two or more basins simultaneously. To estimate the average return time one must divide the period length (in years) by the number of droughts that occurred in the basins during that period.

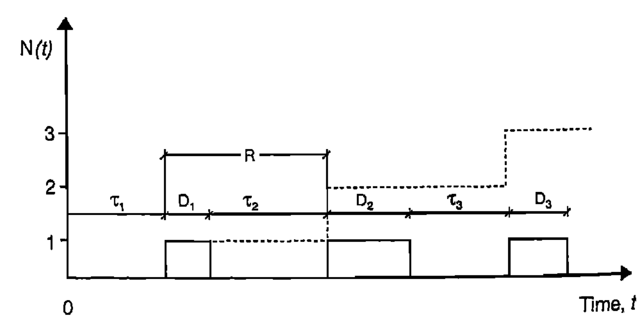

Fig. 3. Histograms of drought duration and interoccurrence

Table 1 summarizes the results for the estimates of the average interocurrence times of droughts in the study areas (a simultaneous drought lasting at least three years occurs whenever below-median streamflow conditions prevailed in the basins concurrently for at least three years). Notice in Table 1 that for the four basins there were no simultaneous droughts registered by the tree-ring reconstructed streamflows and it was not possible to estimate the average recurrence time. For three basins the average recurrence time is approximately equal to or in excess of 100 years. These long average recurrence times can be misleading, however, in assessing drought threat because drought occurrence in single basins that are critically important, such as the Sacramento and Upper Colorado river at Lees Ferry, represent a significant threat on their own right. The estimates in Table 1 indicate that, on the average, one can expect below-median droughts lasting at least three years once every 18 and once every 15 years in the Sacramento and Upper Colorado basins, respectively. For two basins at a time, it follows from Table 1 that simultaneous drought in California (i.e., in the Sacramento and Southern California basins) is to be expected once every 45 years. Interestingly, there have been two such events since the inception of streamflow gaging (i.e., a period of about 87 years), which yields an estimate of the recurrence time based on the historical record of about 44 years, in good agreement with the long-term estimate derived from the reconstructed streamflows.

The relatively long average recurrence times for simultaneous droughts reported in Table 1 reflect a weak correlation of hydrologic conditions in California and Colorado river basins. This situation arises from complex climatic systems that govern atmospheric transport and surface moisture in the form of snow and rainfall in those basins. The major sources of precipitation in the four studied basins are midlatitude winter storms, although the Colorado river basins receives substantial summer rainfall from summer convective activity. Drought in any basin is produced by persistent pressure blocking ridges in the westerlies. Given the large size of the Colorado basin and its distance from California, it is not common to find blocking ridges dominating both basins simultaneously. (The winter of 1976-77 is a counter example). The relatively long average recurrence interval of simultaneous drought in the Sacramento and Southern California basins suggests that droughts are not frequently of equal severity throughout the State. Periods of strong pressure blocking in the westerlies and concomitant drought in Northern California are often associated with southwesterly flow into southern California, bringing in enough storms to moderate the drought there. On the other hand, during periods of severe drought in southern California the storm track will often penetrate far enough south to produce at least moderate precipitation in northern California [Cayan and Roads, 1984].

Drought Durations and on Renewal Times

Duration is another important variable in the study of droughts. Figure 3 has shown the frequency distribution or histogram of below-median droughts in the Sacramento basin. Similar histograms can be constructed for the basins individually or for combinations of them. The empirical frequency, F_D, is the proportion of times that streamflows were simultaneously below-median for D consecutive years in one or more basins. It is calculated by dividing the number of below-median runs that lasted D years by the total number, m, of below-median runs of durations 1,2,3,.... (for example, in reference to Figure 3, the frequency $F_4 = 6/85$). A 95% confidence interval $C.I._{0.95}^{D}$ for the probability that a D-year run of below-median annual streamflows occurs simultaneously in one or more basins is given by [Loaiciga, 1989]

$$C.I._{0.95}^{D} = F_D \pm 1.96\, S_D \quad (3)$$

where

$$S_D = \left[F_D\ (1 - F_D)/\ m \right]^{1/2} \quad (4)$$

Table 2 summarizes the probability estimates (in percent) for below-median droughts that last at least three years. The numbers within parentheses are the midpoints of the 95% confidence intervals of the probability estimates. For single basins the probabilities are in all cases larger than 1/4. For two and three basins they range between 4 to 10 % and 2 to 4%, respectively. For the four basins considered simultaneously there were no events of simultaneous droughts registered in the reconstructed streamflows yielding a probability estimate of zero. Had the reconstructions been much longer, unquestionably the four basins probability would have had a finite, nonzero value.

