VOLUME

HYDROLOGY and WATER RESOURCES in ARIZONA and the SOUTHWEST

PROCEEDINGS OF THE 1971 MEETINGS OF THE
ARIZONA SECTION—
AMERICAN WATER RESOURCES ASSN.
AND THE
HYDROLOGY SECTION—
ARIZONA ACADEMY OF SCIENCE

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TABLE OF CONTENTS

AUGMENTING ANNUAL RUNOFF RECORDS USING TREE-RING DATA

Charles W. Stockton and Harold C. Fritts

Laboratory of Tree-Ring Research
The University of Arizona, Tucson, Arizona 85721

INTRODUCTION

Any statistical work involving hydrologic records is handicapped when the records are of relatively short duration, as are most such records in the Southwestern United States. This is because the short records are not necessarily a random sample of the infinite population of events, and consequently any statistical descriptions are likely to be in error to some extent.

Work recently completed at the Laboratory of Tree-Ring Research [*Stockton*, 1971] has shown that tree-ring data can be used to extend available runoff records backward in time, thereby providing a longer record from which to more accurately estimate the three most common statistics used in hydrology: the mean, the variance, and the first order autocorrelation.

STATISTICAL PARAMETERS

In statistical analysis of hydrologic phenomena, it is usually assumed that a record of events that is of finite length represents a random sample from an infinite population, the occurrence of each event being governed by some probability distribution. Any change in the hydrologic regime with which a given record of events is associated results in a change in the probability distribution.

For practical purposes, a probability distribution is described by the mean (a measure of central tendency), the variance (a measure of the average spread of the events about the mean), and the skewness (a measure of the asymmetry of the distribution of the events about the mean). In some cases these three parameters uniquely define a probability distribution and are useful for describing hydrologic phenomena. For most annual runoff and tree-ring index series, the variables are normally distributed (skewness equals zero) and the probability distribution is completely described by the mean and variance. In almost every mathematical model of runoff time series, the first order autocorrelation (a measure of persistence in a series of events) is used along with the mean and variance.

The population values of these statistics are usually unknown and therefore must be estimated from the existing record of observations. Consequently, the reliability of the estimates depends primarily upon the length of record of the observations—in other words, the total number of observations.

If there are errors in the estimates of the population parameters owing to shortness of observed records, these errors are preserved in any synthetic series that is generated from the available data. Recently, *Rodríguez-Iturbe* [1969] showed that if the length of an annual runoff record is 40 years or less, there may be an error of 2% to 20% in estimation of the mean, from 15% to 60% in the estimation of the variance, and as much as 200% in the estimation of the first order autocorrelation. The high error in the autocorrelation is probably related to the inadequacy of short records for estimation of the low-frequency persistence in climatologic data, which *Mandelbrot and Wallis* [1968] have dubbed the "Noah and Joseph effects" after the well-known Biblical calamities.*

Fiering [1962], *Matalas and Jacobs* [1964], and *Julian and Fritts* [1968] have demonstrated the use of the correlation technique for augmenting hydrologic records. In each of these cases, a *single* record was used to augment another. *Fiering* [1963] also approached the problem using multiple linear regression—that is, using several independent variables to predict a dependent variable. He showed that a better estimate of the mean can be obtained in the multivariate case if $R^2 \geqslant q_i/(n_1 - q_i)$, where R is the combined correlation coefficient, q_i is the number of variables included in the prediction equation, and n_1 is the length of the record to be extended. In the case of the variance, the variance of the reconstructed record is a better estimate if the relative information ratio I (the ratio of the variance to that estimated from the original record) exceeds 1. When I exceeds unity, it implies that the variance of the estimate of a moment made from the original record is longer than that of the estimate made from the combined record, and therefore a more precise estimate is computed from the combined data. As a general rule the estimate from the longer series is more reliable if R exceeds 0.80 [Table 3 of *Fiering*, 1963; p. 2 of *Matalas and Jacobs*, 1964]. However, *Matalas and Jacobs* [1964] point out that these requirements can be reduced and that the parameters estimated from the longer series are an unbiased estimate if a noise factor is added to the estimated values.

*By "Noah effect" is meant that extreme precipitation tends to be very extreme, the archetype being the 40-day rains that resulted in inundation of the entire earth (Gen. 7:11-21). By "Joseph effect" is meant that a period of unusually high (or low) precipitation is commonly an extended one, so named after the widespread famine of seven years' duration that Joseph had predicted from Pharaoh's dream (Gen. 41:51-57).

CLIMATIC INPUTS

The basis for comparing annual runoff series with tree-ring series is the hypothesis that the two series respond to a common climatic signal or signals that permit prediction of annual runoff from the annual ring-width index.* A schematic diagram of the climatic variables influencing both of the series and the resultant predictability is shown in Figure 1.

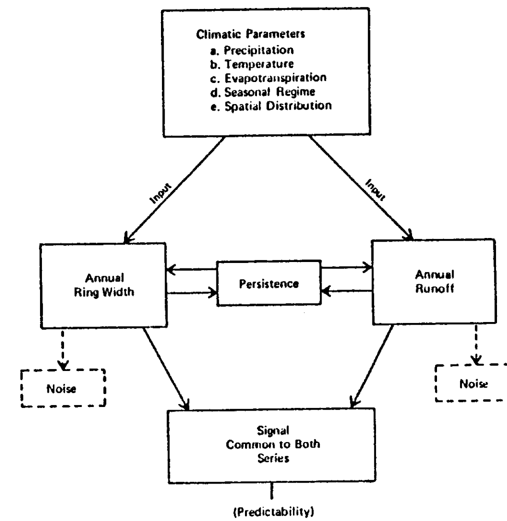

Fig. 1. Schematic diagram of relationship between ring-width series and annual runoff series for medium and large watersheds.

Precipitation (a), temperature (b), and evapotranspiration (c) influence the water balance of both runoff and tree growth. However, in the case of tree growth, these variables, and especially temperature, have physiological influences not directly related to the water balance; these influences are diagrammed in *Fritts et al.* [1970]. The seasonal distribution of the variables (d) influences both runoff and tree growth, and in the case of tree growth the influence of the monthly distribution extends to at least a 14-month period—from the July prior to the growing season in which the ring is

*"Indexing" (standardization) is necessary to convert the nonstationary ring-width series to a stationary time series [*Stokes and Smiley*, 1968].

formed to the July concurrent with the growing season [*Fritts et al.*, 1970]. Spatial distribution of precipitation and temperature (e) within large watersheds may influence both the annual runoff regime and the variability in growth of trees from site to site.

The noise component in Figure 1 represents both the model's inability to adequately describe the two series and the differences in the way the two series respond to climatic inputs.

Of major concern in the reconstruction of annual runoff series from tree-ring records is the difference in persistence within each of the two series—that is, how much do events of the previous year or years influence the current year? During this study, differences in persistence were resolved by using lagged dependent variables on the right-hand side of the reconstruction equation, as described by *Johnston* [1963]. Unfortunately, this causes the residuals to be dependent upon residuals of prior reconstructed values. Also, the regression coefficients tend to be biased although they have the properties of consistency and efficiency [*Johnston*, 1963] if the residuals are normally distributed. Another remedy would be to use a matrix of the tree-ring data, lagged up to three times, and extract principal components from this supplemental matrix. The covariation in this matrix can be decomposed by extracting the eigenvectors. A new set of uncorrelated variables is obtained from the amplitudes of the eigenvectors [*Fritts et al.*, 1970]. These amplitudes may be lagged in certain ways with the runoff data, and multiple regression may be used to weight the respective series so that the differences in persistence are accounted for.

EFFECTS ON TREE GROWTH AND RUNOFF

It is now necessary to determine how both tree growth and runoff respond to the climatic inputs. *Fritts et al.* [1970] described a method for modeling the response of trees to different climatic variables. Their method, which provides a means of determining the importance of monthly temperature and precipitation throughout the 14-month period prior to actual growth, uses multiple linear regression to predict ring-width indices from the amplitudes of eigenvectors of monthly precipitation and temperature along with variables representing the persistence within the ring-width series. That is, the tree-ring indices are fit to the model

$$y_t = \theta_1 \xi_{1t} + \theta_2 \xi_{2t} + \ldots + \theta_p \xi_{pt} + \phi_1 y_{t-1} + \ldots + \phi_3 y_{t-3} + e_t, \quad (1)$$

where

y_t = normalized ring-width index in year t
θ_p = least squares coefficient for variable ξ_p
ξ_{pt} = amplitude for year t of p eigenvectors extracted from a correlation matrix of climatic variables
ϕ_{t-n} = least squares coefficient for variable y_{t-n}
y_{t-n} = the normalized ring-width index at time $t-n$
e_t = error component.

Because of the transformations performed on the climatic data, i.e., the derivation of the amplitudes of the eigenvectors, the climatic variables are orthogonal and fulfill one major assumption—that of independence of the "independent" variables. Additionally, use of the principal components reduces the number of variables, thereby reducing the dimension of the problem. The use of these transformations, however, somewhat obscures the physical relationship of the effects of climate upon ring width. *Fritts et al.* [1970] suggest that a solution to this undesirable effect is in the "response function," which transforms the principal components back to the original variables. If the components are expressed in terms of the original variables, $x_1, x_2, \ldots x_n$, Eq. (1) is transformed to a linear equation in x. Each additional component changes the coefficients attached to the several x_i terms, these changes being proportional to the elements of the eigenvector (corresponding to the amplitude) newly added. Thus,

$$y_t = \theta_0 + \theta_1(a_{11}x_1 + a_{21}x_2 + \ldots) \qquad \text{for } \xi_1 \quad (2)$$

or

$$y_t = \theta_0 + \theta_1 a_{11} x_1 + \theta_1 a_{12} x_2 + \ldots + \theta_2 a_{21} x_1 + \theta_2 a_{22} x_2 + \ldots$$
$$= \theta_0 + x_1(\theta_1 a_{11} + \theta_2 a_{21}) + x_2(\theta_1 a_{12} + \theta_2 a_{22}) + \ldots \qquad \text{for } \xi_1 \text{ and } \xi_2, \quad (3)$$

where the a's are elements of the respective eigenvectors and the x's are observed values of the climatic variables. Thus, if the variable x_i is factored out of any term, the resultant term is the sum of the regression coefficient times the eigenvector elements. Since these regression coefficients and eigenvector elements are determined in an unbiased manner from the observed values of the variables, the result should be a way to compare the response of the dependent variable y against the respective independent variables x. By plotting these sums of regression coefficients times eigenvector elements for the same independent variables but different dependent variables, one can compare "response functions" for various dependent variables.

Figure 2 shows the response functions to regional temperature and precipitation for (1) tree growth at a site within Upper San Francisco River basin, and (2) total annual runoff at Glenwood, New Mexico. In both cases, temperatures are based on monthly averages and precipitation on monthly totals.

The response function for tree growth shows that above-average growth results when precipitation is above normal in November, December, and February-July and below normal in August, coupled with below-normal temperatures in November-February, April-July, and September, and above-normal temperatures in March and August.

Above-normal annual runoff occurs when precipitation is above normal especially in November, January, February, April, May, and July-September, coupled with temperatures below normal in November, January, March, July, and September and above normal in December, April, and May.

The similarities between the response functions for tree growth and those for runoff represent climatic signals present in both series; the disparities represent the part of the signals lost as noise. One noticeable difference in the responses to precipitation is the consistently positive response of runoff, especially in November, January, April, and July, whereas the effect of precipitation on tree growth is less pronounced, noticeably in August. The responses for average monthly temperatures show major disparities in December and April-May (below normal for maximum growth, above normal for maximum runoff), and in March and August (above normal for maximum growth, below normal or normal, respectively, for maximum runoff). From the above, it is not hard to imagine conditions under which high runoff would occur but maximum growth would not occur. For example, high precipitation in November and January with high temperatures in December would lead to high runoff but would not contribute as markedly to tree growth.

RECONSTRUCTION OF RUNOFF SERIES FROM TREE-RING INDICES

With the above limitations in mind, it is possible to develop an equation for reconstructing a pattern of past annual runoff from tree-ring indices.

If the tree-ring data are sampled at widely dispersed sites over a moderately large watershed, say 2000 square miles, a means is needed to incorporate into the model the spatial distribution of the

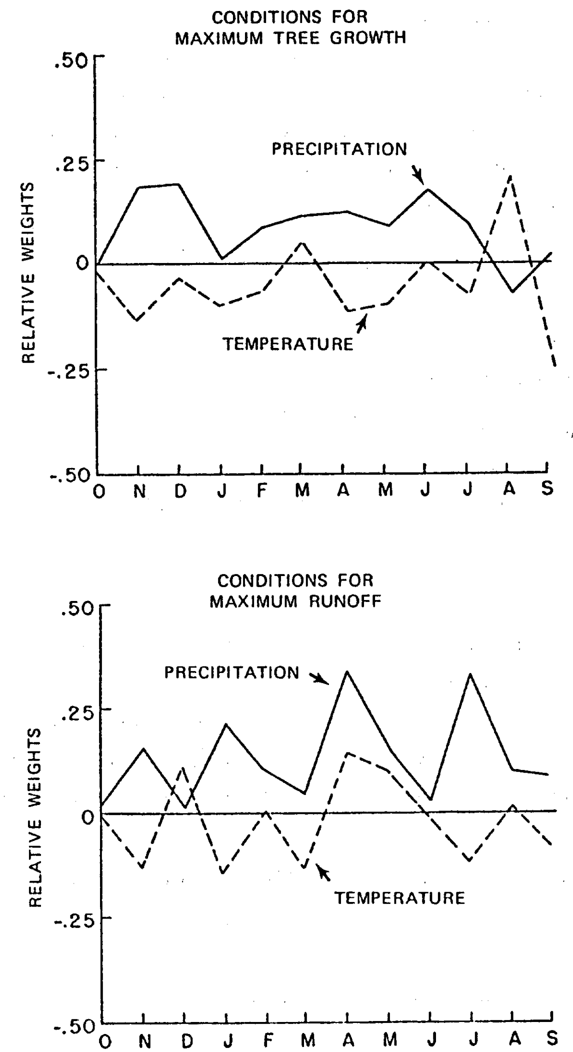

Fig. 2. Comparison of response functions of monthly climatic variables (water year) for tree growth and annual runoff in Upper San Francisco River basin.

tree-ring data at any time t. In addition, the persistence with time may vary among tree-ring sites, and a way is needed to compensate for this difference in persistence and at the same time model the generating mechanism within these data so that it can be compensated for in the reconstruction equation. By lagging the matrix of tree-ring series in time up to $t-3$ and extracting the eigenvectors from this combined matrix, a space-time distribution of the tree-ring series is accomplished. Thus, a least squares reconstruction equation is obtained:

$$f_t = \beta_0 + \beta_1 \xi_{1t} + \beta_2 \xi_{2t} + \ldots + f_{t-1} + f_{t-2} + f_{t-3} + e_t, \qquad (4)$$

where

f_t is runoff at time t,

β's are least square regression coefficients,

ξ_t's are the amplitudes of the eigenvectors extracted from the correlation matrix of the combined, lagged matrix,

f_{t-n} are previous-year runoff values, and

e_t is the error resulting from inadequacy of the model itself.

It was found, subsequent to the work of *Stockton* [1971], that by lagging the values of runoff with respect to the tree-ring series, one can compensate for the generating mechanism differences in the two series. That is, the runoff at time t is a function of the tree-ring data x at times $x_{t+1}, x_t, x_{t-1}, x_{t-2}$. This provides an expression of the mixed moving average-autoregressive model established by *Stockton* [1971] as typical for Douglas fir series in the Upper San Francisco River basin. In this case, prior runoff was not included as an independent variable.

In using a reconstruction equation like Eq. (4), five basic assumptions are made:

1. The climatic interaction between runoff and tree growth is constant and does not change with time.
2. A linear relationship exists between the tree-ring series and the annual runoff series.
3. The variables are multivariate normal distributed.
4. The residuals are independent (i.e., the cross product of the residuals is zero).
5. Expected value of residuals, e_t, is zero.

APPLICATION TO TWO WATERSHEDS

Tree-ring samples of a single species, Douglas fir, were taken in two watersheds of diverse hydrologic character, one in Arizona and one in New Mexico.

The first, Bright Angel Creek watershed, is an area of 100 sq. mi. on the north rim of the Grand Canyon in north-central Arizona. The annual precipitation regime (mean of 25 in.) shows two maxima, one in July-September and the other in December-January. The winter maximum, however, is dominant and results in an average annual snow accumulation of approximately 150 in. The runoff pattern reflects this tremendous snow accumulation, in that 97% of the annual runoff occurs during April and May as the result of melting snow.

