THE UNIVERSITY OF ARIZONA
University Libraries

UA CAMPUS REPOSITORY

Hydrology and Water Resources in Arizona and the Southwest, Volume 1 (1971)

Item type	text; Proceedings
Publisher	Arizona-Nevada Academy of Science
Journal	Hydrology and Water Resources in Arizona and the Southwest
Rights	Copyright ©, where appropriate, is held by the author.
Downloaded	2-May-2016 17:21:14
Link to item	http://hdl.handle.net/10150/300135

VOLUME 1

Peter F. Ffolliott

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

APRIL 22-23, 1971, TEMPE, ARIZONA

VOLUME 1

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

APRIL 22-23, 1971, TEMPE, ARIZONA

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.

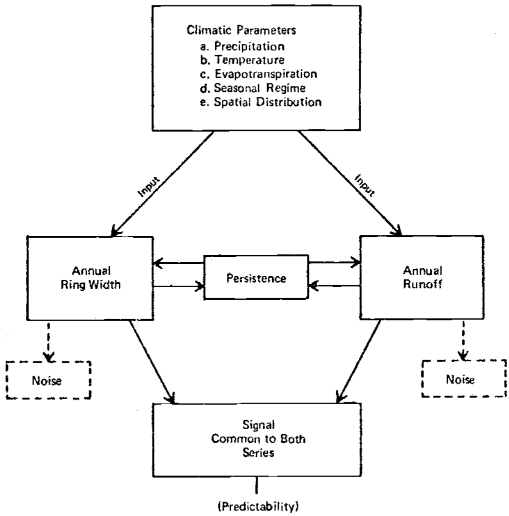


Fig. 1. Schematic diagram of relationship between ring-width series and annual runoff series for medium and large watersheds.

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

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

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, $x_1, x_2, ... x_n$, 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,

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

or

$$\begin{aligned} y_t &= \theta_0 + \theta_1 a_{11}x_1 + \theta_1 a_{12}x_2 + ... + \theta_2 a_{21}x_1 + \theta_2 a_{22}x_2 + ... \\ &= \theta_0 + x_1(\theta_1 a_{11} + \theta_2 a_{21}) + x_2(\theta_1 a_{12} + \theta_2 a_{22}) + ... \qquad \text{for } \xi_1 \text{ and } \xi_2, \end{aligned} \tag{3}$$

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

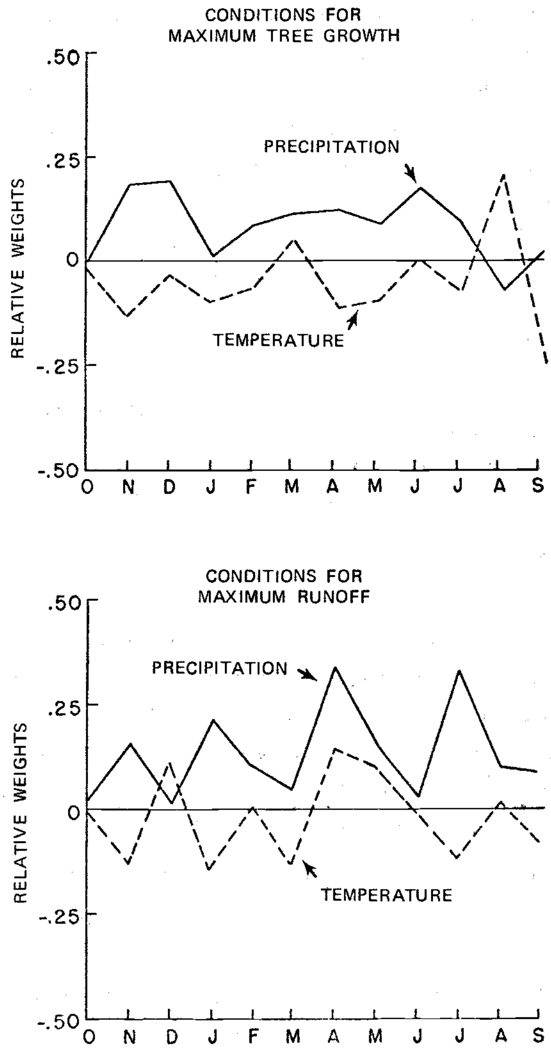


Fig. 2. Comparison of response functions of monthly climatic variables (water year) for tree growth and annual runoff in Upper San Francisco River basin.

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

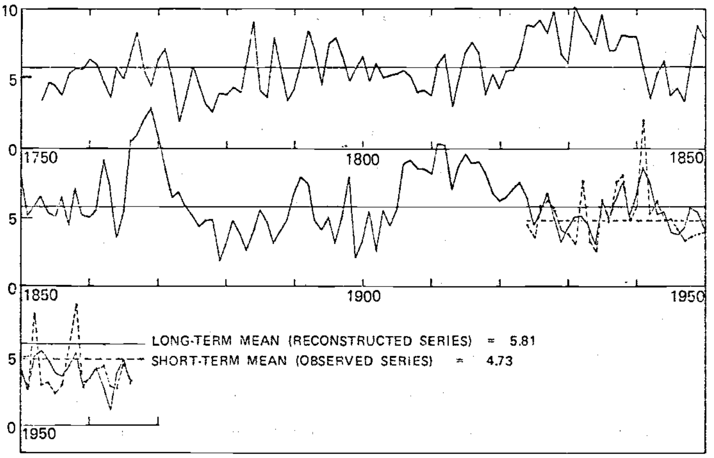


Fig. 3. Reconstructed hydrograph for Bright Angel Creek, 1753-1966 (214 years). Runoff data for this period have been predicted from tree-ring data for the same period. Observed runoff data for 1924-1966 are superimposed with dashed line.

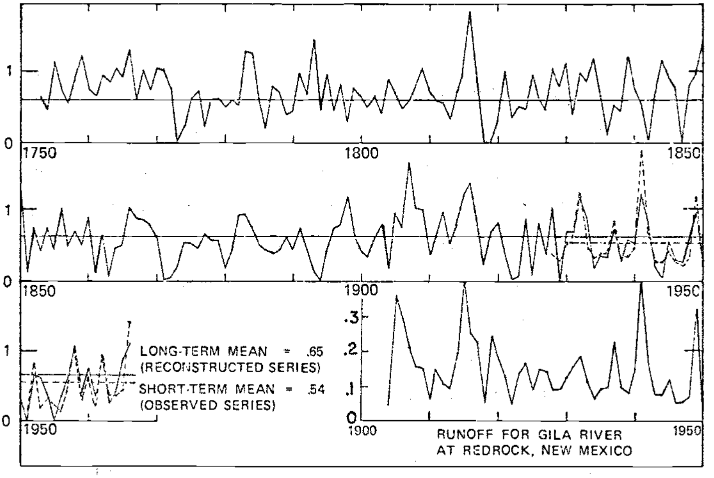


Fig. 4. Reconstructed hydrograph for Upper San Francisco River, 1753-1966 (214 years). Runoff data for this period have been predicted from tree-ring data for the same period. Observed runoff data for 1928-1966 are superimposed with dashed line. For comparison, the runoff record for the Gila River near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

Acknowledgments. The research described herein was made possible by a grant from the Department of Interior, Office of Water Resources Research. The Computer Center at the University of Arizona provided some of the computer time used in the study.

REFERENCES CITED

Fiering, M. B., On the use of correlation to augment data, *J. Amer. Stat. Ass., 57,* 20-32, 1962.

Fiering, M. B., Use of correlation to improve estimates of the mean and variance, 9 pp., *U.S. Geol. Surv. Prof. Pap. 434-C,* 1963.

Fritts, H. C., T. J. Blasing, B. P. Hayden, and J. E. Kutzbach, Multivariate techniques for specifying tree-growth and climate relationships and for reconstructing anomalies in paleoclimate, 48 pp., *Final Report Prepared for Laboratory of Environmental Data Research, Environmental Science Services Administration, Contract E-41-70(N),* 1970.

Johnston, J., *Econometric Methods,* 300 pp., McGraw-Hill, New York, 1963.

Julian, P. R., and H. C. Fritts, On the possibility of quantitatively extending climatic records by means of dendrochronological analysis, pp. 76-82, *Proc. First Statistical Meteorol. Conf.,* Hartford, Conn., May 27-29, 1968.

Matalas, N. C., and B. Jacobs, A correlation procedure for augmenting hydrologic data, 7 pp., *U.S. Geol. Surv. Prof. Pap. 434-E,* 1964.

Mandelbrot, B. B., and J. R. Wallis, Noah, Joseph and operational hydrology, *Water Resour. Res., 4*(5), 909-918, 1968.