Besides the important results concerning return intervals and probabilities of duration of simultaneous droughts, streamflow reconstructions facilitate fitting theoretical models to variables such as the renewal time R of drought recurrence (see Figure 2). For example, when the drought duration D and the interarrival time τ in Figure 2 are independent and geometrically distributed [Loaiciga and Marino, 1991] with parameters p_1 and p_2, respectively, the distribution of the renewal time R becomes

$$P(R = n) = [\ (p_2^*)(p_1^*)\ p_1^n - (p_1^*)(p_2^*)\ p_2^n\ ]/\ p^* \quad (5)$$

where $n = 1,2,3,\cdots$; $p_1^* = 1 - p_1$; $p_2^* = 1 - p_2$; $p^* = p_1 - p_2$; and $p_1 > p_2$. The parameters p_1 and p_2 are estimable from the data on drought duration and interarrival times. Upon fitting the theoretical probability of equation 5, a number of important questions can be addressed on drought phenomena, such as the probability of having at least one drought in an n-year period (i.e., the risk), the expected value and the number of droughts in an n-year period, and the like. The richness of issues that can be addressed demonstrates the value of having long-term

Table 1. Average recurrence times (in years) of below-median droughts lasting at least three years

Single basin	$(18)_1$		$(14)_2$		$(15)_3$	$(16)_4$
Two basins	$(45)_{12}$	$(44)_{13}$	$(65)_{14}$	$(23)_{23}$	$(65)_{24}$	$(30)_{34}$
Three basins	$(99)_{123}$		$(196)_{124}$	$(196)_{134}$		$(196)_{234}$
Four basins				*undetermined*		

The numbers within the parentheses are the average recurrence times in years. The subindices represent combinations of river basins for which the recurrence times were calculated, with 1, 2, 3, and 4 representing the Sacramento, Southern California, Upper Colorado (Lees Ferry) and Lower Colorado basins, respectively.

Table 2. Probability (in percent) of below-median droughts lasting at least three years

Single basin	$(28)_1$		$(29)_2$		$(42)_3$	$(26)_4$
Two basins	$(6.0)_{12}$	$(7.0)_{13}$	$(4.7)_{14}$	$(9.7)_{23}$	$(4.4)_{24}$	$(8.6)_{34}$
Three basins	$(4.0)_{123}$		$(2.6)_{124}$	$(2.4)_{134}$		$(2.0)_{234}$
Four basins				$(0.0)_{1234}$		

The numbers within the parentheses are the midpoint probabilities (in percent) of the 95% confidence intervals. The subindices represent combinations of river basins for which the joint probabilities were calculated, with 1, 2, 3, and 4 representing the Sacramento, Southern California, Upper Colorado and Lower Colorado basins, respectively.

streamflow reconstructions from which to draw accurate statistical and probabilistic inferences.

Conclusions

This study has applied methods of probability and statistics in conjunction with long-term tree-ring reconstructions of streamflow in a novel approach to discern the simultaneous behavior of drought recurrence and duration in important river basins of the arid western United States. The average recurrence time of droughts was derived for individual basins and combinations of basins. It was found that even though simultaneous droughts in two or more basins tend to have relatively large average return intervals (over 100 years for three basins), the return intervals for single basins indicate a rather frequent drought incidence (more than once every 20 years), and, therefore, considerable drought hazard in the study areas.

Similarly, the results for the probability of duration of droughts indicates that for individual basins the estimates of the probabilities of a drought lasting at least three years are all larger than 25%, whereas the same probabilities drop below 10% when combinations of two or more basins are considered. The low probabilities associated with two or more basins reflect a low hydrologic dependence across the study areas, a consequence of the complex climatic systems that govern surface moisture in the the studied river basins. Lastly, we have shown by theory and analysis that long-term tree-ring reconstructions of streamflow provide a means for a complete characterization of the probabilistic structure of droughts in ways that are not feasible by other traditional hydrologic methods and models.

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