The Douglas fir in Bright Angel Creek basin are characteristic of a forest interior site and are less sensitive to climate than would be those from either a lower or upper forest border site. This means that the ring widths yield less climatic information than would be desirable. This deficiency was known when this watershed was chosen, but it was chosen anyway in order to contrast results obtained under less than desirable conditions with those of conditions closer to ideal.

An equation of the type of Eq. (4) was developed to reconstruct the record of past annual runoff from the tree-ring indices. The criterion for including or excluding any given variable (ξ's and f's) was that its F-ratio must equal or exceed 4.0. This gave an equation that accounted for 51% of the variance in the actual record. Using the equation, the record was reconstructed for the period 1753-1966 (214 years) as shown in Figure 3. (Superimposed on the graph is the actual observed record for the period 1924-1966.) The low-frequency Noah and Joseph effects are quite noticeable in the reconstructed series. These results, although not highly useful for reconstructing the past record on a year-to-year basis, do provide an improved estimate of the mean according to the criterion of *Fiering* [1963]. That is, the long-term mean from the reconstructed series (5.81 in.) versus the mean from the observed series (4.73 in.) is considered to be closer to the true population mean. If a noise element were added to each estimate, as discussed by *Matalas and Jacobs* [1964], this reconstructed series would also yield a better estimate of the variance.

The second watershed was the Upper San Francisco River basin in west-central New Mexico. The hydrologic characteristics are quite different from those of Bright Angel Creek basin. As at Bright Angel Creek, the annual precipitation (mean of 15 in.) shows two maxima, one in July-August and the other in December-January. Here, however, the July-August maximum is dominant, but owing to

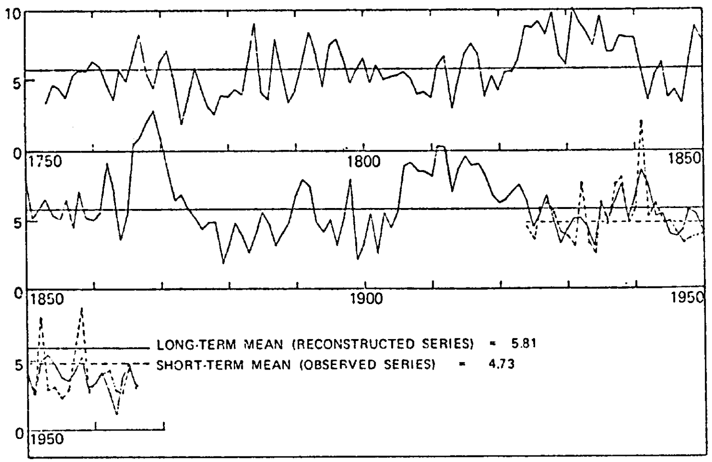

Fig. 3. Reconstructed hydrograph for Bright Angel Creek, 1753-1966 (214 years). Runoff data for this period have been predicted from tree-ring data for the same period. Observed runoff data for 1924-1966 are superimposed with dashed line.

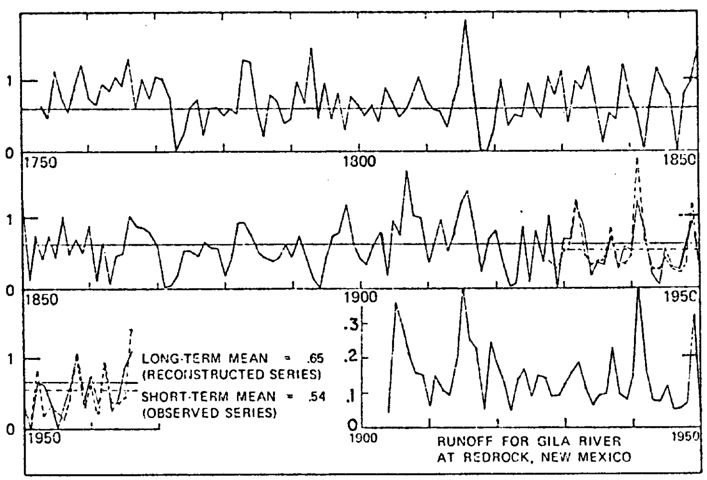

Fig. 4. Reconstructed hydrograph for Upper San Francisco River, 1753-1966 (214 years). Runoff data for this period have been predicted from tree-ring data for the same period. Observed runoff data for 1928-1966 are superimposed with dashed line. For comparison, the runoff record for the Gila River near Redrock (1904-1950) is also shown.

evaporation losses, most of the runoff, about 88%, occurs during the winter, November-May. Very little results from melting of accumulated snow.

In this basin, the tree-ring data are from a lower forest border of Douglas fir and thus they are far more sensitive to climate than at Bright Angel Creek. Consequently, a better correlation was expected between the ring-width series and the runoff series in this basin.

The reconstruction equation of the form of Eq. (4) for this basin accounted for 72% of the variance in the observed runoff record. (Again the criterion for inclusion of variables was $F \geqslant 4.0$.) The reconstructed hydrograph for the period 1753-1966 is shown in Figure 4 along with the observed record for the period 1928-1966. In this case the reconstructed record conforms with the observed record much better than in the first case. As in the first case, the long-term mean of the reconstructed series is higher than that of the observed series, 0.65 in. versus 0.54 in., which represents about 58,000 acre-feet per year versus about 47,000 acre-feet. Again, according to the criterion of *Fiering* [1963], this long-term record represents a better estimate of the true population mean. An improved estimate of the variance can also be gained from the reconstructed series.

Also shown in Figure 4 is the observed record for a nearby station, on the Gila River, for the period 1904-1950, which allows visual comparison of the reconstructed record against one that was actually observed in the same region. Comparison of the Gila record at Redrock with the reconstructed series for the Upper San Francisco River illustrates one of the precautions that must be taken in using the tree-ring technique. As was pointed out in the section on response functions, certain monthly climatic regimes that result in maximum runoff are not conducive to maximum growth. One such regime occurred in 1904, when December and January were exceptionally wet and probably above average in temperature–a condition for maximum runoff but less than maximum growth. The result is that the reconstructed value for 1904 is only about half of what actually occurred.

From Figure 4, one sees that the Noah and Joseph effects, although not as pronounced as in the case of Bright Angel Creek, are nonetheless quite evident in the reconstructed record. As shown by *Stockton* [1971], the long-term, low-frequency component (Joseph effect) results in a substantially different correlogram than does that of the observed record. Thus, the long-term reconstructed series should provide an improved estimate of the correlogram of the annual runoff series because the Joseph effect is included.

CONCLUSIONS

It has been shown that tree-ring data can be used to augment annual runoff records. Although the two examples cited differed substantially in the degree of conformance of the actual versus the reconstructed records, the conformance in both cases was still close enough that improved estimates of the mean and variance could be obtained. In interpreting runoff records reconstructed from tree-ring data, it must be borne in mind that there are certain monthly climatic regimes that result in high runoff but may not be as favorable to growth. An example of one such occurrence was illustrated. Fortunately, such occurrences are rare.

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SOME REGIONAL DIFFERENCES IN RUNOFF-PRODUCING THUNDERSTORM RAINFALL IN THE SOUTHWEST [1/]

H. B. Osborn [2/]

INTRODUCTION

Regional differences in rainfall amounts and intensities in the Southwest have been noted by numerous investigators. However, quantitative descriptions of these differences, usually as depth-duration frequencies, generally have ignored differences in the storm system that generated the rainfall and have lumped essentially different storm populations together. Sellers (1960) suggested that rainfall in Arizona could be subdivided into roughly three categories--frontal winter rainfall, air-mass thunderstorm rainfall, and frontal-convective rainfall. Frontal-convective storms include those that result from tropical storms off Baja California and occasionally, as described by Sellers (1960), come "rampaging through southern Arizona."

In this paper, estimates by Leopold (1944) and Hershfield (1961) of rainfall depth-duration frequencies for Arizona and New Mexico are compared with more recent rainfall records from U.S. Weather Bureau rain gages in southern Arizona and New Mexico and Agricultural Research Service rain gages on the Walnut Gulch Experimental Watershed in southeastern Arizona and the Alamogordo

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1/ Contribution of the Agricultural Research Service, Soil and Water Conservation Research Division, USDA, in cooperation with the Arizona Agricultural Experiment Station, Tucson, Arizona.

2/ Research Hydraulic Engineer, Southwest Watershed Research Center, 442 East Seventh Street, Tucson, Arizona 85705.

Creek watershed in eastern New Mexico. Some regional differences in thunderstorm rainfall depths and intensities are indicated, and possible reasons for these differences are advanced. Stations along the "rim" in central Arizona were not included in this analysis, since the orographic effects on rainfall are much greater along the "rim" than across most of southern Arizona. The "rim" should be analyzed separately and then compared with records at other stations.

RAINFALL DEPTH-DURATION FREQUENCY

Leopold (1944) made the first in-depth study of characteristics of heavy rainfall in New Mexico and Arizona. He referred to earlier work by Yarnell (1935), but pointed out that Yarnell had only 5 long-term stations with which to make his analysis. Leopold admitted that he was handicapped by a scarcity of data, particularly at higher elevations, but he did have several more years of record at the long-term stations and many more short-term records to analyze.

Leopold's analysis was restricted to 24-hour rainfall, since almost all of the available data were from standard rain gages. He determinedd the 100-year, 24-hour rainfall for a large number of stations in Arizona and New Mexico but did not try to group or compare stations topographically or climatically.

Hershfield (1961), on the other hand, determined rainfall depths for return intervals from 2 to 100 years and durations from 30 minutes to 24 hours for the United States. These values were produced in U.S. Weather Bureau Technical Paper 40 as a rainfall atlas of the United States. Depth-duration frequencies for individual stations were averaged or "smoothed" to develop design curves. These curves are still used widely throughout the United States.

Three long-term stations in Arizona (Casa Grande, Tucson, and Tombstone) and the long-term station at Santa Rosa, New Mexico were chosen specifically to illustrate some similarities and differences in point rainfall in the Southwest, and because the Tombstone and Santa Rosa stations are the closest long-term stations to the Walnut Gulch and Alamogordo Creek watersheds, respectively (Fig. 1).

Selected 100-year frequencies for these four stations, as determined from Technical Paper 40, are shown in Table 1. These data suggest that short-duration rainfall (2 hours and less) is greater in southeastern Arizona (Tucson and Tombstone) than in the remainder of southern Arizona or eastern New Mexico, or that the more intense short-duration rainfall is more likely to occur in southeastern Arizona than in the remainder of southern Arizona or eastern New Mexico.

On the other hand, the expected 100-year, 24-hour rainfall depth is 0.5 inch higher in south-central Arizona than in southwestern or southeastern Arizona or eastern New Mexico. Leopold, with much less available information, estimated 24-hour, 100-year rainfall depths of 3.6, 3.3, and 3.5 inches for Tucson, Tombstone, and Santa Rosa, respectively, but 6.0 inches for Casa Grande. The 100-year, 24-hour rainfall depths for other stations near Casa Grande were less than 3.0 inches in all cases.

The explanation of the much higher estimate for Casa Grande may be largely chance, as will be shown later in this paper.

WALNUT GULCH RAINFALL

The Agricultural Research Service has operated the 58-square-mile Walnut Gulch Experimental Watershed in southeastern Arizona since 1954. Of the 95

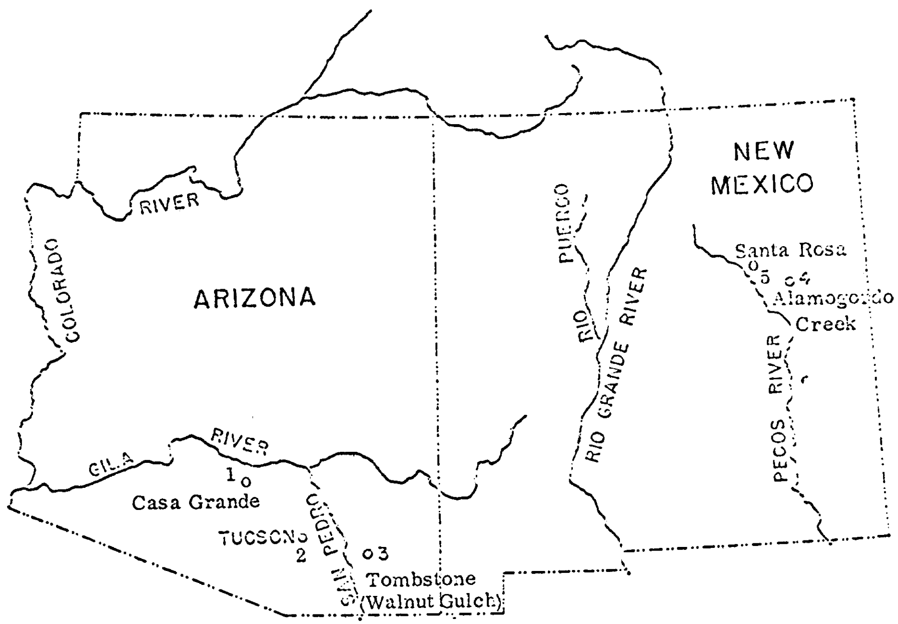

Fig. 1. Location of selected rain gage stations in southern Arizona and eastern New Mexico.

TABLE 1. One-hundred-year storm depths for four durations at selected stations in Arizona and New Mexico (from U.S. Weather Bureau Technical Paper 40)

Duration	Casa Grande	Tucson	Tombstone	Santa Rosa
30 minutes	2.25	2.5	2.5	2.25
1 hour	2.75	3.0	3.0	2.75
2 hours	3.0	3.5	3.5	3.0
24 hours	5.5	5.0	5.0	5.0

recording rain gages on or immediately adjacent to Walnut Gulch, about 80 are evenly scattered over the watershed.

The maximum one-hour point rainfall recorded on Walnut Gulch was 3.45 inches on September 10, 1967. The maximum 30-minute rainfall for the same storm at the same point was 2.52 inches. Between 2.5 and 2.65 inches of rainfall in 30 minutes was recorded at three points almost simultaneously on August 17, 1957. Also, just over 2.5 inches of rainfall in 30 minutes was recorded at two rain gages on Walnut Gulch on October 4, 1954. These are the only known occurrences of rainfall exceeding 2.5 inches in 30 minutes on Walnut Gulch in 15 years of record.

A thorough search of U.S. Weather Bureau data for southern Arizona did not uncover a record of more than 2.5 inches in one hour other than on Walnut Gulch. If each U.S. Weather Bureau recording rain gage is assumed to be an independent sampling point, there are about 1000 gage-years of record in southern Arizona. If all recording gages on Walnut Gulch are independent points, there are also about 1000 gage-years of record from Walnut Gulch; if they are all dependent points, there are 15 years of record. Studies by Osborn, Lane, and Hundley (1969) and Osborn and Renard (1970) suggest that the true value is closer to 1000 gage-years than to 15 gage-years.

The U.S. Weather Bureau record for southern Arizona includes several stations with 30 or more years of record and about 30 stations with 20 to 30 years of record. One might expect to find greater recorded intensities in the U.S. Weather Bureau record since it covers a longer period, a wider range of topographic and climatic locations, and the stations are almost certainly independent sampling points, at least for sampling air-mass thunderstorm rainfall. Yet,

three separate events on Walnut Gulch greatly exceeded anything recorded at USWB recording rain gages in southern Arizona. This suggests that something other than chance is responsible for the difference between the 1000-gage-year USWB record and the Walnut Gulch record.

Two possible explanations are that (1) southeastern Arizona experiences more intense air-mass thunderstorm rainfall than does south-central and southwestern Arizona, and (2) the gages on Walnut Gulch represent enough independent points, at least for sampling "record" rains, that the dense network on Walnut Gulch is, in some way, a more efficient "measure" of maximum point rainfall than is the 1000-gage-year USWB record.

For the first hypothesis, summer rainfall as recorded at USWB stations generally decreases from east to west across southern Arizona. In general, the elevation of the recording rain gage stations also decreases from east to west across southern Arizona. The decrease in elevation may be the primary reason for decreasing rainfall. For example, Walnut Gulch gages (4000-6000 feet) record about 60 percent more summer rainfall than Tucson (2600 feet). The three long-term (over 30 years) USWB recording stations in southern Arizona are Tucson (2600 feet), Phoenix (1100 feet), and Yuma (near sea level), and there is considerably less summer rainfall at Phoenix than at Tucson and much less at Yuma than at Phoenix. Also, Walnut Gulch is closer to the primary source of summer moisture, the Gulf of Mexico.