Rodríguez-Iturbe, Ignacio, Estimation of statistical parameters for annual river flows, *Water Resour. Res., 5*(6), 1418-1426, 1969.

Stockton, C. W., The feasibility of augmenting hydrologic records using tree-ring data, 172 pp., *Ph.D. Dissertation,* The University of Arizona, Tucson, 1971.

Stokes, M. A., and T. L. Smiley, *An Introduction to Tree-Ring Dating,* 73 pp., The University of Chicago Press, Chicago, 73 pp., 1968.

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

---

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

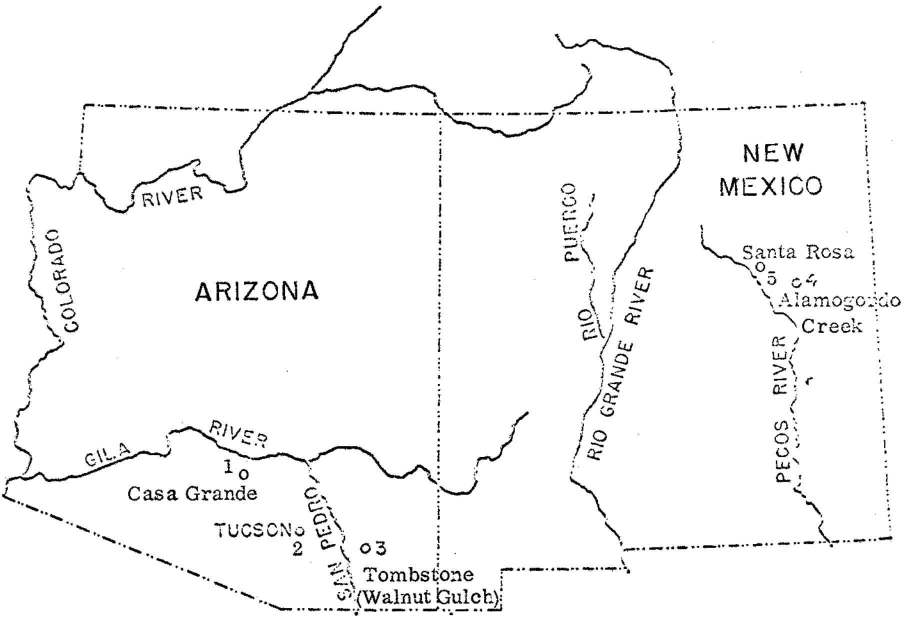


Fig. 1. Location of selected rain gage stations in southern Arizona and eastern New Mexico.

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.

SELECTED BIBLIOGRAPHY

Fogel, M. M. The effect of spatial and temporal variations of rainfall on runoff from small semiarid watersheds. Dissertation, Dept. of Watershed Management, Univ. of Arizona, 90 pp., 1968.

Gifford, R.O., Ashcroft, G.L., and Magnuson, M.D. Probability of selected precipitation amounts in the western region of the United States, Agr. Expr. Sta., Univ. of Nevada, Oct. 1967.

Hershfield, D. M. Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. U.S. Weather Bureau Tech. Paper 40, 1961.

Keppel, R. V. A record storm event on the Alamogordo Creek watershed in eastern New Mexico. J. Geophys. Res. 68(16):4877-4880, 1963.

Leopold, Luna B. Characteristics of heavy rainfall in New Mexico and Arizona. Trans. Am. Soc. Civil Engrs. 109:837-862, 1944.

Osborn, H. B., Lane, L. J., and Hundley, J. F. Optimum gaging of thunderstorm rainfall in southeastern Arizona. Presented AGU National Meeting, San Francisco, Dec. 1969. (Accepted for publ. by AGU.)

Osborn, H. B., and Renard, K. G. Thunderstorm runoff on the Walnut Gulch Experimental Watershed, Arizona, U.S.A. Presented and published Proc. IASH Symp. on Results of Research on Representative and Experimental Basins, Wellington, New Zealand, Dec. 1970.

Sellers, W. D. The Climate of Arizona. In Arizona Climate by C. R. Greene and W. D. Sellers, University of Arizona Press, Tucson, pp. 5-64, 1960.

Yarnell, David L. Rainfall intensity-frequency data. Miscellaneous Publ. No. 204, USDA, August 1935.

UNCERTAINTIES IN DIGITAL-COMPUTER MODELING OF GROUND-WATER BASINS[1]

Joseph S. Gates
U.S. Geological Survey, Tucson, Arizona

Chester C. Kisiel
Hydrology and Water Resources, University of Arizona

INTRODUCTION

Digital-computer modeling of ground-water basins is rapidly becoming a popular method of modeling the response of basins to various stresses of water development. A digital model of the Tucson basin has been constructed for use as a research tool in studies of the errors related to digital models and of the worth of hydrologic data to such models. Much future modeling may be poorly done if errors and limitations in digital models are not fully appreciated by ground-water hydrologists. This progress report briefly discusses modeling errors in general and discusses the potential use of statistical decision theory in determining the worth of additional data for model improvement. The Tucson basin model is being used to evaluate this technique, although definitive results have not been obtained as yet.

THE TUCSON BASIN MODEL

The digital model of the Tucson basin covers about 470 square miles over a length of about 50 miles of the basin north of the Pima County-Santa Cruz County line. Figure 1 shows the area included in the model as well as the area of the electrical-analog model of the basin constructed by the U.S. Geological Survey, from which much of the initial data was obtained. Two digital models actually have been constructed, one with 1,890 nodes of $\frac{1}{4}$-square-mile area each and one with 509 nodes of 1 square mile each. The less detailed model was developed to reduce computation times during worth-of-data studies.

---

[1]Publication authorized by the Director, U.S. Geological Survey.

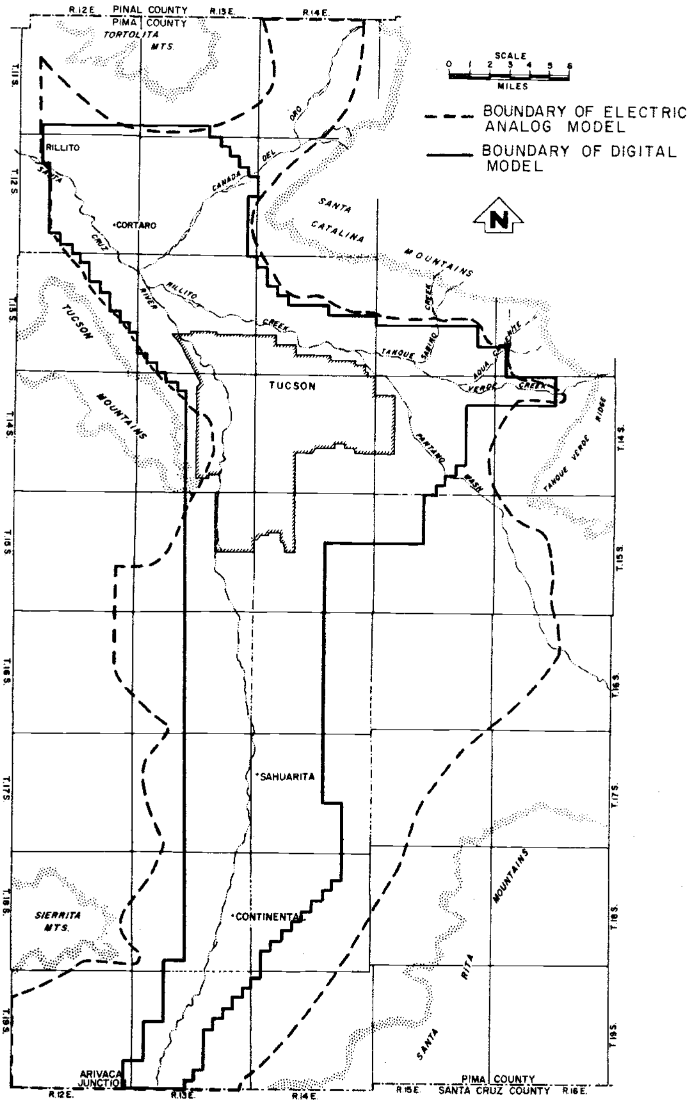


FIGURE I. MAP OF THE TUCSON BASIN, ARIZONA SHOWING THE AREAS INCLUDED IN THE ELECTRIC-ANALOG COMPUTER MODEL AND THE DIGITAL COMPUTER MODEL.

Essentially another model was modeled, in that the starting point for the digital model was the two-dimensional, linear, parabolic, time- and space-invariant differential equation of incompressible flow through porous media

$$\frac{\partial}{\partial x} T \frac{\partial h}{\partial x} + \frac{\partial}{\partial y} T \frac{\partial h}{\partial y} = S \frac{\partial h}{\partial t} + Q \qquad (1)$$

in which h = head (in units of length, L),

S = coefficient of storage (dimensionless),

T = transmissivity (L^2/t), and

Q = inflow or outflow (L/t).

Equation (2) is the finite-difference equivalent of this differential equation (after some rearrangement of terms).

$$\frac{\left[T_{i-\frac{1}{2},j}(h^n_{i-1,j} - h^n_{i,j}) + T_{i+\frac{1}{2},j}(h^n_{i+1,j} - h^n_{i,j}) + T_{i,j-\frac{1}{2}}(h^n_{i,j-1} - h^n_{i,j}) + T_{i,j+\frac{1}{2}}(h^n_{i,j+1} - h^n_{i,j})\right]}{(\Delta x)^2} = S(h^{n+1}_{i,j} - h^n_{i,j})/\Delta t + Q(x,y) \qquad (2)$$

where the i,j notation is a standard matrix or grid reference system, n refers to the time step, $\Delta x (= \Delta y)$ = nodal spacing, and Δt = time-step size.

A set of simultaneous equations (one per node), similar to the above explicit equation, was put in implicit form and solved by the alternating-direction-implicit algorithm. Using this method, the set of 1,890 equations can be solved for a period divided into three time-steps (which involves solving the set of equations three times) in less than 20 seconds on the University of Arizona's CDC-6400 computer, at a cost of about $2.00.

ERRORS IN DIGITAL MODELING

The errors related to the Tucson digital model were classified as shown below:

I. Errors associated with computation and related effects
   - A. Roundoff
   - B. Truncation (discretization)
   - C. Algorithm

II. Errors associated with major assumptions of the mathematical model
   - A. Two-dimensional representation
   - B. Constant transmissivity and coefficient of storage with time
   - C. Confined aquifer
   - D. Miscellaneous

III. Errors associated with basic data
   - A. Parameters
     - 1. Transmissivity
       - a. Value
       - b. Variation with time
     - 2. Coefficient of storage
       - a. Value
       - b. Variation with time
   - B. Input and output functions
     - 1. Recharge
       - a. Value
       - b. Location
       - c. Variation with time
     - 2. Discharge
       - a. Value
       - b. Location
       - c. Variation with time
   - C. Initial conditions (water levels)
   - D. Boundary configuration and idealization

Roundoff errors occur when the computer rounds numbers (due to finite word-size) during arithmetic operations; this probably is not a major source of error. Truncation (or discretization) error results from the approximation of a differential equation by a finite-difference equation, and essentially results from approximation of derivatives by assuming linear changes in head between nodes or between time-steps. Truncation error is also proportional to $(\Delta x)^2$ and the size of time steps. This error can be studied using the Taylor series expansion. A preliminary analysis suggests that it is not a major source of error, although it can be significant at some nodes. Errors related to the algorithm have been studied little but include such things as different tolerances used in iterative algorithms.

Errors inherent in the assumptions of the mathematical model have been studied by those who have worked with the Theis equation -- a solution of a special case of the general flow equation. Jacob (1950), for example, stated that if the saturated thickness of the aquifer is large relative to change in water level, the general flow equation for confined flow can be used to represent unconfined flow.

The Tucson digital model could be modified to recompute values of transmissivity after each time-step, so as to approximate variations in transmissivity with time corresponding to changes in water level. However, available data on aquifer thickness and vertical variations in permeability may not be sufficient to make such calculations meaningful. In addition, three-dimensional digital models could be constructed, although again data may not be sufficient to define such models.

Miscellaneous assumptions that may lead to errors include the assumptions that wells fully penetrate the aquifer, that water is released from storage instantaneously with decline in head, that the laws of Darcy and Hooke hold, that temperature is constant, and others. In general there has been little attempt in this study to evaluate errors related to all the assumptions of the mathematical model, but it is an area that needs more work.

Errors in the basic data used in the model are probably one of the major sources of error and have been the focus of much of our work. Most of these errors are well-recognized by modelers, although some, such as time variations in parameters and in input-output functions and errors in boundary configurations, commonly receive less attention. Errors in data can come from several sources, such as instrumental or measurement error, interpolation error, and errors due to data not being representative of the aquifer under study. Instrumental or measurement error probably is always present, although it probably is a minor problem. Interpolation errors arise when field data are contoured to yield estimates at all nodes in the model, as is commonly done for transmissivity, storage coefficient, and initial water level. Some field data, however, may not be representative of the aquifer. Measurements of water levels in wells that are being influenced by nearby pumping, or in wells tapping perched water bodies, for example, will not be representative of aquifer conditions.

Little has been published on the effects of time variation in recharge or discharge on model results. Discharge is commonly lumped over periods of years when it actually fluctuates daily. Recharge, and especially stream-channel recharge in the Southwest, also varies in time. Recharge moving into a ground-water basin across the basin boundaries is commonly assumed constant, but it likely varies due to long-term changes in precipitation and changes in hydraulic gradients at basin margins.

Models of ground-water basins commonly are calibrated before being used for predictive purposes. Calibration involves modifying the initial estimates of parameters, input and output functions, and initial conditions in such a manner that the model will reproduce known values of water level at historical points in time. However, there is no guarantee that modified values are thus true values, or even that modified values are improved relative to initial estimates. Many combinations of various values of parameters, input and output functions, and initial conditions can produce identical water-level configurations, so in effect the true values are indeterminate.

WORTH OF ADDITIONAL DATA FOR A DIGITAL MODEL

The focus of this study has been on a problem often faced by field hydrologists—that of deciding what data to collect at what locations in the field. More specifically for this study, what new data collected in the Tucson basin would give the most improvement in the digital model? Statistical decision theory was used by Davis and Dvoranchik (1971) to study worth of surface-water data, and their approach has been modified here to study worth of ground-water data.

The loss (L) (or what an error costs) for this problem is defined

$$L(V^n_{k,p,q}, m) = \sum_{i=1}^{I} \sum_{j=1}^{J} C_{i,j} \left\{ \left| h^n_{i,j} - \hat{h}^m_{i,j} \right| \right\} \quad (3)$$

where i = row location in grid (north-south coordinate),

j = column location (east-west coordinate),

I = total number of rows in model grid,

J = total number of columns in model grid,

$C_{i,j}$ = cost per foot of error at node (i,j),

V_k = the k^{th} variable at any node in the model (in the Tucson model we assume the K variables to be storage coefficient, transmissivity, initial water level, discharge, and recharge),

$h^n_{i,j}$ = predicted water level (head) using the n^{th} possible value of the k^{th} variable at node (p,q) (or $V^n_{k,p,q}$),

$\hat{h}^m_{i,j}$ = water level (head) assuming the m^{th} value of $V_{k,p,q}$ is the true value, and thus

L = loss related to using the n^{th} value of $V_{k,p,q}$ instead of the "true" m^{th} value.

Normally loss functions are defined as the economic loss pertaining to a given decision in light of the unknown true state of nature. The definition here is in terms of feet of error in predicted water levels, although the cost coefficient in equation (3) might be used to give the loss in economic terms. This definition was used for simplicity and to retain generality, because economic losses can only be computed for specific management problems. The cost coefficient also can be used to weight losses over the model, if errors in one place cost more than in others. In addition, other error criteria can be used in the loss function, such as the square of the error in predicted water levels, the maximum nodal error, or the numbers of nodes with errors more than specified amounts.

The risk (R) for each possible choice of a value of a variable is defined as

$$R(V^n_{k,p,q}, P_{pr}) = \underset{m}{E}(L)$$

$$= \sum_{m=1}^{N} \sum_{i=1}^{I} \sum_{j=1}^{J} C_{i,j} \left\{ \left| h^n_{i,j} - \hat{h}^m_{i,j} \right| \right\} P_{pr} \left\{ V^m \right\} \qquad (4)$$

where E = the expectation operator;

N = the total number of possible values of V; and

$P_{pr}\left\{V^m\right\}$ = the probability of occurrence of the m^{th} value of V which is distributed $\sim N(\mu_{pr}, \sigma^2_{pr})$ (normally with mean μ_{pr} and variance σ^2_{pr}), a prior probability in Bayesian terms where pr signifies prior.

The risk is the expected value of loss given any choice of a value of a variable, where losses are weighted by the prior probability of occurrence of all other possible true values of the variable. This definition requires the variable to be a random variable that can be described by a probability distribution, in this example a discrete distribution.

The expected opportunity loss (EOL), defined as

$$EOL = \underset{n}{Min}(R) \qquad (5)$$

where $\underset{n}{Min}$ = the minimum value of risk over the N values of the variable, is the value of the variable that yields the minimum risk (under the assumption that there is no loss if knowledge of the variable is perfect). This, under normal conditions, is the value with the highest probability of occurrence and would be the logical choice for the variable value if no further sampling were possible.