It is difficult to establish that the record for Walnut Gulch is a more efficient "measure" of maximum point rainfall than the 1000-gage-year record for southern Arizona. At present, it seems that some element of chance combined with more intense summer rainfall on Walnut Gulch is the probable answer.

However, one might say that the network of rain gages on Walnut Gulch represents a 58-square-mile "rain gage" located in a region that receives more intense summer rainfall than do USWB recording rain gage stations in south-central and southwestern Arizona.

Walnut Gulch records suggest that on a 58-square-mile watershed in southeastern Arizona air-mass thunderstorm rainfall of 2.5 inches or more in 30 minutes might be expected about once in five years. Rainfall of 2.75 inches or greater in 30 minutes has never been recorded on Walnut Gulch or at any USWB recording rain gage in southern Arizona. (No storms with short-duration rainfall as high as those recorded on Walnut Gulch have been measured at USWB recording rain gages in northern Arizona.)

ALAMOGORDO CREEK RAINFALL

The Agricultural Research Service has operated the 67-square-mile Alamogordo Creek watershed in eastern New Mexico since 1955. At present, there are 65 recording rain gages on the watershed. The maximum known 30-minute rainfall recorded on a rain gage in the Southwest was 3.5 inches on Alamogordo. Keppel (1963) reported that this record rainfall resulted from combined convective heating and a weak cold front moving rapidly across the watershed on the afternoon of June 5, 1960. The combination of available moisture, convective heating, and frontal activity appeared ideal for producing an extreme thunderstorm rain.

On Alamogordo Creek, there were three frontal-convective storms in 15 years in which over 3.0 inches of rainfall was recorded in 30 minutes at one or more points on the watershed. This suggests a recurrence interval for such an event of about five years. No storms in which 3.0 inches or more was measured

have been recorded at USWB recording rain gages in New Mexico. There are fewer recording rain gages in New Mexico than in Arizona, and the network of rain gages on Alamogordo Creek is less dense than the one on Walnut Gulch. Therefore, the occurrence of three "greater-than-3.0-inch" storms on Alamogordo Creek and none greater than 2.75 inches on Walnut Gulch would appear to be for some reason other than chance.

ANALYSIS OF STANDARD RAIN GAGE RECORDS IN SOUTHERN ARIZONA

A different picture of air-mass thunderstorm rainfall is suggested from analysis of U.S. Weather Bureau standard rain gage records in southern Arizona. Fogel (1968) and others have suggested that 24-hour records from standard gages in southern Arizona in July and August generally represent short-duration thunderstorm rainfall which occurred in the afternoon or evening of the day before the standard 8:00 a.m. reading was taken.

If the U.S. Weather Bureau network of standard gages is assumed to be made up of independent sampling points, there are about 2900 gage-years of record--700, 1400, and 800 gage-years in southeastern, south-central, and southwestern Arizona, respectively. All storms of more than 3.0 inches for air-mass thunderstorm days, as determined from standard rain gage records, are shown in Tables 2, 3, and 4. Those records suggest that expected point 100-year air-mass thunderstorm rainfall is about 3.0 inches throughout southern Arizona. Also, on four occasions significantly greater storm depths have been recorded in south-central Arizona than in either southeastern or southwestern Arizona, suggesting that the likelihood of such an extreme rainfall (about 4.5 inches) may be greater in south-central Arizona than in southeastern and southwestern Arizona.

TABLE 2. Standard gage 24-hour point rainfall depths of over 3 inches for air-mass thunderstorm days in southeastern Arizona (700 gage-years of record)

Station	Depth	Date
Flying H Ranch	3.53	Aug. 20, 1955
Bisbee	3.37	Aug. 8, 1970
Granville	3.32	July 25, 1964
Cochise Stronghold	3.22	July 18, 1941
Fort Grant	3.20	Aug. 20, 1955
Rucker Canyon	3.01	July 20, 1938

TABLE 3. Standard gage 24-hour point rainfall depths of over 3.0 inches for air-mass thunderstorm days in south-central Arizona (1400 gage-years of record)

Station	Depth	Date
Superstition Mountains	4.93	Aug. 19, 1954
Casa Grande	4.50	July 26, 1936
Ruby	4.43	July 22, 1941
Cortaro	4.41	July 14, 1953
Sahuarito	3.90	July 21, 1970
Tempe Citrus Station	3.87	Sept. 15, 1967
Pisinemo	3.80	Aug. 7, 1955
Sasabe	3.50	Aug. 15, 1960
Stewart Mountain	3.48	July 17, 1967
Tumacacori	3.47	Aug. 5, 1958
Kitt Peak	3.46	July 30, 1964
Casa Grande	3.42	Aug. 12, 1964
Willow Springs Ranch	3.15	July 21, 1954

TABLE 4. Standard gage 24-hour point rainfall of over 3.0 inches for air-mass thunderstorm days in southwestern Arizona (800 gage-years of record)

Station	Depth	Date
Santa Margarita	4.10	Aug. 22, 1935
Yuma	4.01	Aug. 16, 1909
Kofa Mountains	4.00	July 28, 1958
Covered Wells	3.82	July 29, 1958
Alamo	3.60	Aug. 2, 1964
Ajo	3.25	Aug. 10, 1960

The information presented in these tables points out the importance of increasing sample size in developing such records. For example, in Table 2, the earliest recorded storm over 3 inches is that in 1938 in Rucker Canyon. All of the other observations are since 1941. A similar situation exists in Table 3, but it is even more noticeable, for only the 1936 storm predates 1940, and there are only two storms before 1953 in the maximum thirteen. There were approximately 600 gage years of record prior to 1940, 600 gage years from 1940 to 1950, 750 gage years from 1950 to 1960, and 950 gage years from 1960 to 1970. Only about 20 percent of the record predates 1940, and 60 percent of the available record is for the 20 years between 1950 and 1970.

The reason for higher 100-year, 24-hour estimates for Casa Grande by both Leopold and Hershfield is indicated in Table 3. An exceptional rainfall at Casa Grande in 1936 heavily biased Leopold's frequency analysis for this station and probably biased Hershfield's estimates for the region around the station as well. The maximum recorded rainfalls from air-mass thunderstorms in south-central Arizona actually approach the 100-year, 24-hour estimates of rainfall depth for that region given in U.S. Weather Bureau Technical Paper 40.

CONCLUSIONS

Conclusions from analysis of thunderstorm rainfall in Arizona and New Mexico are somewhat conflicting. Recording rain gage records suggest that air-mass thunderstorms produce a greater number of more intense short-duration (about one hour and less) rains in southeastern Arizona than in south-central or southwestern Arizona. Furthermore, possibly because of more frontal activity and less distance from the principal source of summer moisture, the Gulf of Mexico, the thunderstorms in eastern New Mexico can be more intense than those in southeastern Arizona.

On the other hand, records from standard rain gages in southern Arizona suggest that rainfall from individual air-mass thunderstorms may be greater in south-central Arizona than in southeastern or southwestern Arizona. However, a frequency analysis of air-mass thunderstorms, based on standard gages, indicates that the 100-year point rainfall is about 3 inches in all three regions.

Finally, with more data becoming available from stations in the more inaccessible regions in Arizona and New Mexico (such as along the Mogollon Rim), in-depth studies may soon be possible that would include more exact separation of thunderstorm types and a better definition of rainfall according to station location. In any case, thunderstorm rainfall models, to be useful, must take into account regional differences evident in recording rain gage data from Arizona and New Mexico.

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BLUE-GREEN ALGAL EFFECTS ON SOME HYDROLOGIC PROCESSES AT THE SOIL SURFACE

W. F. Faust
Water Resources Research Center, The University of Arizona, Tucson

It has been suggested, with experimental fact, that blue-green algae have an effect on runoff, infiltration, and erosion at the soil surface by *Booth* (1940), *Fletcher and Martin* (1948), and *Osborne* (1950).

The information presented here was obtained from simulated rainfall experiments using soil plots upon which blue-green algae was grown under an artificial wetting regime *(Faust* 1970). A 30 percent clay-content soil of the Pima series and a contrasting eight percent clay-content, river bottom alluvium of the Anthony series were used. Simulated rainfall intensities of one and two inches per hour were applied for sixty minutes or until the infiltration rate became relatively constant.

The micro-vegetation was predominantly blue-green algae although some mold hyphae of undetermined genera were observed in microscopic examination of the soil crusts. On the Pima soil Scytonema hoffmanii (Vauch.) Gom. and Microcoleus vaginatus (Ag.) (Gom.) grew. Schizothrix calcicola (Ag.) Gom. developed on the Anthony soil.

After heavy watering, moisture conditions conducive to algal development were maintained for three months by covering half of six-by-twelve-feet test surfaces with an air-tight envelope of clear polyethylene plastic sheeting. Dripping condensate from the underside of the plastic sheets kept the three-by-twelve-feet areas wet.

Results of this study indicate that blue-green algal growths significantly reduced the amount of suspended soil material in runoff water originating from soil surfaces showing these growths. No statistically significant differences in response factors of settleable sediment in the runoff water, runoff-infiltration volumes, and time to the onset of surface runoff could be attributed to the presence or absence of the algae on test plot surfaces.

The bar graphs in Figure 1 show large differences in suspended sediment movement between soils, this being caused in part by the relatively larger and smaller amounts of clay material in the soils. The lower intensities of simulated rainfall produced considerably less erosion because of low kinetic energy of the drop impact which powers the disloding and saltating of fine soil particles. The micro-vegetation effect on suspended sediment reduction, while apparent on both soils for high and low intensities, is less strongly expressed on the Anthony soil.

From Table 1 we may get some statistical verification for what is to be seen in the graphs. The observed F values are marked with a double asterisk when they exceed the required F value for the one percent confidence level. The highly significant differences in sediment movement due to soil, intensity, and micro-vegetation factors are in agreement with the graphed mean values. Each mean value is of six replications of a given treatment combination. Table 2 shows mean values for each treatment combination.

In addition, the small differences in suspended sediment production on the Anthony soil due to the micro-vegetation treatment is verified by the highly significant soils-micro-vegetation interaction labeled "CA interaction" in Table

AVERAGE SUSPENDED SEDIMENT PRODUCTION RATE UNDER SIMULATED RAINFALL

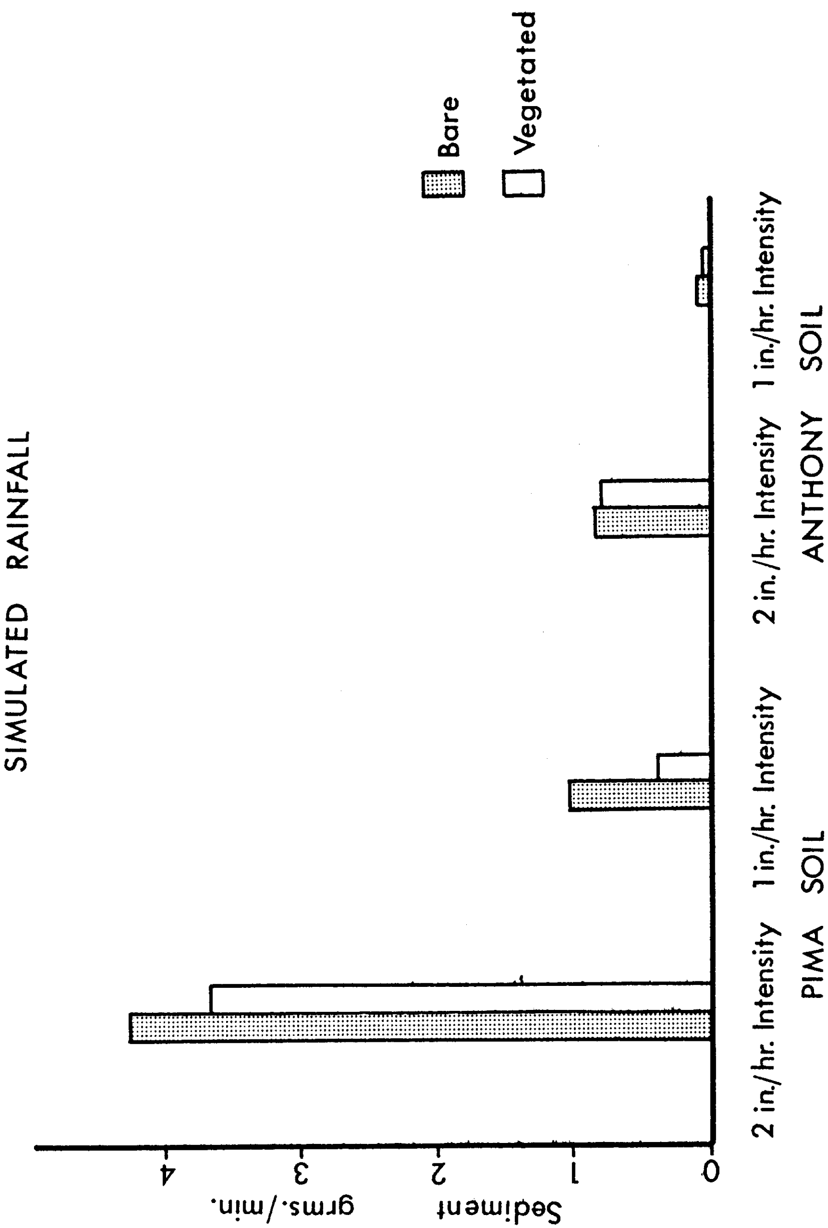

TABLE 1

MEANS OF THE RESPONSE FACTORS

Response Factor	Fixed Factors							
	Micro-Vegetated (a_1)				Bare (a_2)			
	Pima (b_2)		Anthony (b_1)		Pima (b_2)		Anthony (b_1)	
	Rainfall Intensity				Rainfall Intensity			
	High (c_2)	Low (c_1)	High (c_2)	Low (c_1)	High (c_2)	Low (c_1)	High (c_2)	Low (c_1)
	$a_1b_2c_2$	$a_1b_2c_1$	$a_1b_1c_2$	$a_1b_1c_1$	$a_2b_2c_2$	$a_2b_2c_1$	$a_2b_1c_2$	$a_2b_1c_1$
Suspended Sediment Production grams/minute	3.743	0.394	0.724	0.049	4.228	1.061	0.766	0.097

TABLE 2

ANALYSIS OF VARIANCE FOR SUSPENDED SEDIMENT PRODUCTION RATE

Source of Variation	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Squares (ms)	Observed F	Required F 5%	Required F 1%
B[a]	1	45.474	45.747	255.40**	4.96	10.04
Error A	10	1.780	0.178	-	-	-
A	1	1.161	1.161	21.18**	4.96	10.04
AB Interaction	1	0.849	0.849	15.49**	4.96	10.04
Error B	10	0.548	0.055	-	-	-
C	1	46.307	46.307	385.66**	4.35	8.10
CA Interaction	1	0.026	0.026	<1	4.35	8.10
CB Interaction	1	20.052	20.052	167.00**	4.35	8.10
CAB Interaction	1	0.023	0.023	<1	4.35	8.10
Error C	20	2.401	0.120	-	-	-

[a]A is the micro-vegetation condition factor; B is the soil type factor; C is the simulated rainfall intensity factor.

1. A least significant difference (LSD) test may be used to explain the interaction. Consider the array of means of mean pairs for testing the CA interaction:

a_1b_1		a_2b_1		a_1b_2		a_2b_2
0.387		0.432		2.067		2.644
	0.045		differences		0.577	

The calculated LSD for which a real disparity in the response factor may exist due to presence or absence of micro-vegetation within soil types is 0.213. This value is not exceeded by the differences for the b_1 or Anthony soil. It is for the b_2 or Pima soil.

As indicated earlier, the Pima soil is amply provided with fine material which may become water-borne when there are no algal filaments or trichomes to form a matrix into which the fine particles may lodge. The Anthony soil is not so endowed. Too, the precision of the experiments was probably too low for detecting the small differences in suspended sediment commensurate with the supply in this soil. Examination of the surface five millimeter thickness of soil crusts did indeed show that the Anthony soil contained less micro-vegetation than the Pima soil based on total carbon and nitrogen analyses. The Anthony soil in natural situations may not be observed to harbor algal growths as heavy as the Pima soil.

The exact nature of the binding of soil particles is not within the scope of this article. Beyond the mechanical binding of soil particles, an electrostatic affinity between soil particles and algae may exist as well as a cementation

between mineral particles and the cellulosic investments which enclose trichomes and filaments of the blue-green algae.

In conclusion, then, one may expect that when site conditions will support algal growths, algal-covered surfaces will not permit as much fine material to enter the overland flow as their soil counterparts which have no algal growths.

Differences in runoff and infiltration volumes, and in settleable sediment amounts could not be detected between surfaces covered with and denuded of blue-green algal growths.

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TREE-RING DATING OF COLORADO RIVER DRIFTWOOD IN THE GRAND CANYON

C. W. Ferguson

Laboratory of Tree-Ring Research
The University of Arizona, Tucson, Arizona 85721

BACKGROUND OF THE STUDY

The development of a millennia-long tree-ring chronology for bristlecone pine, Pinus aristata Engelm. (Pinus longaeva, D. K. Bailey, Sp. nov.), has been my major project in recent years. The chronology of nearly 8,200 years [Ferguson, 1969] has been used to calibrate the radiocarbon time scale [various contributors in Olsson, 1970]. A major deviation, with radiocarbon dates being as much as 1,000 years too recent, became evident in the C-14 time scale. The direction of this anomaly beyond the present tree-ring chronology posed intriguing questions, and interest focused upon the search for even earlier bristlecone pine remnants as well as for material of a different species and in other and varied situations that would predate the bristlecone pine chronology. Such wood should contain more than 300 annual rings and be of a sound quality usable for radiocarbon analysis.

An extensive deposit of driftwood in Stanton's Cave, at Mile 32 (32 river miles below Lees Ferry, Arizona) in the Grand Canyon, was a possible source of older wood. Based upon the 4,095-year radiocarbon age of a split-twig figurine found on the surface of the cave floor [Euler and Olson, 1965; Euler, 1966], and the depth and character of the deposits, it was felt that the underlying wood was deposited on the cave floor in the range of 12,000 years ago [Ferguson, discussion pp. 320-321 in Olsson, 1970]. However, the initial driftwood specimen, collected in the 1969 excavation, gave the rather surprising C-14 range of greater than 35,000 years (University of Arizona A-1056; $t_{\frac{1}{2}}$ = 5568). This date [Ferguson and Long, manuscript in preparation], much too early to be of value in the C-14 calibration studies, resulted in a change in emphasis. The major objective in the dendrochronological study of wood from Stanton's Cave itself is now to prove or disprove the contemporaneity of the deposit. Some crossdating was found in the tree-ring chronologies of separate specimens, but units of two or more crossdated specimens could not be matched with each other, indicating a possible spread in time for deposition in the cave.

The mouth of Stanton's Cave is 141 feet (43 meters) above the present level of the Colorado River. How this cave became filled with driftwood is a question for much conjecture that will not be further considered here. But it did lead to the idea that jams of driftwood elsewhere along the river might contain deposits of more recent age, and that a collection of available driftwood (now rapidly being used as firewood by river-running parties) would permit us to learn something of species, site relationships, and sources of origin for the period predating the construction of Glen Canyon Dam.

Archaeological excavations, especially at Unkar Delta (Mile 73), produced C-14 dates too early to fit the assumed time period [Schwartz, D. W., personal correspondence]. Could it be that the prehistoric people were burning old driftwood?

To form a basis for evaluating various aspects of driftwood, two collections

were made of present-day driftwood along the Colorado River. I made the first at various points along the 226-mile stretch of the river between Lees Ferry and Diamond Creek during a nine-day river trip through the Grand Canyon in August, 1970. The second collection was made along the bank of the river from above South Canyon delta to opposite Redwall Cavern when Stanton's Cave was re-excavated by Prescott College in September, 1970 by an assembled team of specialists (the Prescott College objective was to recover a total sample of artifactual, floral, and faunal specimens to further derive and clarify a climatic record for the Grand Canyon area from 4,000 to 40,000 years ago).

Hence, tree-ring dating of present-day driftwood along the Colorado River in the Grand Canyon was undertaken (1) to evaluate the driftwood deposit in Stanton's Cave, (2) to provide a basis for interpreting C-14 dates from archaeological sites in the canyon, and (3) to document a technique for deriving some concept of pre-dam hydrology, especially maximum high-water levels.

FIELD PROCEDURE

Cross sections or core samples were taken from more than 100 driftwood specimens, mostly from the present river level, although a few were from the pre-dam level, some 20 feet above the present river and higher. Pinyon, *Pinus edulis* Engelm., as a recognizable species, was given priority. Representative samples were taken of other pines; Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco; white fir, *Abies concolor* (Gord. and Glend.) Lindl.; cottonwood, *Populus fremontii* S. Wats.; juniper, *Juniperus* sp.; oak, *Quercus* sp.; and big sagebrush, *Artemisia tridentata* Nutt.

Criteria for the selection of pinyon were (1) ready field identification based upon physical appearance, resin ducts, density, and resinous qualities; (2) datability of the species by the tree-ring method; (3) prehistoric use as fuel and as building material and, therefore, the use of the species in both tree-ring and radiocarbon dating; and (4) indicated age of a specimen (based upon personal judgment through studies of other species, especially the millennia-old bristlecone pine).

LABORATORY PROCEDURE AND ANALYSIS

Dendrochronological dating of the specimens followed standard practices at the Laboratory of Tree-Ring Research [Stokes and Smiley, 1968; Ferguson, Chapter 7, in Berger, 1970]. Greater use was made of plotted ring measurements than of the skeleton-plot techniques. Visual correlations of the plotted ring-width measurements were attempted with the master chronologies and between individual specimens. Apparent matches were confirmed by re-examining the wood. Finally, all of the dated ring series were standardized to simplify comparisons and to facilitate statistical analysis. The visual crossdating, in two representative cases, was expressed by the correlation coefficient at the match point and throughout a limited interval on either side.

Six modern regional chronologies, in the form of indices (absolute ring-widths standardized and expressed as percentages), were used as dating controls:

1. Pinyon, A.D. 1376-1956, from the Western Sector of the Navajo Land Claims study [Stokes and Smiley, 1964, Table 7, pp. 26-27].

2. Douglas-fir, A.D. 1500-1951, from the North Rim of the Grand Canyon

[Ferguson and Black, 1952, Tables 1A, 1B, p. 16].

3. Colorado River Basin pinyon, four stations, eight 650-year trees, A.D. 1320-1948 [Schulman, 1956, Table 60, p. 106], and an extension from three stations, three 850-year trees, A.D. 11-1540 [ibid., Table 59, p. 106].

4. Utah Douglas-fir, mean of nine from the area of Bryce Canyon National Park, A.D. 1270-1964 [Stokes et al., unpublished].

5. Utah ponderosa pine, mean of 19 from the Bryce-Water Canyon area, A.D. 1336-1964 [ibid.].

6. Utah pinyon, mean of seven from the east bench of the Kaiparowitz Plateau, A.D. 1605-1965 [ibid.].

These were extended in time by one chronology derived from archaeological material: pinyon from Tsegi Canyon, Arizona, A.D. 385-1283 [Laboratory of Tree-Ring Research, unpublished data].

Nineteen dated specimens are tabulated (Table 1) and the time intervals they represent are shown graphically (Figure 1). The year of the outermost ring provides a date that is the earliest possibility for deposition as driftwood, i.e., the wood could not have been deposited before that time. Any lag effect is due to either erosion of the wood or time since its death, or a combination of the two. Erosion may be due to damage by insects or fire, abrasion through river transport, or deterioration by the elements; loss is usually limited to the sapwood, leaving the denser, more stable heartwood intact. Time since death has two phases: the period between death of the tree or branch and the "breakaway" that makes it vulnerable to water transport, and the time required to move it from its place of origin to its present site. A study of debris-flow conditions in the White Mountains of California has shown a lag of many centuries

TABLE 1. Dated Specimens of Colorado River Driftwood.

Specimen*	Mile	Form	Species	Interval, A.D.	
SC-1	11	section	Pinyon	1764 to	1958
S-10	32	section	Douglas-fir	1650	1841
S-15	32	section	Pinyon	1576	1668
S-19	32	core	Pinyon	1226	1702
S-27	32	section	Pinyon	1603	1829
S-28	32	section	Douglas-fir	1893	1919
S-33	32	section	Pinyon	1605	1830
S-48	32	section	Pinyon	1830	1942
S-53	32	section	Pinyon	1625	1874
S-58	32	section	Pinyon	1335	1594
S-65	32	section	Pinyon	1565	1940
S-81	32	core	Pinyon	1624	1750
TA	46	section	Pinyon	1438	1654
M-126	126	section	Pinyon	1344	1617
FG-1	168	core	White fir	1869	1968
FG-2	168	core	Douglas-fir	1832	1942
FG-7	168	core	Douglas-fir	1689	1939
FG-8	168	core	White fir	1607	1914
FG-9	168	section	Pinyon	1602	1773

*Specimens in the "S" series were collected in the area of Stanton's Cave; "SC" at Soap Creek; "TA" at Triple Alcoves; and "FG" at Fern Glen.

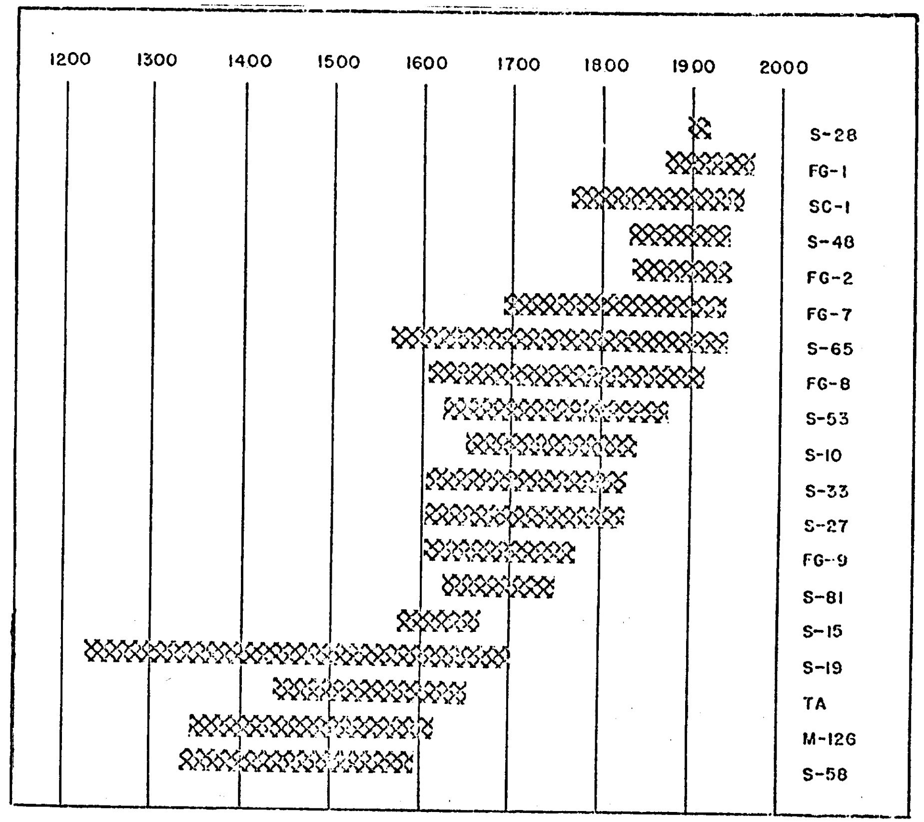

Fig. 1. Time intervals (A.D.) contained in 19 pieces of tree-ring dated driftwood from various sites along the Colorado River in the Grand Canyon.

between the dates of bristlecone pine wood and the known dates of debris flows in which the wood was found [Beaty and Ferguson, manuscript in preparation].

Since the outside ring on a single specimen may vary by more than 100 years, due to partial cambium dieback, fire, or erosion, it becomes critical to locate the outermost ring. For example, specimen S-48 was a branch, as indicated by a severely non-concentric center and heavy compression wood (a structural thickening of the latewood zone in the annual ring) in the longer (bottom) radius. The upper portion had either died about 100 years earlier than had the bottom, and/or had eroded to that extent. Specimen S-65 was a large piece, consisting of a buttressed branch on a spike that was dead above the branch junction. The outermost ring of the spike was A.D. 1765, on the branch, 1940. Hence, two areas of the same piece had outside rings differing by 175 years. The innermost ring, at 1565, was common to both portions.

As the dating of specimens progresses, a sample moves from the unknown toward one that is completely dated, with each ring identified as to the year it was formed and the outside thoroughly searched for the outermost ring. Because driftwood came from trees that originally grew anywhere on a huge watershed and because it may date anywhere in the span of centuries, dating presents problems not found in, for example, the dating of cores from a group of living trees of the same species on one slope. The uncertainties of origin undoubtedly are responsible for the apparent lack of quality in crossdating. For these reasons, some of the driftwood specimens in the Colorado River collection are not yet reported. These include more material from the vicinity

of Stanton's Cave as well as samples from Fern Glen, Buck Farm (Mile 41), Nankoweap Canyon (Mile 52), Tanner Canyon (Mile 68), Unkar Creek (Mile 72), Clear Creek (Mile 98), and Dubendorff Rapid (Mile 132). All dated specimens reported in Table 1 have been examined and verified by two or more members of the staff of the Laboratory of Tree-Ring Research. Some data may be slightly modified by further examination, through the location of a more complete outside or by verification of the presence of a locally absent ring.

A representative illustration of the crossdating between individual specimens and a control chronology is given in Figure 2. Plotted measurements of two ring series of about 100 years are shown in comparison with a master chronology. Specimen S-10 is a Douglas-fir section from the Stanton's Cave area, FG-9 is a pinyon section from the beach at Fern Glen, and the master chronology, A.D. 1645-1755, is for Utah ponderosa pine. Although the specimens and the master chronology are totally diverse in species and origins, they demonstrate visual crossdating. The small rings, those of most value in crossdating, match especially well at 1654, 1670, the three-year low in the 1680's, 1703, 1722, 1729, and 1735-36.

The cross-correlation figures (Table 2) show the statistical relationships between the standardized ring series of the two driftwood specimens shown graphically in Figure 2 and the indices for the six master chronologies used as controls. It may be noted that for these two specimens the Utah Douglas-fir master chronology would have provided a better correlation than did the Utah ponderosa pine illustrated. However, the data show that all of the master chronologies are of usable quality. Closer study of correlations such as these could be used to approximate the point of origin for individual driftwood specimens.

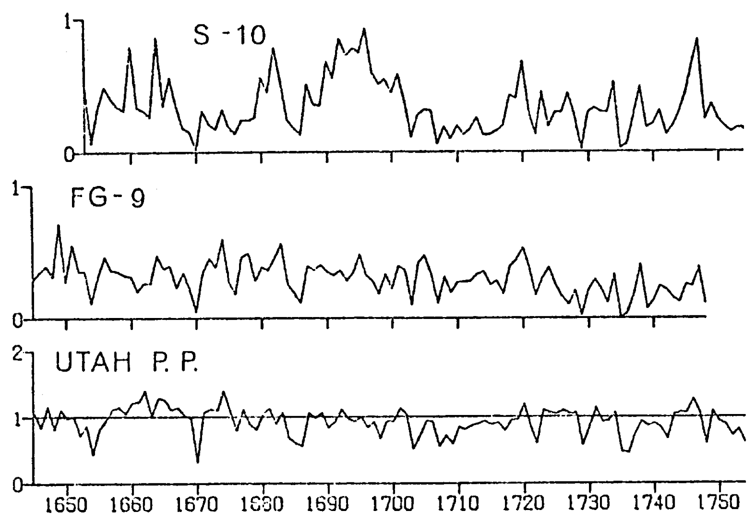

Fig. 2. Plotted ring measurements (0.0 - 1.0 mm) for S-10 (Douglas-fir) and FG-9 (Pinyon) shown in comparison with the standardized master chronology (percent) for Utah ponderosa pine for the interval A.D. 1645-1755.

Standardized values for FG-9 and S-10 for the 96-year interval A.D. 1653-1748 were correlated with the Utah Douglas-fir and the Utah ponderosa pine master chronologies at succeeding one-year intervals starting at A.D. 1600 and ending at A.D. 1799. Of the 104 pairs of correlation coefficients, the resultant high values, .60 and .57 with the Douglas-fir and .57 and .46 with the ponderosa pine (Table 2), were at the match point indicated by visual crossdating and were an order of magnitude greater than the second and third "best fit" in the random series extending approximately 50 years on both sides of the match point.