It would be useful to know what improvement could be made in our model by sampling for more data. This improvement could be defined as the difference between the expected opportunity loss before sampling and the expected opportunity loss after sampling. For every possible result of sampling the unknown variable, a new probability distribution (called a posterior probability distribution) can be computed for the variable by means of Bayes Theorem. This theorem, put in the context of our example, is

$$P_{ps}\left\{V^m \middle| X^x_{k,p,q}\right\} = \frac{P_{pr}\left\{V^m\right\} P_{\ell}\left\{X^x \middle| V^m\right\}}{P\left\{X^x\right\}} \tag{6}$$

where $X^x_{k,p,q}$ = the x^{th} possible result of sampling $V_{k,p,q}$ ($x = 1, 2, \ldots N$);

$P_{\ell}\left\{X^x \middle| V^m\right\}$ = the probability of sampling X^x given that V^m is the true value of $V_{k,p,q}$, distributed $\sim N(V^m, \sigma_s^2)$ where σ_s^2 is the variance of a sample (P_{ℓ} is a likelihood function in Bayesian terms where ℓ signifies likelihood); and

$P\left\{X^x\right\} = \sum_{m=1}^{N} P_{pr}\left\{V^m\right\} P_{\ell}\left\{X^x \middle| V^m\right\}$, the total probability of observing a sample X^x; and thus

P_{ps} = the probability of a value V^m given that a sample yields a result X^x (a posterior probability in Bayesian terms, where ps signifies posterior).

Using these distributions, the expected opportunity loss after sampling, or more specifically the expected value of the expected opportunity loss (EEOL), can be calculated, as defined in equation 7.

$$\text{EEOL} = \underset{x}{E}(\text{EOL}) = \sum_{x=1}^{N} \left[\underset{n}{\text{Min}} \sum_{m=1}^{N} \sum_{i=1}^{I} \sum_{j=1}^{J} C_{i,j} \left\{ \left| h_{i,j}^{n} - \hat{h}_{i,j}^{m} \right| \right\} \cdot P_{ps} \left\{ V^{m} | X^{x} \right\} \right] P \left\{ X^{x} \right\} \tag{7}$$

The EEOL is determined by (a) computing the risk for each choice of a variable value assuming a given sample result, (b) determining the value with the minimum risk for each possible sample result, and (c) weighting the sum of these minimum risks by the probability of observing each sample result.

The expected worth of sample data (EWSD) is defined as

$$\text{EWSD} = \text{EOL} - \text{EEOL} \tag{8}$$

This is the difference between expected opportunity loss before and after sampling. The optimum bit of data to collect for the model is the bit with the largest EWSD (EWSD*), defined as

$$\text{EWSD*} = \underset{k,p,q}{\text{Max}} \left[\text{EWSD} \right] \tag{9}$$

where $\underset{k,p,q}{\text{Max}}$ = the maximum EWSD over all k variables (k = 1, 2, . . . K) at each node (p,q) (p = 1, 2, . . . I), (q = 1, 2, . . . J). Alternately, the variables at various locations could be ranked in order of the worth of additional samples of data on V for improving model results.

This technique has the advantage of including basin dynamics in estimating worth of additional data, by means of using the digital model to compute all values of predicted and "true" water levels included in the loss function. There are as yet few results from this technique, although, as an illustration of some initial results, table 1 includes computed values of EOL and EWSD for five

TABLE 1. Computed Values of EOL and EWSD for Five Variables at Selected Locations in the Tucson Basin Digital Model

Variable	Row	Column	EOL, in feet per 509 nodes	EWSD, in feet per 509 nodes
Storage coefficient	15	23	2.43	0.29
Transmissivity	20	14	57.19	5.36
Initial water level	11	13	23.01	4.72
Discharge	5	4	59.09	6.02
Recharge	25	12	9.73	1.92

variables at selected locations in the model. Interpretation of such results must await more comprehensive studies. These data, and additional data using other error criteria, were computed using about 110 seconds of computer time at a cost of about $13.00. It is hoped that this technique will yield some useful information, such as whether samples of one type of data give the most improvement over the whole basin, or whether the optimum type of data depends on location or basin dynamics.

REFERENCES

Davis, D. R., and W. M. Dvoranchik, Evaluation of the worth of additional data, Water Resour. Bull., 7, in press, 1971.

Jacob, C. E., Flow of groundwater, in Engineering Hydraulics, edited by H. Rouse, pp. 321-386, John Wiley, New York, 1950.

Acknowledgments. The research described in this paper was partially supported by Allotment Grant Number 5010-5351-71 of the Water Resources Research Center, The University of Arizona. The computations were done at The University of Arizona Computer Center on the CDC-6400 installed there.

Sulfuric Acid: Its Potential For Improving Irrigation Water Quality[1]

H. L. Bohn and R. L. Westerman
Department of Agricultural Chemistry and Soils
University of Arizona, Tucson

Two major environmental problems facing Arizona and the Southwest are the alkalinization of soil and water by irrigation and the air pollution from copper smelting. In this paper we propose that the amelioration of soil and water alkalinization and of sulfur dioxide pollution are interrelated.

Alkalinization causes decreased agricultural productivity. Many plant nutrients become unavailable and deficient at high soil pH. The increased Na^+ concentration lowers water infiltration rates and decreases water use efficiency. Ancient and modern societies have destroyed the productivity of large areas of agricultural lands by allowing alkalinity to accumulate. Proper management of water, soils, and crops, however, can maintain a permanent agriculture.

One way to prevent alkalinization would be to utilize the sulfur dioxide (SO_2) now dissipated in large quantities and irretrievably lost by copper smelting. Sulfur dioxide is a valuable natural resource which can readily be removed from smelter effluent gases by conversion to sulfuric acid (H_2SO_4). This acid can neutralize the alkalinity of the irrigation waters of the Southwest.

Dutt and McCreary (1970) recently reported the status of the quality of Arizona's water supplies. They compared these data to analyses 30 years ago from the same areas and concluded that the alkalinity and salinity of these waters has

---

[1]Supported in part by Rockefeller Foundation grant 70073
Journal Paper No. 18 of the Arizona Experiment Station

increased markedly. Salinity is not amenable to chemical treatment, but alkalinity, which is a high sodium/calcium (Na^{+}/Ca^{++}) ratio and bicarbonate (HCO_3^-) concentration, can be treated by adding acidifying agents to soils and water.

Gypsum ($CaSO_4 \cdot 2H_2O$) and elemental sulfur are already used in small amounts to counteract alkalinization of soils. Sulfur is oxidized by soil microorganisms to sulfuric acid which dissolves calcium carbonate and thus lowers the Na^{+}/Ca^{++} ratio in the soil. Gypsum dissolves in the soil or water and lowers the Na^{+}/Ca^{++} ratio directly. In place of sulfur, sulfuric acid could be used beneficially in large amounts and would probably be cheaper.

The McKee (1969) report compiled the loss and recovery of sulfur in 1968 from copper, zinc, and lead smelting in the U.S.A. Smelters east of the Mississippi River recover 86% or 350,000 tons of the sulfur from their ores. Markets for the sulfuric acid produced are nearby and transportation is readily available. The smelters west of the Mississippi River, however, recover only 23% of the 2,450,000 tons of sulfur mined as part of copper, zinc, and lead ores. Of the 1,900,000 tons of sulfur dissipated in the atmosphere as air, more than 1,500,000 tons comes from southwestern copper smelters (McKee, 1969; Walker, 1970). These copper smelters are generally far removed from large industrial markets for sulfur and its products.

The cheapest and easiest way to recover sulfur from the ore presently is to make sulfuric acid from the sulfur dioxide in the smelter's effluent gas. The most easily marketable product, however, is elemental sulfur even though it is used almost entirely as a source of sulfuric acid. Compared to smelter sulfuric acid, sulfur is easier to handle, can be stored indefinitely, is more concentrated, yields a purer and more concentrated sulfuric acid as well as a variety of other industrial chemicals. Elemental sulfur is usually burned and converted to sulfuric acid near its use site primarily because sulfuric acid is more corrosive, demands more storage facilities, and is expensive to ship since it contains only 33% sulfur. One way to encourage smelters to utilize the sulfur in their ore would be to develop a large, local, and stable market for sulfuric acid.

The McKee report found the 1968 market for sulfuric acid in the Southwest to be 571,000 tons annually which might increase to 1,860,000 tons in 1975. Most of the sulfuric acid would be used by the copper industry itself for leaching of ores and tailings. This projected amount, however, is still only 49% of the sulfur now mined as copper ore. The projections do not include new agricultural markets that might develop if a cheap source of sulfuric acid were available.