TABLE 2. Cross-correlation figures for the interval A.D. 1653-1748 for: 1. FG-9, 2. S-10, 3. Utah Douglas-fir, 4. Utah ponderosa pine, 5. Utah pinyon, 6. Colorado River pinyon, 7. Western Sector pinyon, 8. North Rim Douglas-fir.

r	1	2	3	4	5	6	7	8
1	---							
2	.50	---						
3	.60	.57	---					
4	.57	.46	.68	---				
5	.49	.53	.53	.57	---			
6	.48	.49	.46	.54	.66	---		
7	.55	.57	.58	.57	.68	.64	---	
8	.54	.58	.49	.44	.59	.56	.71	---

One specimen of the contemporary driftwood collection seemed to offer a possibility of extreme age, i.e., intermediate between the wood in Stanton's Cave and that presently on the river bank. The specimen (M-126) was a large, waterworn piece of pinyon driftwood found on the upper edge of the talus, on a shelf at the base of the canyon wall, at Mile 126. It was an estimated 70-100 feet above the present river level and hence was thought to represent a pre-dam high-water level. Although the specimen contained 269 measured rings, no immediate attempt was made to date it dendrochronologically. Instead, a 20-gram sample from the 10-year interval between ring 60 and ring 70 (on an arbitrary scale) was submitted for radiocarbon analysis. This procedure is sometimes used to steer us in the right direction for dendrochronological study, such as with the bristlecone pine specimens that might fall anywhere in an 8,000-year time span. The C-14 date provided a time placement and made possible a quick crossdating with the master chronology. The log had a ring sequence from A.D. 1344 to 1617, one of the older driftwood pieces, admittedly, but not of the hoped-for great age. But the position of this specimen, high above even the pre-dam high-water mark, seems to indicate a possibility of some very high flood levels in the not too distant past. Alternate explanations, such as use or deposit by Indians or fall from the cliff directly above, do not seem as acceptable as the theory of high-water deposit, especially since the log was waterworn.

Of the undated specimens, one (S-9) was interesting because it has the longest series of rings--at least 630 rings in 13.5 cm of radius (only 6.5 cm on the short radius). Although the small average ring width combined with a fairly sensitive sequence (with some rings small to the point of

being locally absent about the circuit) seemed to offer little possibility for definite dating, the specimen was tentatively placed in the chronology. Since I did not consider it verified, it was not included in Table 1. Then, just as I was completing this manuscript, a pinyon specimen collected by Austin Long in June, 1971 from below Basalt Canyon (Mile 70) was dated with the Tsegi archaeological pinyon chronology as a control. The date of the new specimen, A.D. 1011 to 1291, prompted a re-examination of S-9, which was immediately crossdated with the Basalt Canyon specimen at the same point as my tentative dating. I now consider S-9 dated, with a range from A.D. 1040 to 1698. These two new dates raise the number of dated specimens to 21 and provide a driftwood chronology of 957 years.

GUIDELINES AND INTERPRETATION

When looking for samples of wood that may be old, one is guided by the external appearance of the specimen, especially the extent to which it has been eroded by time and transport. One result of dating the driftwood specimens, primarily of one species (pinyon), is a refinement of the implied time gradient evidenced by the external erosion character of the wood. Obviously, pieces with bark intact and with ax-cut ends would be recent. Various progressive stages of surface deterioration generally represent successively older time periods. Arbitrary stages and the suggested time range they represent are (1) intact bark and/or ax-cuts, A.D. 1960-present; (2) no bark but a smooth, consistent external surface with no fissures; beetle galleries and passageways with sharp edges, 1930-1960; (3) beetle galleries and passageways still evident, but with smoothed edges; small radial fissures developing, 1900-1930; (4) outside ring generally consistent; sapwood still present, but with deeper fissures, 1850-1900; and (5) fissures deeper and more evident and some staining of the wood along the fissure; sapwood very deteriorated or absent; and a general discoloration of the wood, prior to 1850. These general estimates are subject to modification, however, by such unknown factors as length of time before the branch or stem became waterborne, distance traveled, damage by fire, or activities of man. As the number of dated specimens increased, it became possible to effectively apply these criteria and this proved to be a great time-saver. The centuries-long period within which specimens could fall combined with the difficulties presented by narrow rings and local absences would have made dating even more time-consuming.

SUMMARY

Considering that some of the hundred-plus pieces collected were exploratory as to species, the percentage of dated specimens indicates that the approach--using driftwood to date or interpret events in the Grand Canyon--is feasible. The 957-year period spanned by the tree-ring series in contemporary driftwood provides a basis for interpreting the scattering of tree-ring sequences in the Stanton's Cave deposit. The distribution of ring sequences through time, with a general grouping of specimens in the three intervals A.D. 1300-1600, 1600-1800, and 1830-1940, indicates that two or more specimens that crossdate with each other may not crossdate with other such units.

Charcoal from our own campfires (utilizing trimmings from some of my samples) would have provided radiocarbon dates spanning five or six centuries. This would provide one interpretation of the seemingly early C-14 dates from archaeological

sites in the canyon, such as on the Unkar Delta: prehistoric man used old driftwood.

Tree-ring dates from a collection of wood found well above the pre-dam high-water mark, such as the Mile 126 specimen, could be used to provide evidence of the maximum "100-year" floods. In summary, tree-ring dating of driftwood along the Colorado River in the Grand Canyon offers a tool for problem-oriented research, provided river parties have not burned up the necessary specimens by the time they are needed.

Acknowledgments. Initial and continuing interest in dating driftwood came from the Stanton's Cave study, an interdisciplinary project conducted by Robert C. Euler of Prescott College under terms of a grant from the National Geographic Society for the "Paleoclimatic History of the Grand Canyon." The exploratory collection of contemporary driftwood was made on a 226-mile river trip, sponsored by the Arizona Academy of Science, 18-26 August 1970. Partial financial support for the river trip was provided by the Laboratory of Tree-Ring Research. The Sanderson Brothers crew, quite interested and research oriented, stowed the specimens aboard the raft and assisted in other ways. During the Stanton's Cave excavation 20-27 September 1970, Martha H. Ames, Barney T. Burns, Austin Long, and Paul S. Martin assisted with collecting. Austin Long collected seven additional samples for me on a river trip 13-22 June 1971. Specimen preparation and laboratory analysis were done by Cynthia Bergstedt, Susan Bliss, Dennie O. Bowden, Thomas P. Harlan, Donna Marcynyszyn, and Judith Mikevich at the Laboratory of Tree-Ring Research. Computer analysis for the driftwood program has been effectively administered by Linda G. Drew of the Laboratory's data processing section. A radiocarbon date (unpublished) provided by Hans E. Suess, University of California, San Diego, greatly facilitated the tree-ring dating of the Mile 126 specimen. And my wife Eileen aided in the collecting during the river trip and in the final editing of the manuscript.

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Physiographic Limitations Upon the Use of Southwestern Rivers

Carol S. Breed
Museum of Northern Arizona, Flagstaff

Southwestern rivers are few and far between and they do not carry much water. Figures from the three large drainage basins of the Southwest...the Great Interior Basin of Nevada and California, the Rio Grande Basin, and the upper and lower parts of the Colorado River Basin...show that surface water runoff from those basins is either nonexistent or very small compared to figures from humid parts of the United States such as the Ohio River Basin, the lower Mississippi, and the Columbia River Basin. (National Research Council, 1968).

Running water is scarce in the Southwest because of the physiography of the region (Hunt, 1967). Events in geologic history determined that the Southwest would stand today high above sealevel, in the rainshadow of the Sierra Nevada Mountains to the west, and almost wholly dependent upon the Rocky Mountains to the east for its water supply. Our modern river, of course, are themselves very young geologic agents, and our famous landscapes have been carved by these rivers only in the later (Cenozoic) part of geologic time.

The Southwest lies entirely west of the 100th meridian, that boundary recognized by John Wesley Powell a century ago as the westernmost limit of reliable rainfall in this country. To the east of the 100th meridian, rainfall can be relied upon to grow crops; west of the 100th, there is a chronic deficit of water, droughts are frequent and inevitable, and lifestyles must be adapted accordingly. Rainfall is the key factor, because all of the water that flows in any drainage basin got there by falling in as rain, either past or present.

Because no natural surface is perfectly flat, even in the initial stages of its development, falling rain lands on a sloping surface and begins to run downhill. Depending on the intensity and duration of the rainstorm and upon the infiltration capacity of the ground surface, a certain amount of rain will sink in and will travel downward through the soil toward the groundwater. The groundwater is simply the stored water from earlier rains.

A very high percentage of the rainfall evaporates or is taken up by plants. What is left (perhaps no more than 3% in the Southwest (Water Resources Council, 1970) moves downhill as surface runoff. Sheetwash coalesces into rills; rills become gullies; gullies flow into fingertip tributaries, and so the water runs through tributary streams of increasing order until it reaches the main stream, which transports the water through its mouth out of the basin and into the sea.

The groundwater, too, moves downslope, slowly, toward a mainstream exit from the basin. Where the top of the water table intersects the ground surface, a spring will occur and a perennial stream will ensue. Few of our Southwestern rivers are perennial. Rather, they are intermittent, receiving discharge from groundwater only along parts of their courses. Many Southwestern tributary streams are ephemeral, dry washes that run only after a rainstorm. None of the major rivers of the Southwest originate in the lowland, Basin and Range Province; all head in mountainous areas on the margins of the basin, remote from population centers. The Little Colorado, the Gila, and the Salt Rivers all head in the high country near the state line region of Arizona-New Mexico. The Rio Grande gets its water from the southern Rocky Mountains, and from Albuquerque seaward, it picks up almost no tributary water. The main Colorado and its partner, the Green River, owe

their existence to the melting snowpack of the Front Range and the Wyoming Basin, on the farthest reaches of the basin. Once these rivers leave the high country and enter the desert lowlands, they begin to be used up, to the last drop.

A stream should be appreciated as more than a handy flume for carrying a water supply and removing sewage at the convenience of Man. A stream, to a geomorphologist, is a beautifully and dynamically balanced, open system tending toward a state of near-equilibrium (grade) (Leopold, 1964). The tendency of a stream to adjust its morphometry to changes in the amount of water coming into the system and to the amount and type of sediment available for transport result in a lot of work being done. We call this work erosion, and deposition, and the result of this work is our landscape.

A change in any of several variables such as velocity of the water, depth or width of the channel, bed roughness and so forth will bring a change in the behavior, or regimen, of the stream. Building a dam, for instance, affects the velocity of the water that flows into the lake behind the dam. The streamflow is abruptly checked, and so the river drops its load of sediment. Tributaries to the mainstream above the dam are affected by the change in baselevel and they, too adjust their gradients by silting up their channels. Meanwhile, clear water released below the dam quickly picks up a new laod of sediment, scouring its channel and increasing erosion in the basin below the dam. These are immediate effects. The long-term effects follow from the fact that rivers are the most important elements of our landscapes and are, in fact, responsible for producing nearly all of our landscapes, as well as for providing essential habitats for wildlife and perhaps equally essential refuges for urban Man. Some geomorphologists now are trying to establish a scale against which esthetic values of various riverscapes could be measured, quantitatively (Morisawa and Murie, 1969). Certain

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MAN - THE DESERT FARMER

James E. Ayres

Arizona State Museum
University of Arizona, Tucson

My rather brief and somewhat oversimplified discussion of the prehistoric desert farmers of Arizona will center around the Hohokam Indians and their efforts to control water resources. These people were only one of several early groups to use and abuse the rivers of the Southwest. The Hohokam occupied major river drainages of central Arizona, expecially the Gila, Salt, Verde, Santa Cruz, San Pedro and Agua Fria, primarily within the Sonoran Desert.

From the earliest times prehistoric populations were concentrated in the major river valleys and tributaries in the Southwest. Prior to the Hohokam people the Cochise hunters and gatherers (ca. 5000 - 2000 B.C.) began gathering wild maize. Remains of attempts to control water by these incipent agriculturists have not been found and indeed it is likely there were none. Their effect on the environment was apparently rather insignificant.

The Hohokam were the first in Arizona to have made use of rivers for agricultural purposes. Two types of water control seem to have been utilized. One involved the direct exploitation of rivers through the use of irrigation canals. The other, an indirect use, controlled runoff within micro-drainages at higher elevations before it reached the rivers. This latter method utilized linear and grid borders, terraces and trincheras (check dams across small and shallow washes) and Ak Chin farming. Both of these types of uses were designed to preserve or improve the productivity of available land suitable for agriculture.

Canals taking water from rivers were apparently constructed and used from the beginning of Hohokam culture. These canals served to take water from permanently or nearly permanent flowing streams and make it available for the irrigation of fields and for village use. Well developed canal systems were found by Haury [1967] from the Vahki phase (beginning about 300 B.C.) onward at the Snaketown site. Most of the canals were constructed on river terraces and often carried water 10 to 15 miles. During Hohokam times several hundred miles of canals and feeder ditches were dug by hand. Not all were in use at the same time, of course. Washouts and the need for new fields necessitated changes in the canal systems from time to time.

With irrigation we have a case where, to meet the needs of an increasing population, a redistribution of land and water resources had to take place at the expense of the environment. Concomitant with an expanding population was an increase in social and political complexity. In order to support the population it became more and more necessary to modify the landscape so as to maximize production.

The soils available to the Hohokam were primarily fine grained alluvial soils laid down by heavy seasonal flooding. This type of soil is characterized by differential deposition - some areas of very fine grained soils and some coarser and more gravel filled. With very fine grained soils it is difficult to drain the subsurface and they are usually dense and hard to break up. The coarser soils are often too well drained. In the dense soils moisture loss

is only through evaporation or transpiration. This introduces a further complication - the deposition of salts and alkalis left behind when the water evaporates.

The accumulation of excessive amounts of salts and alkalis would render a field unsuited for agriculture. Some crops grown by the Hohokam, such as maize, had a lower tolerance to salts than did some types of beans [Woodbury 1962]. Conceivably, if salt levels became too high the dependence on maize as a primary source of food, would have to be transferred to lesser foods such as beans.

At first the Hohokam probably used only those parcels of land best suited for agriculture, i.e., where the soil and drainage were good, the land easiest to irrigate, and so on. The pattern of clearing, irrigating and subsequently abandoning fields increasingly used up the better quality farm land. Later, marginal lands had to be utilized.

Thus, there are two basic limitations caused by soil: (1) the density, either too compact or too loose; and (2) the accumulation of salts and alkalis due to the lack of adequate drainage. Water logging has also been suggested as a serious problem to prehistoric agriculture. The Park of Four Waters canal has been suggested by Woodbury [1960] as a drainage canal for water logged soil rather than an irrigation canal.

In addition, extensive agriculture would require clearing of natural vegetation found where the best farm lands were located. The more clearing, the greater the possibility of erosional problems. Clearing would include removal of mesquite, cholla and similar vegetation which was also a source of food to the Hohokam. Thus, while expanding agricultural fields they were at the same time reducing the available native food resources upon which they had to rely if crops failed.

Water control devices were primarily designed to reduce the rate of flow of the runoff from rainfall, increase penetration, control erosion and build up soil. This was especially true if linear and grid borders, terraces and trincheras. The Ak Chin method directs water to the mouth of a wash where it is then spread out onto fields located in that wash. The water is controlled so as to brake the rate of flow.

Those water control devices that regulated runoff before it reached the rivers were basically conserving techniques and in general modified the existing runoff pattern without doing appreciable damage to the environment. A balance is maintained between exploitation and conservation in these cases. Salts and alkalis and water logging do not seem to have been problems. Although they are more primitive in construction than irrigation canal systems, this does not imply, I think, that they are necessarily older. In fact, the reverse is probably true. The use of these devices is difficult to date. Archaeologists do not know if these controls were in use by the Hohokam throughout their existence as a viable culture.

So far there is little evidence that these techniques of water control were utilized by the Hohokam for any length of time. I suspect that they came into use late in the cultural sequence after major problems developed in the canal irrigation systems fed by the rivers. By late I mean during the Classic Period or about A.D. 1300-1400. The runoff control techniques appear to have been used from then until relatively recent times. Classic Period (A.D. 1300-1400) linear and grid border fields have been reported near Cave Creek, Arizona

[Ayres 1967].

The water control devices were probably less damaging to the environment than large scale irrigation because little clearing was done and they were usually located where drainage was good. However, there seem to be a few cases where these have been detrimental.

Historically the Papago Indians utilized the Ak Chin method of farming. Recently, Ronald Cooke, a geographer, looking at aerial photographs of the Papago Reservation in the Crow Hang village area suggested the possibility that attempts to control runoff at the head of arroyos actually created those arroyos. Due to poor management small, shallow drainages suitable for utilization for Ak Chin farming became increasingly bigger and deeper. The level of available technology made it impossible to use the water because of increased size and depth of the water courses. Papago informants at Crow Hang village verified this practice. Dunbier [1968] reports similar occurrences in Sonora among neighbors of the Papago Indians. Overgrazing and lack of rainfall are often held responsible for these entrenched arroyos but cultural factors are also involved. The overall effect would be a decrease in acreage of available agricultural land and would cause a shift from main to smaller and smaller drainages. The Hohokam may have experienced similar problems although no evidence of the use of Ak Chin farming by them has been found.

Although the Hohokam use of river water for irrigation began around 300 B.C., it was not until the Sacaton phase, some 1200 years later, that the maximum extent of their irrigation systems was achieved. By about A.D. 1450 the Hohokam had disappeared as a viable culture. These people apparently had been forced to readjust their way of life. The readjustment was so drastic that the Hohokam culture as such ended abruptly. Exactly why they had to change is unknown, but probably much of their problem can be laid directly to their manner of exploiting the rivers for irrigation purposes. Their lack of suitable technology to control drainage and salt and alkali problems could have been a major factor in the collapse of their cultural system.

Understanding the cultural factors involved is important in determining how, where and why particular types of water control and use took place and why and when they failed. Factors such as prehistoric political and social systems are crucial, although at this point in time they are too poorly understood to be of much help.

There is more archaeological information available on use than on abuse of rivers. Archaeologists until recently have not been particularilly concerned with abuse.

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USE AND ABUSE OF SOUTHWESTERN RIVERS

THE PUEBLO DWELLER

Charles C. Di Peso

The Amerind Foundation, Inc.
Dragoon, Arizona

I make no pretense of being a practitioner of the science of Pollution, even though most of my life has been spent in pre-Iberian garbage pits looking for archaeological remains left by the previous occupants of this southwestern land of ours. I have participated in this game of rag-picking, hoping that these pieces of debris were meaningful and that, if properly studied, would permit one to reconstruct the unwritten history of people such as the Puebloans, who, through time, dared to accept the challenge of Nature's arid gauntlet. Some of these folk accepted the role of simple soil members, as they quietly gathered their diet of seeds and fruits and hunted the fauna of their territory. In so doing, they were completely commanded by the whims of Nature. Others assumed the character of the soil parasite and, to a degree, adapted to their ecological niche by de temporal farming in order to supplement a gathering-hunting subsistence pattern. Finally, there were a few soil exploiters who knowingly endeavored to conquer Nature with technological skills.

For the past ten years, it has been my good fortune to investigate the proficiency of one of these groups which utilized engineering devices designed to modify, that is, exploit their terminal river niche to the benefit of a group of city farmers who had certain sophisticated economic and social needs.

Perhaps, burdened with the weight of these various social problems, they made the same mistakes as those made by us today, because they knew less about their natural role as participating animals than most animals know instinctively and, as inheritors of the Earth, were insensitive judges of their own future. A number of scientists, including a few archaeologists, have become concerned by our twentieth century crisis, and are trying to learn more of man's various modes of environmental exploitation. The question is--will we, today and tomorrow, follow the way of the technocrat and create man-centered, urban ecological systems throughout the world which are divorced from Nature, under the proposition that meaningful progress and technology go hand-in-hand? Or will we modify our stand in the light of Francis Bacon's tenet that, "We cannot command Nature, except by obeying her"?

The Pueblo occupants, adherents of the latter doctrine, were basically upland corn farmers, who, after A.D. 1000, found it necessary to exploit their environment because of varying combinations of climatic change and increased population pressures. These 11th Century social demands did not include such present-day needs as hydroelectricity, the tapping of underground water basins for the increased production of "cash" and "specialty" crops, nor were the Puebloan leaders involved with the problems of a herding economy, such as was brought to the New World by the pastoral Iberians during one of their own economic depressions.

These indigenes did not pond vast amounts of river water except on occasion, as for example, in the Animas Valley where a large, earthen prehistoric dam (Gaillard, 1896) existed. Consequently, they were not involved with such issues as silting and excessive water evaporation. Rather, some of these folk, such as those who lived in the Chaco Canyon and Mesa Verde districts, designed series of small city reservoirs, which were parts of larger, interconnected soil/water control systems. These devices were not "invented" by the Puebloans, such as those who occupied the Colorado drainage (Plog, 1970), the Kayenta

(Lindsay, 1970), Mesa Verde (Rohn, 1970), Chaco Canyon (Vivian, Personal communication), and Zuñi (Woodbury, 1970) areas, their eastern neighbors who lived in the Rio Grande (Ellis, 1970) or in the Casas Grandes Valley, but were ideas borrowed from the hydraulic technologies developed centuries earlier south of the Tropic of Cancer by the sophisticated Mesoamericans. However, all exploited the surface water of their districts in order to increase subsistence agricultural production.

In the northwestern corner of the state of Chihuahua, and particularly in the Sierra Madre portion, urban engineers, ca. A.D. 1050, harnessed the entire Casas Grandes dendritic pattern by installing a set of linked hydraulic appointments, which included various upslope protective devices, such as linear borders, check dams, riverside and hillside terraces. These were built to protect the canals, aqueducts, reservoirs, and sluices of the lower valley. The various villagers, mentioned above, used these same technological elements, but in different combinations dependent upon the requirements of their particular environmental setting. However, in each case, the overall purpose was to conserve and to fully utilize the flow of the sporadically-produced surface waters by taking the violence out of local thunderstorms. These pre-Iberian engineers were primarily motivated by concepts of checking water speed by means of pervious dams located in mountainous areas. Essentially, these hydraulic farmers played the role of human beavers, as they were (1) able to visualize an entire dendritic pattern as the target area and (2) were able to conceive of topsoil and rainfall as a single factor in their control designs. From observation, they knew that the land about them destroyed itself if aggravated by too many broken natural cycles and, consequently, these exploitative societies attacked their demographic/food supply problems in what might be called a "naturally observant" way. Further, their overall solution was not excessively costly in terms of raw material, as only natural surface stone was needed. However, as in the case of Casas Grandes, these systems demanded considerable labor force, not only to create, but also to maintain. For example, these folks constructed check dams in dry arroyos, and these altered the natural aggrading channel into a series of staircases, each having a series of dry stone risers which, like beaver dams, slowed the water flow, checked suspended mud, and thus built up the soil mantle. In the deeper and larger branches of a dendritic pattern, some of these engineers placed staggered stone terrace diversions, which did not tie river banks together, but merely jutted out to the center of the stream beds in order to slow the water flow by shunting it back and forth within its own channel. By such measures, when the mountain-born waters reached the lower valleys, they were clear and sluggish and did not flood the bottomlands, and because of the reduced speed, could easily be diverted into canals and reservoirs, which then supplied the local cities not only with their domestic water needs, but sustained the farmers as well. These pre-Columbian systems are still under study, for it is important that we learn whether or not the terminal rivers, such as the Mimbres or Casas Grandes, were harnessed differently from such flow-through systems as the Colorado and the Rio Grande. But even now, the underlying philosophy behind this engineering concept is most apparent, for the Anasazi and their frontier neighbors strove to inhabit their drainages without disrupting the harmony of river life. Further, these systems, while they were maintained, protected and rejuvenated the mountain slope soils simply by controlling the flow of surface waters.

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USE AND ABUSE OF SOUTHWESTERN RIVERS

HISTORIC MAN--THE SPANIARD

Rev. Charles W. Polzer

Southwestern Mission Research Center, Tucson, Arizona

Without benefit of carbon-dating, geological stratigraphy, or calendric stele we can affirm that the first Spaniards tramped down an Arizona river -- the San Pedro -- four hundred and thirty-two years ago. If it were not for the written record, none of us today would ever have known that Esteban and Fray Marcos de Niza had left their foot-prints in the shifting gravel and sand of an Arizona river.[1] The caravans of Coronado and Melchior Diaz, the scouting parties of Tovar and Cardenas, the slavers of Nuno Guzman, and the prospecting parties of Francisco Ibarra all knew the rivers of Arizona or their counterparts in the mountain drainages of northern Mexico.[2] But for all their presence and for all their ambitions in the land of Cibola traces of these men and their works along the rivers have vanished like the foot-prints they left behind. Then the missionaries came to pacify scores of Indian tribes and shape difficult harmonies between the out-classed Indian and the avaricious miner. These Spaniards did leave traces of their occupation in the labyrinthine workings of silver mines and sometimes elegant churches that dominated the landscapes of desert valleys. But the Spanish presence in the Southwest never left extensive evidence of how the rivers were used, as was the case with the pre-historic peoples of Arizona. And after the Spaniards came the Mexicans. Some priest had shouted something in a Mexican village, and suddenly Spaniards were Mexicans.[3] The family names were the same; the villages, the same; rivers, the same. For most people of an Anglo heritage this pretty well sums up the Spanish contribution to American history -- a conquistador's sword in the desert, a missionary's cross in the valley, and revolution everywhere. So why ask questions about today's rivers when it is perfectly obvious Spain let all that water flow so we could worry about it manana.

When I began research for this paper on the uses and abuses of Arizona's rivers in the Spanish and Mexican periods, I asked myself the usual questions. Where can I find evidence to show that the Spaniards dammed the San Pedro or the Santa Maria (the Santa Cruz today)? What dreams did they have for inundating the dry desert with the voluminous Colorado? What plans did they entertain to resurrect the splendid city of Montezuma on the banks of the Gila? How did they measure and record the flow of their rivers and streams? What court cases would best illustrate the conflict between the Spanish consumer and the inevitable fiend who clutched the water deed in his hand? After reading Spanish documents for several years my notes should reveal something. They did. The Spanish did not dam any rivers. They held no dreams for the Colorado other than hoping it might lead eventually to Anian. They thought only about a modest presidio on the Gila. They measured water flow and rainfall by prayers of petition or thanksgiving for the rain that fell and litigation over water rights is rarer than heresy trials.[4] In short, there are no Spanish answers to Anglo questions. And that should be the end of that. But is it?

Doesn't it strike you as odd that Cabeza de Vaca walked from Florida to Sonora? Or that no Spaniard tried to antedate John Wesley Powell by running the

rapids of the muddy red river? Isn't it curious that Manje did not eventually bring some canoes to explore the Gila? We have too quickly surmised that the Colorado wasn't explored by boat because the canyon was too deep and precipitous, or that the desert rivers were too shallow and short-coursed. But the real answer is that the Spaniards were not riverine explorers. They possessed both the opportunity and technology to explore Arizona's rivers by boat, but their natural preferences leaned toward overland exploration. Bred in the culture of an arid land, the Spaniard first chooses a horse; his last resort, his feet. An Englishman or Frenchman builds a raft -- after all, there's always water, isn't there? So I ceased searching for information to answer questions we always ask about dams and water flow and looked, rather, at Spanish culture. And there were the clues.

As Jose Ortega y Gasset, the twentieth century Spanish pundit, says, a particular culture is a group of solutions by which man responds to a group of fundamental problems.[5] And fundamentally life in the desert Southwest differs very little from life in peninsular Spain. The Spaniard found fertile lands along rivers of limited water supply. He was uncomfortable with the scattered rancherias of the Indians, so he invited and sometimes forced the Indians to dwell in a Spanish style pueblo. Technologically there was little difference between the Indian's use of water for his rancheria home and the Spaniard's use for the pueblo. Both cultures responded to the problem of water supply and use in ways that were wise about arid-land living. Pueblos were built on river banks where alluvial fans could be easily irrigated. The houses were clustered together to conserve valuable arable land and to shorten the trek to the town well. Small check dams diverted the flow of water through arroyos into acequias that fed wells and tanks in the towns. In the river beds diversion dams were built to draw water into the canals from which the fields of grain, beans, squash and melons were irrigated. Water flowed through orchards, fields, and barrios; then it seeped back to the river bed and flowed sluggishly and warm to the next pueblo to repeat the same cycle of service.

The key to the Spanish concept of water use resides in the expression aqua viva -- living water, and living water is flowing water. Nowhere do we find instances or plans among the Spaniards to dam the torrents of summer to provide for the scarcity of the winter. When the Spaniard builds a dam, he does not think of a reservoir, a saving-up against scarcity; rather, he calls his dam a presa, a clutching, a capturing of water in motion. When he supplies a pueblo with water, he does not think of water-mains and water-meters; he thinks of open aqueducts, of gurgling fountains, and convenient wells. When he irrigates his fields, he does not change the course of rivers or stop their flow entirely; he diverts only what he needs to provide for his pueblo. The rest is allowed to flow on because others need that water for survival not only as animals but as humans.

In constructing diversion dams, when beavers didn't provide the services, the dams were designedly weak and efficient only to the point of channelling sufficient water for the purposes of the pueblo. A sudden summer cloudburst or flash flood could send the churning waters of a river slashing through the soft alluvial soils; a greed for too much water might be the cause for winter's famine. Once in 1639 when the first governor of Sonora Pedro Perea insisted on large diversion dams to irrigate his newly planted fields of wheat, thundering floods obliterated

the three dams, ripped out the fields and soil and sent the Indians scurrying to the bluffs to live in safety.[6] The Spaniards learned from the Indians that it was better to have a weak dam and a modest system of irrigation than a stong dam that might change the course of a river and the history of a local village.

The occasional reference to water use in the Spanish records is innocuous at best. Padre Juan Nentwig, who compiled a most worthy book on colonial Sonora, describes the rivers of Arizona more geographically than culturally. Speaking of the Rio Matape which was east of modern Hermosillo, he said:

> The other so-called rivers ... are merely rivulets. There is so little water in the Rio Matape that after irrigating a moderate orchard and ten or twelve fanegas of wheat, there is hardly any left for the consumption of the people.... The river sinks into the ground so that most have to dig wells to recover the water.[7]

To Nentwig the Gila was magnificent; the Verde was so named because of the groves along its banks; and the Salado was voluminous but unpalatable. Padre Eusebio Francisco Kino, who probably had more expansionist dreams for the whole of the Southwest than any colonizer before or since, never suggested the taming of the Colorado or the Gila. In his opinion the Indians were already doing a good job that could only be improved on, not radically changed.[8] Padre Jacobo Sedelmayr pushed the exploration of the Colorado northward and circled back into central Arizona by way of the present Bill Williams river; his assessment was the same as his predecessors in claiming that the rivers of Arizona could provide for many new missions and settlement -- but there was no change in the patterns of use that extended all the way up from Mexico.[9]

Nicolas de LaFora, making a reconnaissance of the presidios of northern New Spain in 1767, recorded only one reference to a dam. His comment is revealing because the dam at the hacienda San Gregorio near Chihuahua held back the water from two springs to run a small mill, "thus obviating the need for river water."[10] But there were few mills in Arizona; grinding was quicker and more reliable with metates or arrastres.

Few people will dispute that the reputation of the Apaches among both Spaniards and Americans was one of savage fear. In the late eighteenth century, however, Spain was making headway in pacifying even this belligerent tribe. Several Apache familes had been settled along the Rio Santa Cruz just north of the presidio of Tucson. Their land was poor and water-starved so they requested a transfer to better lands closer to the pueblo. In a letter to a fellow Franciscan Fray Juan Bautista Llorens commented that the Apaches were to be given some land continuous to the pueblo and that one-fourth of the water supply furnished to Tucson would be allowed to flow on to irrigate their holdings.[11] Again, this example cites only a minor event in the history of water usage, but the generosity of the Spaniard cannot be overlooked. Equitable sharing and responsible cooperation meant survival, if not even comfort, for all who would live under the Southwest sun.

The Mexican period adds little to our report. The turmoil and confusion that Independence brought to Mexico swirled like a dust devil on the frontier as well. The pattern of life was much the same, only a bit more trying because the support of the Crown had ceased. Land holdings became dubious in the fights for title. But the water kept flowing. In all probability the Gadsden Purchase changed little or nothing for many years in the economy of the desert. Consequently the observations of Phocian Way in 1858 would be a valid description of

water use in the Mexican period:

> A small creek runs through the town [of Tucson]. The water is alkaline and warm. Hogs wallow in the creek and the Mexicans water their asses and cattle, wash themselves and their clothes, and drink the water out of the creek. Americans have dug a well and procure tolerably good water which they use. A few acres of land along the bottom are cultivated by irrigation.[12]

This excerpt from Way's diary brings up a subject as yet untouched in this report -- the abuses of Arizona's rivers. Here we are injecting a system of values into our observations on the use of water in the desert. Obviously Phocian Way was not enamored of the multiples uses the Mexicans were making of the Santa Cruz. Water that hogs wallow in, that asses drink from, that humans bathe in, is not fit for consumption. The peasant enjoys more immunities than his urban cousin; he also is cautious about boiling the water he drinks at table. What really constitutes abuse of a water supply? Our clean, piped and purified water would be a luxury beyond comprehension for the Spaniards of history who never knew such benefits of wealth and technology.

Man-caused water pollution goes unmentioned in the documents from missionaries and soldiers. Nature-caused pollution, however, was recorded whenever a cieniga became stagnant or a putrefying animal contaminated one of the scattered mountain-top tanks. I doubt very strongly that this lack of reporting man-caused pollution was an omission. Desert peoples know their very survival depends on the unwritten codes of human decency and cooperation. What water was needed was used; what was not needed was left for the next unknown traveller or resident, whether friend or foe. Apaches might poison water-holes in western novels, but real western Indians did not make that a practice in the real world.