Historically markets have rapidly sprung up in response to the availability of new products. A century ago alkali chemical industries in England were required to scrub the highly toxic hydrogen chloride from their exhaust gases. Although a market at that time for the hydrogen chloride was almost nonexistent, within five years the demand had expanded so fast that these factories began producing hydrogen chloride directly. A second case of making a silk purse out of a sow's ear is that of the zinc smelter in Trail, British Columbia. After considerable international litigation, the smelter was compelled almost half a century ago to remove sulfur dioxide from its gaseous exhaust. The sulfur product that emerged from the scrubbing process was ammonium sulfate, a useful agricultural fertilizer. The market for ammonium sulfate has expanded so much that the smelting company now has a large fertilizer branch and imports sulfur because the amount recovered as the by-product of zinc smelting is inadequate.

There is good reason to assume that markets for sulfur compounds will similarly develop in the southwestern U.S.A. The copper smelter in Ajo, Arizona, will convert its sulfur dioxide into ammonium sulfate, a useful nitrogen source for plants in the nitrogen-deficient soils of the Southwest. In a sense this is not a constructive use for sulfur except that air pollution will be reduced in that area. The sulfate in ammonium sulfate is little more than an inert additive. Arid soils generally contain sufficient sulfate for plant needs.

In addition to ammonium sulfate fertilizer, arid land agriculture has a second use for sulfur and one for which the lower quality, smelter by-product acid is eminently suitable. Soils and irrigation waters of arid regions are often high in salts so that continued irrigation tends to cause harmful accumulations of sodium and bicarbonate ions in the soil. Salt accumulation *per se* is not amenable to the treatment outlined below but the increase in sodium and bicarbonate ions can be slowed and reversed by sulfuric acid.

Added to irrigation water or the soil in the proper amounts, sulfuric acid could reduce the residual carbonate content (Eaton, 1950) by removing bicarbonate ions, mitigate the sodium concentrations in the water and soil, yet would not produce any foreseeable undesirable side effects. The acidified water would increase the solubility of calcium carbonate in the soil and shift the ratio of exchangeable sodium and calcium ions toward the more desirable calcium-saturated state. This is illustrated by

$$2Na_{ex} + Ca^{++} = Ca_{ex} + 2Na^{+}$$

where the subscripts refer to the exchangeable ions adsorbed by the soil. The sodium ions in the soil solution can then be leached from the soil.

A conservative estimate of the beneficial amount of sulfuric acid to be added to irrigation water is that which would titrate 90% of the bicarbonate ions. This reaction is illustrated by

$$H_2SO_4 + 2HCO_3^- = SO_4^= + 2CO_2 + 2H_2O$$

Carbon dioxide is volatilized to the air, the alkalinity of the water is reduced, and even the effective salinity of the water is somewhat reduced by substituting the less phytotoxic sulfate ion for bicarbonate. Only 90% is titrated because removal of the reamining bicarbonate requires high acidity which might cause secondary problems. The carbonate ion has been disregarded here because its concentration is insignificant for our purpose of estimating the useful amount of sulfuric acid to be added. More sophisticated treatment of ion exchange in soils would yield more refined estimates of the optimal quantities of sulfuric acid to be used. These were deemed unnecessary here.

Titration of 90% of the bicarbonate would increase the water's acidity to nearly pH 5. The pH should not cause the deterioration of irrigation facilities and equipment which has been noted with the use of sulfur burners. These burners produce high concentrations of H_2SO_4 in irrigation water for the object of reclaiming alkaline soils.

Each part-per-million of bicarbonate ion in an acre-foot of water requires 2 lbs of sulfuric acid to titrate 90% of the bicarbonate. Since most of the 5,000,000 acre-feet of Arizona's irrigation water is pumped from wells whose bicarbonate concentrations are well above 200 ppm, a reasonable estimate of this potential sulfuric acid market in Arizona is about 1,000,000 tons (or 330,000 tons sulfur) annually.

The areas contiguous to Arizona could similarly make profitable use of sulfuric acid. Colorado River water containing 200 ppm bicarbonate irrigates the Imperial Valley of California and the adjoining Valle de Mexicali in Baja California. Assuming a combined irrigation demand of 3,000,000 acre-feet, this area could benefit from 600,000 tons of sulfuric acid (200,000 tons sulfur) annually. These estimates are summarized, and compared to the potential H_2SO_4 production, in table 1. Irrigation water in Nevada, New Mexico, Utah, and west Texas could similarly utilize sulfuric acid.

Table 1. Potential use and production of sulfuric acid in the Southwest

	Tons H_2SO_4/yr
Arizona irrigation water	1,000,000
Imperial Valley and Valle de Mexicali irrigation water	600,000
Mining processes	1,860,000
Total	3,700,000
Sulfuric acid equivalent of sulfur mined as copper ore (1968)	4,800,000

The cost of treating irrigation water with sulfuric acid is difficult to estimate. The cost of producing sulfuric acid by scrubbing sulfur dioxide from smelter exhaust is variable (McKee, 1969; Day, 1970) but \$5/ton of H_2SO_4 is not an unreasonable estimate. Since the production of one ton of copper (worth approximately \$1000/ton) would yield 4 to 6 tons of sulfuric acid (Walker, 1970) assuming reasonably complete recovery, the cost of scrubbing SO_2 and producing sulfuric acid is a small fraction of the copper industry's gross income (Day, 1970). The McKee report considered that copper smelters might, if necessary, give away the sulfuric acid. The report suggested, however, that the smelters would be unwilling to pay shipping costs. A cost to users of \$5.00/ton would make it equivalent to the cost of gypsum treatment of irrigation water.

Wildermuth, Martin and Rieck (1969) established estimates of costs and returns data for crop production in representative areas in Arizona. The average costs of surface irrigation water in Yuma, Maricopa (Salt River Project) and Graham

Counties were $2.60, $3.20 and $2.48 per acre-foot, respectively. Based on 200 foot lifts in Cochise County and 400 foot lifts in Maricopa and Pinal Counties, average costs per acre foot of pump water are $7.00 and $8.86, respectively. If the delivered cost of sulfuric acid is $5.00/ton and 200 lbs are added to each acre foot of irrigation water, the increased cost of water would be about 50 cents per acre foot. Most crops use three to five acre feet of water during the growing season which would result in $1.50-2.50 per acre increase in production cost due to the addition of sulfuric acid. With high cash income crops such as lettuce and cantaloupe, income returns above variable costs would be reduced less than 0.5%. With other crops, such as alfalfa, cotton, and barley, reduction in returns above variable costs will be slightly more due to lower income returns per acre. These figures do not include benefits derived from increased water use efficiency, improvement of the physical condition of the soil, and increased availability of plant nutrients. At any rate additions of sulfuric acid to irrigation water is cheap insurance for the maintenance of permanent agriculture.

Sulfuric acid can be conveniently added to irrigation water in the canal or at the pump head; the rate of addition is not critical. The market for sulfuric acid for irrigation water treatment would be seasonal, a maximum in the spring and summer and lower amounts in the other seasons. The slack irrigation periods correspond to the time when sulfuric acid would be applied directly to alkaline soil for reclamation. The amount of H_2SO_4 which could be used for reclamation is difficult to estimate because many factors including net economic returns from agriculture and water availability are involved. Arizona uses more than 10,000 tons of gypsum and other sulfur compounds (equivalent to 6,000 tons H_2SO_4) annually for reclamation of alkaline soils. California uses more than 1,000,000 tons (equivalent to 600,000 tons H_2SO_4) for this purpose. These values overlap somewhat the amounts estimated above for the maintenance of irrigated lands.

Arid lands have a high acid buffering capacity by virtue of their carbonate content. Carbonates add little or nothing to soil productivity and absorb hydrogen ions avidly. These soils are now the sink for sulfur fall out from the atmosphere. Their capacity to absorb sulfur compounds is enormous if the sulfur is applied judiciously. Aside from the sodium problem in alkaline soils, little benefit is obtained from using the soil as a sulfur sink, except that calcareous soils are relatively safe sinks for dissipating sulfur's acidity in the environment. The use of sulfuric acid in leaching ores and tailings is flexible and could be varied to correspond to the rates of smelter activity and rates of sulfuric acid consumption, thus providing an additional means of regulation.

The exchange of sulfate for the bicarbonate ions in soils and irrigation water means that the sulfate will eventually enter drainage water and ground water. However, due to fallout of sulfur dioxide from smelter exhaust, sulfates are already entering the water supply. Atmospheric sulfur dioxide oxidizes to sulfuric acid in the air and soil and accelerates weathering processes at the soil surface. The weathering products and the sulfate ion enter Arizona streams rapidly by soil runoff and add to the salt load of surface waters. The increase is probably small relative to the amounts of salts from normal weathering of soils and rocks. Putting the sulfate into irrigated soils seems the lesser of two evils.

To avoid contributing to the increase of salinity in irrigation waters, the site of addition of sulfuric acid should be relatively near the site of water use. By "relatively near" we suggest the irrigation canals rather than the natural streams which supply the canals. This would minimize the possible ecological effects of the acid added to the water, and avoid increased salinity due to dissolution of sediments in the stream and its bed.

It is not inconceivable that urban waters could be treated beneficially with sulfuric acid. This treatment would largely prevent the accumulations of calcium carbonates in water pipes, water heaters, boilers, etc. The removal of bicarbonate would not affect the quality of water for human consumption. The bicarbonate ion, at least within the range of bicarbonate concentrations found in urban water supplies, has no apparent positive or negative effect on human nutrition. The treated water would be as useful for lawns and gardens as it is for agricultural irrigation. The addition of several sulfur compounds to garden soils to reduce alkalinity is already a common practice in the Southwest.

One real danger exists, however, in treating urban water. Added in excess, sulfuric acid would corrode pipes and add significant and perhaps harmful concentrations of copper, zinc and iron to the water. Since this risk exists and because urban water use in Arizona is still relatively small compared to irrigation water use, wholesale sulfuric acid treatment of urban water seems inadvisable. In addition, some members of society are strongly opposed to urban water treatment. Adding sulfuric acid to municipal water would probably stir up at least as much controversy as has fluoridation.

Summary

The addition of sulfuric acid can improve the quality of alkaline irrigation water. Lower alkalinity results in increased soil permeability and increased efficiency of water use. Based on neutralizing the bicarbonate ion concentration of Colorado River water and Arizona well water, the potential market for sulfuric acid in irrigation is about 1,600,000 tons (500,000 tons sulfur) annually. This represents about one-third of the sulfur now dissipated as air pollution by southwestern copper smelters. The effect of adding acid to irrigation water is to decrease or reverse the gradual alkalinization of arid land soils and water by irrigation and thus maintain a more permanent agriculture.

LITERATURE CITED

Day, John C. The McKee report and smelter air pollution: an economic evaluation. Ariz. Acad. Sci., April 18, 1970.

Dutt, G. R., and T. W. McCreary. The quality of Arizona's domestic, agricultural and industrial waters. Univ. Arizona Agr. Expt. Stn. Report 256, 1970.

Eaton, Frank. Significance of carbonates in irrigation waters. Soil Sci., 69, 123-133, 1950.

McKee, Arthur G., and Co. Systems study for control of emissions by the primary nonferrous smelting industry. U. S. Federal Clearinghouse PB 184 884, 1969.

Wildermuth, J. R., W. E. Martin, and V. H. Rieck. Costs and returns data for representative general crop farms in Arizona. Univ. of Arizona Agr. Expt. Stn. Report 253, 1969.

Walker, Walter W. The ratio of sulfur dioxide emissions to copper production at Arizona smelters. Unpublished report, City of Tucson Advisory Committee on Air Pollution, 1970.

Acknowledgment. We thank Dr. Gordon Dutt for helpful discussion.

NITROGEN BALANCE FOR A 23 SQUARE MILE MINNESOTA WATERSHED

Jack D. Johnson

Office of Arid Lands Studies
University of Arizona, Tucson

INTRODUCTION

Nitrogen compounds are ubiquitous and of significant importance in public health, agriculture, industry, and the ecology of lakes and streams. This study was initiated as a result of the author's concern with the overfertilization of lakes and streams (eutrophication) resulting from excessive nitrogen and phosphorus compounds. The nitrogen balance was a spin-off from the overall study which was conducted for the purpose of developing a math model of the watershed overfertilization process (Johnson, 1971a, 1971b).

Although the actual nitrogen balance for a humid mid-west watershed could not be expected to be the same as for an arid watershed, the processes are the same and should vary only in magnitude. Considerable has been written relative to the nitrogen cycle in the soil system, and it seems appropriate, if not mandatory, that some of this work be recapitulated prior to presentation of the Minnesota balance. The balance and cycle discussion proceeds on a watershed basis; the tested watershed included the city of New Prague, 60 miles south west of Minneapolis, Minn.

THE NITROGEN CYCLE

For convenience of presentation, the cycle will be discussed in four distinct physically separated zones; atmospheric, interface between soil and atmosphere, plant-root and soil-water, and the surface-water zone. Groundwater inter-relates with surface-water and the plant-root zone, and is discussed in each of these zones.

Atmospheric Zone

The atmospheric zone is essentially a zone providing a transport mechanism for nitrogen compounds. All compounds in the atmosphere are subjected to the vagaries of wind action. If the basin under consideration is quite large, several hundreds or thousands of square miles, the effect of the wind action is not as dramatic or unpredictable as is the case for the small basin. Even rainfall patterns on a small watershed can be so obscure as to defy analysis. Nonetheless, the atmosphere, which is 78% N_2, constitutes a vast nitrogen reserve in the environment and cannot be ignored.

(1) Nitrogen Transformation: None of the authors (cited later) considered that microbial activity contributed to nitrogen transformation in the atmosphere. Further, most do not give credence to the hypothesis that lightning is an important source of nitrate. Stevenson (1965) discusses several research results which merely emphasize that little is known about the origin of atmospheric nitrogen compounds. Statistical evidence has indicated that volatilization from the oceans and nitrogen fixation from the trails of meteorites and electrical storms can be considered a minor, if not negligible, source. Feth (1966), who discusses Junge's nation-wide survey of ammonium and nitrate in rain-water, states, "No correlation was found with thunderstorm activity, density of industry, population, or agricultural activity." There apparently was some correlation with soil pH, industrial activity, fertilizers, or smog. The reported rainfall data have shown an ammonia to mineral nitrogen ratio of approximately 2:1 and Stevenson reports that the photochemical reaction;

$$6N_2 + 18H_2O \rightarrow 4NH_4NO_3 + 4NH_4OH + O_2,$$

as proposed by Ångström and Höberg (Stevenson, 1965), satisfies the interdependency and ratio. Stevenson further indicates that Eriksson, Hutchinson, and Virtanen (Stevenson, 1965), in separate reports, concluded that the interdependence of ammonia and nitrate may be explained by the photochemical oxidation of ammonia to nitrate. Allison (1965) attributes the burning of fossil fuels and volatilization from the soil as the principal sources of ammonia. In contrast to others, Allison states, "Electrical discharges in the air probably account for most of the nitrates in rainwater but some oxides of nitrogen are also released from the soil."

Atmospheric gaseous nitrogen is subjected to photochemical and lightning fixation, the end products, ammonia and nitrate, then join with air pollutants causing an increase in storage of the atmospheric nitrogen compounds.

(2) Air Pollution: In addition to the poorly defined natural sources of atmospheric nitrogen compounds, are the sources that are lumped into the air pollution category. Included in this category are the pollutants from processing or manufacturing plants, automobiles, fuel burning, forest or other fires, ammonia which is volatilized from the addition of ammonia fertilizer, and various nitrogen compounds which are carried into the atmosphere by wind erosion of the soil surface.

(3) Depletion Processes: Depletion of nitrogen from the watershed via atmosphere occurs in three ways: denitrification, volatilization, and wind erosion. Losses from fire and volatilization from leaf surfaces were omitted because a fire yielding an appreciable nitrogen loss would be catastrophic in nature and beyond the scope of a balance consideration. Volatilization from leaf surfaces is considered negligible in comparison to the other mechanisms.

Interface Between Soil and Atmosphere

The interface zone includes all animals, the erodible soil surface, and the atmosphere up to the top of the vegetative canopy. The sources of nitrogen contributing to the cycle are sewage spreading, non-grazing animal excretion, and industrial fertilizer application. The depletions are attributed to gaseous nitrogen and wind erosion mentioned in the previous paragraph, harvesting of crops, grazing of animals, and removal of soil and organic matter in runoff and erosion.

(1) Sources of Nitrogen Compounds: Although manure spreading is widely practiced in Minnesota, it is a rather minor source of nutrients. The major benefits derived from manure spreading are the development or stabilization of soil organic matter and the disposition of a waste product. Soil tilth is dependent upon soil organic matter, and it is not uncommon for manure spreading to be instituted for this reason, with a commercial fertilizer providing the required nutrients for crop growth. Although not extensively used in Minnesota, the agricultural use of effluent from primary and secondary sewage treatment facilities has potential economic benefits as indicated in the research conducted by Kardos (1967).

Non-grazing animal excrement contribution to the nitrogen compounds within a basin are difficult to quantify, but migratory birds can supply appreciable nutrients. Commercial fertilizers are, of course, a major source of plant nutrients in most cultivated agriculture.