I am sure you have drawn your conclusions already about this brief paper. When I first reviewed my own sources and evidence, I felt the Spanish presence in the Arizona desert could really offer nothing to the modern ecologist. But I discovered wisdom in the ways of those people. Their technological competence could not propel them to create "humid oases" in a barren wasteland, nor did their ambitions compel them to develop a technology that would. Yet the Spaniard transformed the Sonoran desert into a productive garden land never before excelled by indigenous peoples. But after the collapse of the mission system the discipline that protected the careful balance between productivity and profit-making vanished; the land was raped by ravenous cattle and sheep while arid-minded men cursed the dust and declining wealth.[13]

I am sure you see the point of this lesson from history. More than anywhere else on earth man must be the master of his destiny on the desert. He must seek a better life for himself and his progeny; he must devise an ever more accommodating technology; and he must accept the limitations imposed by the natural world until he has reached a point where he can use that technology in harmony with the land around him. Ortega y Gasset put it this way:

> Landscape does not determine, casually and inexorably, the destinies of history. Geography does not drag history along behind it; it merely incites history. The arid land which surrounds us is not a fate imposed on us, but a problem set for us. Each people finds its problem set by the land before it, and solves it in its own way, sometimes well and sometimes badly. Modern landscapes are the results of that solution.
>
> Just as one knows the inner depths of a man by observing the woman he chooses, so there are few things which reveal a people so subtly as the landscapes they accept.[14]

We live in an arid land that knew the delicate respect of Spanish culture; if it becomes a barren waste, it will only be a sun-drenched monument to our own dried-up inner selves. Arid men make arid lands.

FOOTNOTES

[1] In a frenzy over "firsts" some like to think that Alvar Nuñez Cabeza de Vaca, the ship-wrecked survivor of Narváez' Florida expedition, was the proto-hiker of southern Arizona. His trek took him to El Paso, but after that he followed the customary route to Corazones which took him via Guachinera and into the lower Sonora River valley, missing Arizona by scant miles. Postulating that Esteban and Fray Marcos de Niza returned to the land of Cibola via the village of Corazones, the only logical route north was via the San Pedro that was later followed by Francisco Vásquez de Coronado, in 1540.

[2] Melchoir Díaz was sent westward to meet the naval support for Coronado; that tiny flotilla was under command of Hernando de Alarcón who eventually reached the mouth of the Colorado and made their way at least up to the Gila junction. The rivers were remarkable, but no one knew exactly where they were. Coronado sent Pedro de Tovar to conquer the Hopi and he brought back news of a large river which followed on to a land of giant people (quite probably the Yumas). To ascertain the facts another scouting party went out under Gárcia López de Cárdenas and they managed to stand on the brink of the Grand Canyon without being able to draw on the water far below to slake their thirst.

For Cabeza de Vaca see: Cleve Hallenbeck, Alvar Nuñez Cabez de Vaca, 1940; for Coronado see George P. Hammond and Agapito Rey, editors, Narratives of the Coronado Expedition, 1540-1542, Quivira Society, 1940; for Melchoir Diaz see the same; for Tovar and Cardenas, see the same; for Nuño Guzman see Hubert Howe Bancroft, North Mexican States; for Francisco Ibarra see J. Lloyd Mecham, Francisco Ibarra and Nueva Viscaya, Duke Univ., 1927;

[3] The reference is to the "Grito de Dolores" of Padre Miguel Hidalso in 1810.

[4] In a review of the Archives of Hidalgo del Parral, Chihuahua, Mexico, there were some four listed cases involving water rights or water flow cases, which pertain to the nature of this study. The search was carried through 1726 and the cases are all in the section on Administrativo y Guerra: 1685A, fram 65sq. Aguirre vs. Montenegro; 1697A, frame 354; 1702, frame 371 on water rights; 1704, frame 933, 941 or water use; 1721A, frame 4, appeal for use of water for Conchos Indians. The litigations do not affect the findings of this study although they do corroborate the approach described in the Spanish attitude toward water flow, cooperation, and recycling.

[5] José Ortega y Gasset, "A Theory about Andalusia," in the translation by Mildred Adams published as Invertebrate Spain (W.W. Norton, New York, 1937), p. 92. Unfortunately this volume uses a title of a series of essays by Ortega y Gasset but the collection presented in the English translation is not equivalent, hence the title of this essay is also given in the note.

[6] Information cited in a Requirimiento filed by Leonardo Játino, the newly appointed Visitor of the missions on the Sonora rivers; done in Matape, March 21, 1640. Archivo Histórico de Hacienda (AHH) Temporalidades 1126, expediente 1.

[7] Padre Juan Nentwig, Rudo Ensayo, trans. Eusebio Guiteras, Arizona Silhouettes, Tucson, 1951. p. 9.

[8] Eusebio Francisco Kino, trans. Herbert Bolton, Kino's Historical Memoirs of the Pimería Alta (Berkeley: University of California, 1948) Vol. I, p. 242, sq.

[9] Ronald Ives, trans. Sedelmayr's Relacion of 1746, Smithsonian Institution, Anthropological Papers No. 9, Washington, 1939.

[10] Nicolas La Fora, Relacion of an Inspection of the Frontier, 1767, Quivira Society, 19__. p. 134.

[11] Fray Diego Bringas to the King, unpublished manuscript translation by Bernard Fontana and Daniel Matson, Arizona State Museum Tucson. p. 78 sq. The Bringas report was written but never sent to the King in 1796. Original Spanish is in the Civezza Collection, Aetaneo Pontificale Antonianum, Rome.

[12] W. Clement Eaton, "Frontier Life in Southern Arizona, 1858-61," Southwest Historical Quarterly, Vol. XXXVI, pp. 173-92.

[13] James Rodney Hastings and Raymond Turner, The Changing Mile (Tucson: University of Arizona Press. 1965), p. 5.

[14] Ortega y Gasset, ibid., "Arid Plains, Arid Men," p. 164.

USE AND ABUSE OF SOUTHWESTERN RIVERS

HISTORIC MAN--THE ANGLO

Bert Fireman

Arizona State University, Tempe, Arizona

My able predecessors on this symposium have delineated that in aboriginal times the rivers of the Southwest were greatly used but little abused by native peoples. The limitations of stone tools and native engineering skills could have done little to the rivers other than to sometimes decrease their flow below the brush and rock dams of the weir type that diverted water into hand-dug canals. The amount of clay Indians dug for pottery making, fibers and plants they gathered for weaving and home construction, or for their weapons, and the edible plants they gathered near the streams could not possibly have disturbed nature's balance. Nor did the Spanish, as Father Polzer has explained, pause long enough in their search for gold or their conversion of souls to upset the ecology.

Indeed, there was too little use of the rivers of the Southwest by the horde of Anglo-American Argonauts, immigrants, and settlers in the first half of the nineteenth century to even suggest use of the term abuse.

The first Anglos to use our rivers were the restless, irrepressible trappers who having harvested the best of the abundant beaver from the Missouri River drainage in the first quarter of the nineteenth century, now turned to a similar quest south of the Sangre de Cristo Mountains which until then marked the southern border of the rendezvous country west of the Rockies. Along streams of this Spanish Southwest they hoped to exploit the somewhat smaller, not-quite-soluxuriant but nevertheless desirable and profitable Sonora beaver. Taos became the trappers' new rendezvous; the Santa Fe Trail replaced the Missouri River as the highway for the furs and frolicking of this vagabond industry, while St. Louis remained the huge marketplace for plews now being gathered on the Spanish Borderlands instead of in the Pacific Northwest and the Upper Rockies.

Westward from the Rio Grande trappers of American and French-Canadian origins followed the Gila through the Apache country and into the desert lands of friendlier Pimas and Maricopas. They exploited tributaries of the Gila and even turned northward along the murky Colorado until the Grand Canyon blocked entry into older trapper haunts nearer the sources of the Missouri River network. From the tales told by these trappers American travel and exploration literature was enlivened with the romantic episodes of the Patties, father and son; with the exploits of young Kit Carson and the Ewing Young trapping party; with the observations of George Ruxton, an Englishman who might have been a spy for his King, but who nevertheless described Bill Williams and other trappers with humorous detail and admiration. Among the Anglos was a coterie of French-Canadians who brought their skills and left their traces in the Southwest -- names like Leroux, Roubidoux, and Baptiste Charbonneau, the latter that tiny baby born to the half-legendary Sacajawea during the Lewis and Clark expedition at the dawn of the century.

Aside from quickly exhausting the Sonora beaver, upsetting the political complacency of New Mexico with their scorn of law and regulation, and inciting the enmity of the young men of Santa Fe and Taos with their dynamic wenching, the trappers made little use and did no abuse to the rivers of the Southwest.

They did, however, demonstrate that the river routes were also highways to California, along such early day freeways bordered with good grazing and dependable

water, the drovers of New Mexico and California were, in the years before the Mexican War, to drive their surplus herds across a land where the pious Franciscans Escalante and Garces in the eighteenth century could not quite achieve the desired overland linkage between the Northern frontier capitals of Santa Fe and Monterey. Such drives were by the attritions of the trial to replenish the domestic grazing herds of the desert Indians and often satisfy the hunter Apaches' yearning for fresh meat in a land where wild game was sparse.

These criss-crossing cattle and sheep drives enlarged the riverband trails leading across Arizona, making them more visible and viable for the two American military detachments -- Kearny's Dragoons and Cooke's Mormon Battalion -- which hurried westward toward the conquest of California in the War with Mexico. Even before the war ended the Gold Rush began. The Gila was an all-seasons road, hotter but better watered and less hazardous than the long prairie route through South Pass, along the Humbolt sinks, and over the Sierra Nevada. The ruts of thousands of wagons cut deeply along the south bank of the Gila and other Southern Arizona streams. At the end of the brief, bloody extension of American manifest destiny that culminated in the conquest of Mexico, the Southwestern rivers were assigned a new, political role. The Rio Grande -- or the Rio Bravo as the outmanned Mexicans called it -- already had been the cause of international dispute. Now the Gila was to form part of the new boundary line between helpless Mexico and muscle-proud United States. In the Treaty of Guadalupe Hidalgo dictated in 1848, the possibility of the Gila as a potential railroad route to the Pacific was recognized, but it was not achieved for lack of proper geographical knowledge. Immediately afterwards the U. S. Army Topographical Engineers and privately-funded surveyors fanned out into the Southwest, mapping routes for the iron rails to link the cotton-rich South with the Pacific shore beyond which lay the markets of Cathay. American diplomacy was now directed toward acquiring more land south of this natural boundary, culminating the Mexican acceptance of the Gadsden Purchase in 1854 -- a kind of frothy desert dessert to feed the continuing American hunger for railroad routes to the Pacific even after the gigantic Mexican Cession of 1848.

Into these lands bordered on the north by the Gila and flanked on the east by the Rio Grande and on the west by the Colorado, came American mineral seekers of the post-Gold Rush period. Many Argonauts who did not find their El Dorado in California now joined a backwash into the Despoblado -- the unpopulated area of Arizona, where three centuries before Coronado had unknowingly marched past rich silver and copper deposits, ignoring their worth because his conquistador eyes were focused on the Seven Golden Cities of Cibola, treasure that existed only in imagination.

Reality came with a shock to the Southwest as the miners' horde scattered through Arizona and southern New Mexico along streams that had known white men before only as trappers and transient explorers. Now the Anglo came to dig and delve for riches, and with his avarice and determination he brought to the area the first capability of misusing the land. To provide water for placer or hydraulic mining, he diverted creeks and built up ugly piles of rubble along Lynx Creek and Big Bug Creek in the Bradshaw Mountains that before had only been hunting and gathering sites. The hydraulic mining of Arizona was miniscule compared to that in California, luckily. But Arrastras along streams, the pounding of stamp mills, an occasional water wheel and flume, and the woodcutters' axes bringing

fuel to the hungry boilers of mining hoists and mills soon scarred the hills and streams. With more population came the ponding of streams for watering of cattle, fords and ferries at good river crossings, towns, cities, fields, more roads.

Hard on the heels of this vigorous mining frontier came an expansion of population and the need for home-grown food products. The crude brush-and-rock weirs of the Indians by 1900 were being replaced by storage dams of earth, rock, wood cribs, and even concrete. When these washed out the stored floodwaters did damage downstream more sharp and tragic than even the seasonal floods of the past. The Walnut Creek disaster on the Hassayampa in 1890 took nearly a hundred lives and devastated urban, mining and farming properties for a great distance, signaling that what man has wrought may also be a Frankenstein destroying his own kind.

As Arizona became settled but before railroads could be built, the Colorado River provided a unique chapter in the use of Southwestern streams. From 1852 until 1878 between the mouth of the Colorado River and Yuma, and for another dozen years as far north as the present river crossing at Needles, steamboats of shallow draft sailed the Colorado, hauling soldiers and their baggage and goods from the outside world to the Army posts built in the task of bringing the Indians to submission, supplying the needs of towns springing up rapidly in Arizona. Downstream passage carried ore, wool, hides, mohair and other products of the desert country to coastal markets. The river and its steamers also served internal American political purposes. In 1857 the steamer EXPLORER with Lt. Joseph Christmas Ives in charge penetrated almost to the frontiers of Utah as the U. S. Army tested the river as a means of hemming in the Mormons who were feared growing too independent of federal control. For some years afterwards, before the Central Pacific and the Union Pacific made their famed linkage at Promontory Point in 1869, Mormon merchants and entrepreneurs tried to use the river to import needed goods to Utah at lower cost than by the slow wagon trails across mountains and deserts both east and west of the Salt Lake basin.

Where the railroad came to Arizona in 1878, meeting the river steamers at the mouth of the Gila, the Colorado crossing gave rise to the city of Yuma. There politicians offered a river bluff as a site for the territorial prison which for thirty years provided trade and political jobs for Yuma, wild legends for pulp magazine writers, and Arizona's first major problem of water pollution. The muddy Colorado provided domestic water for Yuma's needs. Nearly everybody in those early years had a barrel in which the silt of river water settled for a few days. Then the water was poured poured into an olla, which was hung in a shady, windy place, and the water soon was cooled to taste. But by the turn of the century it was apparent to the least hygenic of Yuma residents that the raw sewerage from the prison which was dumped into the river was contaminating the local water supply.

The greatest use of Arizona's rivers -- and their misuse within the context of this symposium -- was to wait until the passage of the national Reclamation Act in 1902 provided federal funds where private capital had been unavailable for construction of storage dams and irrigation works. With construction of major projects under this program, such as the Laguna Dam on the Colorado completed in 1909 to turn water into the Imperial Valley, the Theodore Roosevelt Dam dedicated in 1911, and others, the true multiple use of our streams was achieved. Huge quantities of flood waters could now be stored for regulated use during growing seasons. Flood damage was substantially reduced. At Roosevelt Dam a power plant was devel-

developed, initially to manufacture cement for the dam's construction, and later it was expanded to augment pumping in the Salt River Valley. Surplus power was sold to mines over the mountains a short distance at Globe, thus assisting in expansion of the copper mining industry and adding to another aspect of man's misuse of his resources -- air pollution.

With the creation of a series of reservoirs on the Salt and Verde River systems and on the Colorado, recreation use developed as a major by-product of the streams. Fun rather than food became the prime objective of fishermen. Once more habitations crowded against river shores, but now the residents were not Indians living there to draw their domestic needs, to emulsify clay for their pottery, to harvest willows for their arrow shafts and brush for their roof-tops, or even fish protein to supplement a scanty vegetable diet. Along the Colorado, as one example of new uses found for the river, the Mohave tribe has developed tourist facilities to lure the white funseeker. The Indian purpose is not now to lift the white man's hair, as sometimes it was in reaction to the white invasion of the Southwest; now the Indians simply want to separate him from those willingly-spent greenbacks. In place of the simple life of their ancestors, the Indians themselves thus are adding to the misuse of their streams in the growing piles of plastic plates, uncycled beer cans and discarded tires. They have learned some lessons from the whites -- one that the rivers they used only for basic needs a century ago may be more profitable if over used without regard for tomorrow.

POLITICS AND THE COLORADO RIVER

Wesley E. Steiner

Arizona Water Commission
Phoenix, Arizona

The symposium program lists my subject as "Politics and Water Rights." I will take considerable liberty with that subject and will limit my remarks to past and future problems and political solutions on the Colorado River. I do this because this is an area in which I can speak largely from information gained throught an intimate involvement with the Colorado starting in 1965 and continuing to date.