(2) Depletion Processes: The depletion processes include gaseous nitrogen, wind eroded soil, crop harvest, animal grazing, and runoff-erosion. The depletion of gaseous nitrogen is attributed to denitrification and ammonia volatilization. Denitrification is dis-

cussed subsequently. Ammonia volatilization is considered of significance only when present close to the soil surface. Ammonia, when in the soil-water solution, partially forms the ammonium ion which is not subject to volatilization. The ammonia $\rightleftharpoons$ ammonium equilibrium indicates that not all ammonia is converted to the ionic form, and certainly the gaseous phase is subject to volatilization. General prevailing agricultural practice in the New Prague watershed dictates that gaseous or liquid ammonia be tilled to six to eight inch depth.

Wind erosion can only be mentioned as an obvious depletion process -- data relative to quantification of nutrient losses from this mechanism were not found. Similarly, nutrient depletion from animal grazing must be by conjecture and estimate. The quantity of nutrients removed with crop harvest was reasonably documented. Runoff and erosion processes are major factors in nutrient depletion.

Plant-Root and Soil-Water Zone

It is in this zone that in-basin recycle process occurs. Plant and bacteria living separately, in symbiosis, as parasites, or on each other's waste products, continually convert organic nitrogen to mineral nitrogen and back to organic nitrogen, repeatedly. Within this zone, the sources and depletions involve the gaseous state; sources are via nitrogen fixation, while depletions are by denitrification.

(1) Nitrogen Fixation: Nitrogen fixation in the soil is primarily a biological process. Stevenson (1965) states that Dhar's 1960 theory of photochemical nitrogen fixation in the soil "has been conspicuously ignored by soil scientists, a consequence arising from almost complete rejection of the theory." Biological fixation is by four distinct groups of plants: blue-green algae, free-living bacteria, bacteria living in symbiosis with legumi-

nous plants, and bacteria living in symbiosis with nonleguminous plants. Stevenson (1965), Nutman (1965), Vincent (1965), Jensen (1965), Waksman (1952), and Allison (1965), provide considerable detail on the nitrogen-fixation process.

(2) Denitrification: Denitrification occurs both chemically and biologically, and is the reduction of nitrate to nitrite and the further reduction of nitrite to nitrous oxide and/or molecular nitrogen. Allison (1966) limits denitrification to the biological processes only, whereas Broadbent and Clark (1965) use a broader scope of the term which includes chemical and biological reactions that transform nitrate or nitrite to gaseous nitrogen, usually N_2 or N_2O. The term does not include transformation to, or the volatilization of, ammonia. The reduction of nitrate to ammonia is commonly called nitrate reduction, not denitrification. The extent to which nitrate reduction to ammonia occurs in the soil is not well documented and because of this lack of information it is omitted from further consideration.

The denitrification process is considered to be second only to leaching in terms of nitrogen depletion from the soil (The New Prague study indicates more than ten times as much denitrification as leaching). ^{15}N experiments conducted by other investigators, but discussed by Broadbent and Clark (1965), and Allison (1965, 1966) clearly indicate that the process exists and that nearly all of the gaseous nitrogen evolved is derived from nitrate. Although the organisms which perform the denitrification are facultative anaerobes, it has been shown that rather significant denitrification will occur in finely textured, well-aerated soils. Where high microbial activity occurs, particularly in pockets of organic matter such as around root hairs, oxygen levels are reduced and dentrifying microbes thrive. Broadbent and Clark say, "the continuing small losses of nitrogen that occur within small pockets of microbial activity or within the larger-sized soil aggregates in presumably well-aerated soils are probably more serious when taken collectively than the more rapid denitrification that occurs when the entire profile becomes anaerobic or nearly so."

(3) Internal Cycle: Within the plant root zone is the closed loop cycle which circulates nitrogen from organic to mineral forms back to organic, etc. The soil-organic nitrogen fraction may be depleted by three pathways; soil erosion, leaching, and ammonification. The first two, erosion and leaching, effectively remove nutrients and organic matter from the basin. Leached material may return to the cycle through phreatophytes or capillary rise to the root zone. Ammonification is that biological process by which organic matter is mineralized to ammonia and the ammonium ion, and a continuation in the cycle. Sources of soil-organic nitrogen are precipitation, bacterial decomposition of plant and animal wastes, and nitrogen fixation. Precipitation and nitrogen fixation have been discussed, and bacterial decomposition and immobilization will be discussed subsequently.

The ammonia and ammonium ion have five depletion routes; volatilization, leaching, nitrification, immobilization, and ammonia fixation. Sources of ammonia are precipitation, commercial fertilizer, and ammonification. Volatilization is a depletion from the basin, but this may add to the basin storage of atmospheric nitrogen compounds and an indeterminable portion may return in bulk precipitation. Ammonium fixation is adsorption of the ammonium ion onto the clay colloid. Appreciable quantities of the ammonium ion may be bound or fixed in this manner, and subsequently released for plant growth. Fixed ammonium is not readily volatilized nor is it readily available for oxidation to the nitrate form which is so easily leached (Nommik, 1965; Scarsbrook, 1965; Alexander, 1965; Allison, 1965).

Nitrification is the further mineralization of ammonia, through oxidizing bacteria to the nitrite state, and under normal conditions the nitrite is rather quickly oxidized to the nitrate state. Alexander (1965) discusses nitrification in detail.

Nitrite is normally a short lived oxidation state which will accumulate only in alkaline soils containing appreciable quantities of NH_4^+ (Allison, 1966). Nitrite accumulations are toxic to most plants, they are soluble, and leach as readily as nitrate. Broadbent and Clark (1965) discuss chemical means of nitrite reduction and the general instability of nitrite. Nitrite is formed from the oxidation of ammonia or the reduction of nitrate, and its depletion pathways are leaching, reduction to gaseous nitrogen, and oxidation to the more stable nitrate.

Nitrate sources are the oxidation of nitrite, application of fertilizer, or infiltration from precipitation. There are four nitrate depletion pathways; leaching, plant uptake, denitrification, and immobilization. Leaching is reportedly the most important depletion mechanism known, and denitrification is a close second. Plant uptake is not a loss until the crop is removed from the basin, and immobilization is a 'tie up' of the otherwise available mineral nitrogen. Bartholomew (1965) presents an excellent review of the interacting and opposing processes of mineralization and immobilization.

Immobilization denotes the conversion of inorganic nitrogen to the organic form during the process of bacterial decomposition of biological waste products. The reported critical value of the carbon to nitrogen (C/N) ratio of 20 to 25 determines the amount of nitrogen subject to immobilization (Harmson and Kalenbrander, 1965). Material to be decomposed with a C/N ratio greater than 20 to 25 will result in bacterial absorption of nitrogen from the surrounding environment, whereas a lower C/N ratio will permit a net mineralization of the nitrogenous material.

Plant uptake of nitrogen is almost all in the NH_4^+, NO_3^+, or urea form, but other organic forms and minor amounts of nitrite are also absorbed (Scarsbrook, 1965). Scarsbrook says, "Soil inorganic nitrogen in most arable soils is nearly all utilized in the NO_3^-, form regardless of past fertilization practices. Accordingly, NO_3^- is the most important source of available nitrogen for cultivated plants. Since NO_3^- does not react with soil clays, the total supply of NO_3^- in the root zone is available." Alexander (1965) says, "The pendulum is now swingingin in the opposite direction, and the detrimental consequences of ammonium oxidation are becoming more apparent." This statement is made with relation to the high loss of nitrate via leaching, whereas the ammonium adsorbs onto the colloidal material and is stored in the soil. Finally, Allison (1965) states, "The use of ammonia-nitrogen, rather than nitrate-nitrogen, as a means of reducing leaching losses usually has only limited advantages since the ammonia is normally oxidized to nitrate rather rapidly, except when the soil is very cold."

Plant-organic matter is either harvested, consumed by a grazing animal, or returned to the soil. Through animal grazing, some nitrogen is returned to the soil in feces and urine. Even though an entire crop is harvested, appreciable quantities of organic matter remain with the roots and root hairs.

The literature reviewed indicates that leaching is one of the most important depletion pathways. The data from the current New Prague study does not agree with this contention, the greatest loss component at New Prague was identified as the combined runoff and erosion pathway. There is no doubt, however, that leaching is considerable, and once the nitrogen has penetrated into the root zone, it is no longer subject to runoff and erosion losses. Leaching can provide depletion through tile drains and into surface water, into groundwaters which serve as a base flow for surface water, or into groundwater storage. The removal of nitrogen from groundwater storage by capillary rise and phreatophytes is not well documented.