The Colorado River is the only major stream in the United States whose water supply is fully utilized. In achieving this distinction the Colorado has known more than its share of controversy. All problems that couldn't be resolved among the seven states of the Colorado River Basin through negotiation, and that means most of them, ended up either in the courts or on the floor of Congress. Because of the limitations of time, I will present only a very brief history leading up to the Colorado River Basin Project Act of 1968, and concentrate on the political compromises of that Act and the problems that still face us. I would also like to bring to your attention today efforts that we are making within State Government in Arizona to avoid leaving completely to political solution, a problem of great importance to the State. I allude to the allocation of our remaining entitlement in the Colorado River.

The early water history of the Colorado is largely a struggle between the haves and the have-nots, between areas and states slow to develop and those in which development came early and rapidly. The unregulated flows of the Colorado were fully developed and utilized in the Lower Colorado River Basin by the early 1900's. The resulting economy was subject to the vagaries of nature, either too little water or too much, and in 1905 was ravaged by a particularly devastating flood. The need for construction of major conservation and flood control storage along the Colorado became widely recognized, and the river and its problems were subjected to several intensive studies culminating in the Fall-Davis Report of 1920. This report recommended the construction with Government funds of a reservoir at or near Boulder Canyon. Implementation of the Boulder Canyon Project was delayed for a decade, however. The slowly developing Upper Basin States of Colorado, Wyoming, New Mexico, and Utah were apprehensive that the Boulder Canyon Project would result in rapid expansion of irrigation in the Lower Basin and would permit, through the exercise of the western doctrine of prior appropriation, the development of rights to all of the waters of the Colorado River to the detriment of the Upper Basin.

The political impasse resulting from the opposition of the Upper Basin states to the construction of the Boulder Canyon Project led to the negotiation and adoption of the Colorado River Compact, the first Interstate Compact to allocate the waters of an interstate stream. The purpose of the Compact was to equitably apportion the waters between the two basins, and to provide protection for the Upper Basin through a reservation of water for that basin.

The Colorado River Compact was signed on November 24, 1922 by the Compact Negotiators. All states of the Basin except the State of Arizona ratified the Compact by April of 1923.

Numerous conferences were held from 1923 through 1927 in an effort to obtain ratification by Arizona of the Compact and to negotiate a three-state compact dividing the waters allocated to the Lower Colorado River Basin. These efforts failed, however, because of the inability of Arizona and California to agree on the division of the 8.5 million acre-feet allocated to the Lower Basin by Articles IIIA and IIIB of the Compact.

The failure to bring about seven state ratification of the Compact delayed action by Congress on the construction of the Boulder Canyon Project. Finally, in 1928 the Boulder Canyon Project Act was adopted on the basis of California and five other states ratifying with the further proviso that California limit its consumptive use of the 7.5 million acre-feet apportioned by Article IIIA of the Colorado River Compact to 4.4 million acre-feet per year.

California agricultural and municipal interests entered into an agreement in 1931 establishing an internal order to priority of use within the State of California of 5.362 million acre-feet of Colorado River water. Contracts entered into between the California entities and the Secretary of the Interior for a total of 5.362 million acre-feet included these priorities.

In 1944 the State of Arizona, to enable its entry into a contract with the Department of the Interior for 2.8 million acre-feet of water from the Colorado, finally ratified the Colorado River Compact.

The Colorado River Compact recognized the rights of the Republic of Mexico to a supply from the Colorado without setting forth the amount. In 1944 the United States signed a Treaty guaranteeing delivery to Mexico, except in unusual circumstances, of 1.5 million acre-feet annually. The Treaty on the Colorado was part of a larger instrument involving also the waters of the Rio Grande and the Tijuana Rivers. The fact that Mexico was granted in the Treaty approximately twice the supply from the Colorado that she was then using, the fact that Senator Connally of Texas occupied the strategic position of Chairman of the Senate Committee on Foreign Relations, the Committee that had to approve the Treaty; and the fact that Texas gained water on the Rio Grande explains the widely held view among water people of the Colorado River Basin that water from the Colorado was given to Mexico in exchange for additional Rio Grande water for Texas.

As development began to accelerate in the Upper Colorado River Basin the states of that Basin undertook negotiation of a compact to apportion the waters allocated by the Colorado River Compact to the Upper Basin. To their credit they successfully consummated this effort in 1948.

It became obvious soon after completion of Hoover Dam that the Colorado River could not support California's contracts for 5.362 million acre-feet per annum, Nevada's contract for .3 million acre-feet, and Arizona's contract for 2.8 million acre-feet, but the Lower Basin States of California, Arizona, and Nevada remained unable to agree upon a tri-state compact to divide the waters available to the Lower Basin. California insisted that the contracts of California

agencies with the Secretary of the Interior totaling 5.362 million acre-feet remain inviolate and take precedence over subsequent contracts. This position, if honored by Arizona and Nevada, would have left them with little wet water and a handful of paper rights.

When Arizona went before the Congress of the United States in 1948 to seek authorization of the Central Arizona Project and the ability to put its remaining entitlement in the Colorado River to use, she found that she was strongly opposed by the State of California. Arizona made repeated attempts over the next few years to gain project authorization, but was blocked by the superior political force of California. In 1951 Congress deferred further deliberations on a Central Arizona Project in the worlds of the Committee report "until such time as the use of the water in the Lower Colorado River Basin is either adjudicated or binding or mutual agreement as to the use of the waters is reached by the states of the Lower Colorado River Basin."

Shortly thereafter Arizona brought action in the Supreme Court of the United States against the State of California to obtain such an adjudication. A long and expensive case followed. After twelve years of argument and deliberation the Supreme Court on March 9, 1964, issued its decree. It found that California was entitled to 4.4 million acre-feet, Arizona 2.8 million, and Nevada .3 million of the first 7.5 million acre-feet available in the Lower Colorado River. The court did not attempt, however, to establish priorities in the event of shortage, but rather left that problem to the discretion of the Secretary of the Interior or to the future action of Congress. Since none of the hydrologists who testified before the court or, for that matter, any who have subsequently studied the water supply of the Colorado River envision a full 7.5 million acre-feet being available at all times for consumptive use by the three lower basin states, the court's decree left a major issue to be resolved either by the Secretary or by the Congress.

This is a key point, the root of the conflict between the states of Arizona and California as Arizona, having established its water right, renewed its efforts to gain authorization of the Central Arizona Project. California maintained that since, under the court's decree she would be forced as soon as the Central Arizona Project went into operation to reduce from a contractual right of 5.362 million acre-feet and a current use of about 5.1 million acre-feet down to a use of 4.4 million acre-feet, that her 4.4 million acre-feet should have priority over the Central Arizona Project. Arizona argued that all rights should be equal and, in the event of shortage, supplies should be prorated in accordance with the formula recommended by the special master of the Supreme Court. With her 38 congressmen, California prevailed, but only after joining Arizona and the other states of the Colorado River Basin in support of provisions that recognize the Mexican Treaty Burden of 1.5 million acre-feet a year as a National obligation rather than that of the seven Colorado River Basin states alone. Under these provisions, which Congress approved, relief of the Mexican Treaty Burden is the first responsibility of any system developed to augment the Colorado River, and the cost of providing a new supply in the amount of the Mexican Treaty

requirement plus the losses associated therewith is to be borne by the general taxpayers of the United States. Once this provision is implemented, the 4.4 priority to California becomes virtually meaningless. This fact enabled Arizona's Congressional Delegation to agree, even though reluctantly, to the 4.4 priority to California.

Still other political compromises were required to move the Colorado River Basin Project Act through the committees of Congress. In spite of the protection provided by the Colorado River Compact, the Upper Basin states were still fearful that the completion of the Central Arizona Project and the commitment to use of another sizable increment of supply would jeopardize their future development. They feared that the Lower Basin states, with their Compact allotment fully utilized and the unused portion of the Upper Basin entitlement temporarily supporting uses in the Lower Basin with a higher economic return, would be able to successfully oppose the authorization of future Federal projects in the Upper Basin. Hence, the Upper Basin states insisted on concurrent authorization and construction of five projects in Colorado and New Mexico and the Dixie Project in Utah, and priority study of some additional projects in the State of Utah. The State of Wyoming, whose development lags behind that of other Upper Basin states, didn't have a project ready for authorization, and elected to oppose the Colorado River Project Act. The position of Congressman Wayne Aspinall from the State of Colorado, as Chairman of the House Interior and Insular Affairs Committee, assured the success of the Upper Basin concensus position.

The early legislation included construction of Bridge and Marble Canyon Dams on the Colorado River as features of the Central Arizona Project to provide power for pumping project water into the Phoenix and Tucson areas, and to provide surplus revenues to assist in repayment. Preservationist groups opposed these features on the grounds that they would unnecessarily adversely affect the Grand Canyon as coal and nuclear steam generation were less expensive than hydro-power generation. Proponents of the Central Arizona Project, in the face of the mounting political strength of the preservationists, backed off and with the assistance of the Secretary of the Interior, switched to a joint private-federal steam plant at Page for the production of the necessary capacity and energy to pump CAP water into central Arizona. It is interesting to note that this steam plant and all other fossil fuel and nuclear plants which were proposed by preservationists as better alternatives to construction of hydro-electric projects at Bridge and Marble Canyons are now under fire by those same interests.

The Colorado River Project Act as introduced in the House included provisions calling for feasibility level studies of water supplies and requirements, and plans to meet those requirements throughout the West. Importantly, these included feasibility level studies of interregional transfers of water. As the legislation passed the House, it still included provisions for study of interregional transfers; however, in the Senate Interior and Insular Affairs Committee, under the chairmanship of Senator Jackson of the State of

Washington, the studies were downgraded to reconnaissance level and a ten-year moratorium against study of interregional transfers was imposed. The Pacific Northwest argued that they didn't know what their resources were nor what their future requirements might be, and insisted on the ten-year moratorium to provide a study period to make these determinations. It is a fact, moreover, that the desire of the Pacific Southwest to look at the water supplies of the Pacific Northwest made marvelous re-election campaign material for Northwest congressmen.

The legislation, as proposed and as passed, contained strong "area of origin-state of origin" protection--the strongest, I believe, ever written into law. This language sprang from attempts to circumvent the Pacific Northwest argument against study of interregional transfers. Based upon California's experience in its efforts to move water from northern California to southern California, the drafters were aware that the people of an area of origin would demand more than a simple reservation of water to meet their future needs. As the cheapest supplies are normally developed first, those that remain for use in the areas of origin may be so expensive as to not be economically developable. In recognition of this problem the Act includes economic protection for the area of origin in these terms: "In the event that the Secretary shall... plan works to import water into the Colorado River System sources outside the natural drainage areas of the System, he shall make provisions for adequate and equitable protection of the interests of the states and areas of origin, including assistance from funds specified in this Act, to the end that water supplies may be available for use in such states and areas of origin adequate to satisfy their ultimate requirements at prices to users not adversely affected by the exportation of water to the Colorado River System."

In addition, the drafters of the Act recognized that the inhabitants of the areas of origin would have little confidence in projections of their future requirements made by outsiders; that they would insist on studies of their own and, in the final analysis, would demand protection against their own inability to foresee the future with confidence. To circumvent this problem and the endless chain of studies that might result from lack of confidence in future projections the Act guarantees to the areas and states of origin the absolute right of recall in the event future projections are in error. This places upon the importer the full risk that the projections of future use in the area of origin will not be exceeded, and the responsibility to extend, at his own expense, his import system further north to other areas of surplus in the event the projections are exceeded and the area of origin needs additional water. These strong provisions, while offered willingly by the southwest and accepted gratefully by the northwest, did not allay the fears of the northwest, and we find ourselves burdened with the ridiculous situation where mere studies, not construction, are precluded for a ten-year period.

One of the most important political consequences of the passage of the Colorado River Project Act is that it brought the three Lower Basin states--California, Arizona, and Nevada--into a position of virtual unanimity on water matters. This is especially true of the States of California and Arizona and is

largely due to an awakening to the fact that the Colorado River, even under total development, cannot meet the water requirements of the Pacific Southwest and that the future of all areas in the Colorado River Basin require that the supplies of the Basin be augmented from outside. This isn't going to be easy to accomplish and will require a united effort. And while the Colorado River Basin Project Act has brought relative peace to the river it has not resolved all of our problems.

I would like to identify the remaining major problem areas for you. These are all problems for which negotiated solutions among state governments will be sought, but failing that, will end up either in the courts or in the Congress.

The first of these problems involves the responsibility for the Mexican Water Treaty delivery requirement. The Colorado River Compact provides that the Treaty obligation is to be met first from surplus waters above the quantities apportioned to the states, but that if this amount is insufficient, any deficiency shall be borne equally by the Upper and Lower Basins and with the Upper Basin required to deliver one-half of the deficiency at Lee Ferry. Upper Basin representatives interpret the Compact in such a manner as to find that their obligation is zero. On the other hand, the Lower Basin representatives compute the Upper Basin Treaty obligation to be 750 thousand acre-feet plus half of the losses attendant with delivering the water to Mexico, a total of approximately 900 thousand acre-feet a year.

Once the Colorado River Basin Project Act provisions making the Mexican Treaty Burden a National obligation have been implemented, the two basins will be relieved of these responsibilities. Implementation, however, is still many years away, and with full utilization of the Colorado River, settlement of this dispute may be necessary prior to such relief.

As the waters of the Colorado River are used and re-used in their travel downstream, their salt content increases. Much of the salt content originates in the Upper Basin. In January of 1967, the seven Colorado River Basin States agreed upon guidelines for formulating water quality standards for the Colorado River System as a part of the National effort to establish water quality standards. The states, however, stopped short of attempting to define quantitative salinity standards. The states of the Upper Basin feared that the establishment of definitive standards would tend to preclude future growth of use of the Upper Basin's Colorado River entitlement. The Lower Basin states, on the other hand, are being hurt economically by the continued increase in the salt content of the Colorado River. The day will come when definitive standards must be established on the river and when it does, there will be conflict between the two basins unless one or both of the following steps are taken.

The most effective way to solve the salinity problems of the Colorado River is to augment it's flows with supplies of appreciably lower salt content. The Federal Water Pollution Control Administration, in a study that is just concluding, have also identified a number of projects that would reduce the input of salt to the river within the Colorado River Basin itself. It is encouraging to note that the states of the Colorado River Basin are all rallying around in a position in support

of feasibility level studies of these potential water quality control projects.

There are other problems still outstanding between the two basins, but time is running short, so let me now move on to the internal problem within the State of Arizona for which we are attempting to provide a strong technical base so as to limit the impact of political influences.

When then-Secretary of the Interior Stewart Udall met with potential water contractors in Phoenix in January of 1969, he asked them to complete questionnaires expressing their interest in contracting for Central Arizona Project water. The Secretary has received expressions of interest from 68 agencies totaling in excess of 5.2 million acre-feet, or over four times the annual water supply of the Project.

Secretary Udall recognized the importance of the allocation decision to his state and urged that the State come to its own decisions on how this important resource should be allocated. While the Secretary of the Interior has the ultimate authority in allocating these resources, and while the task of making the allocation will be the most controversial yet faced internally in Arizona in implementing the Central Arizona Project, how these valuable resources are apportioned will have such a lasting impact on the future development of Arizona that the charge could not be denied by the State. No other decision, in my opinion, will have a greater effect on what our State looks like in the year 2000 than how we divide and use our remaining Colorado River entitlement.

At the request of Governor Williams, the Arizona Interstate Stream Commission undertook the task of preparing the State's recommendations. To be sure that our recommendations are just and in the best interest of all Arizona, the Commission has undertaken comprehensive investigations of the factors involved and has hired experts in economics, engineering, and law to assist us in these studies. We are attempting to determine the allocation that will maximize the net economic and social benefits to the State. A computerized systems analysis approach has been adopted in the study. Each of the models used in the study has the ability to incorporate realistic constraints, whether physical, economic, political and/or social.

We anticipate presenting the results of our studies to the Advisory Board formed by the Interstate Stream Commission to assist us in our work. The Advisory Board consists of a representative of each potential contractor for Arizona's remaining entitlement in the Colorado River. At last count there were 96 members. The Advisory Board has met four times and has been very helpful in advising us on the assumptions and criteria and necessary input information for the study.

We also plan later this fiscal year a series of public hearings throughout the State to advise the public and seek comments on our proposed water allocations. We have as our objective completion of our studies, review by the Advisory Board and the public, and revision and submission to the Secretary of the Interior by June 30, 1971.

I hope that I have been able to give you some feeling for the political past of the Colorado River and appreciation for the fact that our political problems are not all solved.

INDEX OF AUTHORS