Surface-Water Zone

In the surface-water zone, the nutrients accumulate and create the inland water problem of overfertilization. There are two distinct categories of inland water -- flowing and impounded. Estuaries present still other conditions and will not be discussed in this report. Flowing water provides a transport medium where biological, physical, and chemical action will transform nitrogen compounds, and may result in a change in time of travel within the transport medium, a change of state or chemical nature, or a change in quantity of the nitrogen compounds and/or total nitrogen.

Lotic, or running-water, ecology is discussed in Odum (1959), Reid (1961), and several other texts on freshwater ecology. The uptake and release of nitrogenous material is cyclic in the lotic environment, just as in the soil environment.

The cycle in the lotic environment complicates an accurate measure of stream nutrient load at any given point in time or space. Some of the free-floating organisms will have their organic-nitrogen included in a stream sample of water, whereas those with avoidance reactions or that are attached or rooted will not be included. Thus in the late spring, nutrient uptake by non-measured flora and fauna may be quite high, reducing the levels in the stream. In the fall, the dying organisms may contribute substantially to the nutrient load in the stream.

Certain organisms derive their nutrients from the water and then leave the aquatic environment and possibly the basin. The multitude of insects who spend their larval stages in lotic water or the bottom muds indicate the possibility that such depletion may be appreciable. The bottom muds of most streams (especially those utilized for irrigation drainage) are much higher in nutrient concentrations than is found in the water flowing above. Benthic organisms live in these muds and displace some nutrients into the water. The nutrients in the bottom muds are derived from soil erosion products and from decomposition of dead material which settles to the bottom, decomposes, and remains in the bed.

SOURCES OF NITROGEN COMPOUNDS

In this section the quantitative aspects of the watershed sources will be discussed, particularly as they relate to the New Prague watershed. Where available, existing data are presented and critiqued. Data from the New Prague watershed are included as appropriate. Balance values computed in the following two sections are listed in Table 8.

Atmospheric Fallout

Included in this category are all of the nitrogen compounds which fall directly onto the soil or a water-course. This includes fallout derived from air pollution. It does not include free nitrogen taken from the atmosphere and subsequently oxidized into a nitrogen compound. The term 'fallout' is used here to indicate that not all nitrogen compounds from the atmosphere are deposited with rainfall. Some, and possibly a major portion, settle out with dust or other dry material. Feth (1966) defines bulk precipitation as "rain plus the water soluble constituents in dry fallout that are deposited on the sample collecting surface between rains." Bulk precipitation is a very useful term and will be utilized with slight modification. In the context used here, bulk precipitation includes all of the substances under question which settle to the earth surface. The term 'precipitation' will be used in the classic sense which infers the settling of moisture as rain, sleet, hail, snow, dew, etc.

The bulk precipitation for the New Prague watershed was computed on the basis of snow samples taken at New Prague. A Thiessen Polygon was used to weigh the samples, and considerable published data were reviewed and analyzed (Johnson, 1971a, 1971b).

A value of 54 lbs/ac-yr was computed and is 10 to 17 times greater than the mean rainfall load values reported in the published literature. This seems reasonable in light of Feth's bulk precipitation indicating values about 16 times greater than found in precipitation alone. For the 23.3 mi^2 watershed at New Prague, the bulk precipitation for 1969 would then add 805,000 lbs of nitrogen.

The deposition of material on vegetation will not be considered in detail. The mechanisms of leaching metabolites from plant leaves are discussed in several publications, but little is quantitatively known relative to the process. Tukey and Mechlenburg (1961), utilizing tagged nutrients, found that the process is simply a recycle mechanism. The tagged material was found in the leaves, in the leachate, and was reabsorbed into the root system. Tukey and Morgan (1962) discuss the various metabolites which are leached including nitrogen and phosphorous. It would appear that material in the leachate may also consist of material which was deposited on the plant -- the tagging proves that some, if not all, is derived from within the plant. For the purpose of a nitrogen balance, this particular mechanism will be ignored. It was assumed that all of the bulk precipitation reaches the soil surface, the accuracy obtainable in a nutrient mass balance does not justify future analysis.

Natural Sources

The natural sources of nitrogen input to a watershed are limited to molecular nitrogen fixation, animal excretion, and primary rock decomposition. Recycle mechanisms, such as leaf litter and root decomposition, are not additions to the watershed's supply of nitrogen.

(1) Nitrogen Fixation: Biggar and Corey (1969) report an average of 12 lbs/ac-yr added to cultivated Wisconsin soils. They further indicate that nitrogen fixation adds about 14% of the total nitrogen load entering Lake Mendota. Allison (1955) used 15.2 lbs/ac-yr in his nitrogen balance. If an arbitrary average of 13.5 lbs/ac-yr is selected, for the 20.3 square miles of soil which is either in crops, pasture, or woodland and wildlife, this would then represent an annual addition of 175,000 lbs of nitrogen.

(2) Animal Excrement: The intentional use of domestic animal excrement for a fertilizer is discussed subsequently. Very little data were found giving the expected nitrogen yield from various wild animals. Fortunately, most animals leaving their excrement within a watershed also grazed and derived their nitrogen from the watershed. In such cases, they do not add to the source of nitrogen, they merely recycle it and deplete a minor portion of the total supply by tying up some nitrogen in animal tissue. The major exception to this is, of course, the migratory bird. Mackenthun (1967) indicates that domestic ducks yield 2.1 lb/yr of nitrogen and wild ducks about 1.0 lb/yr. Loehr (1968) indicates a total nitrogen of 29.2 lbs/yr for duck, much higher than Mackenthun's values. Regardless of the exact loadings, it is obvious that in a watershed containing wetlands,

several thousand pounds of nitrogen may be accrued through defecation by migratory birds.

Fertilizers

Included in the fertilizer category are the usual sources of soil-applied fertilizers; i.e., manure spreading and commercial fertilizers. Additionally, drainage from livestock feedlots and spreading of treated sewage effluent will be considered. All of these latter items are actual pollution sources, and they generally drain directly to a watercourse.

(1) Manure Spreading: The prevailing practice at New Prague has been to apply manure during the winter when soils are frozen, and tillage occurs as soon as tractors can traverse the fields. Manure spread on frozen ground does not become a part of the soil-complex, and much of it is carried away during snowmelt or spring runoff. The practice has been outlawed in Wisconsin, and attempts are now being made to make the practice illegal in Minnesota. The total cattle population in the New Prague watershed is estimated at a maximum of 500 cows, and if they produced 81 lbs/animal-day manure (Loehr, 1968), this would amount to about 7500 tons of manure annually. Assuming that they are beef cattle, in order to maximize the computation, the loading would be 14 lb/ton, (Townshend, et al. 1969) and with 7500 tons of manure, the yield should be about 100,000 lbs of nitrogen. This value is probably high, but even as a maximum it represents a rather minor source of nitrogen. Another 150 to 200 head of swine are in the watershed, and by a similar analysis, 200 swine would yield 6400 lbs of nitrogen. Other livestock in the New Prague watershed are minor, and the total manure source of nitrogen for the entire watershed was assumed to be 110,000 lbs annually.

(2) Commercial Fertilizer: Commercial fertilizers can, of course, be applied

to the soil at any desired loading. Much has been written about the various yields under certain crop rotation schemes, soil types, conservation practices, and fertilizer applications. Since the nitrogen balance was developed for the New Prague watershed, commercial fertilizer data pertinent only to New Prague are given. Table 1 indicates the fertilizer application rates for New Prague. The table is quite an oversimplification; for example, soy beans following corn often receive no fertilizer, corn following soy beans will usually receive 130 pounds of N and 175 to 200 pounds of 6-24-24.

A sample of 34 existing cropping schemes for the New Prague watershed were analyzed to determine the amount of land in various crops during the period of the study. Table 2 indicates the cropping schemes, and if these were summed for a five year crop pattern, we have:

Crop	5 Year Acreage	%
Corn (C)	3054	32.5
Beans (B)	140	1.5
Row (R)	979	10.4
Grains (G)	1966	21.0
Hay (H)	2801	29.9
Pasture (P)	440	4.7

Considering that the watershed consists of about 12,600 acres of cultivated land, or 63,000 acres for a five year period, the sample shown in Table 2 represents 15% of the total acreage. This would be a good statistical representation if the samples were ran-

TABLE 1. New Prague Fertilizer Application Rates (Leary, 1970)

Crop and Time of Application	Fertilizer	Rate lbs/ac	N added lbs/ac	P added lbs/ac
Corn - pre-planting	actual-N	200	200	-
- at planting	6-24-24*	200	12	48
Soy Beans or Row - pre-planting	actual-N	150	150	-
- at planting	6-24-24	175	10.5	42
Alfalfa - first cutting	0-30-30	100	0	30
Small Grains - at planting	--	50-40-50	50	40

*Percentage of N, P, and K, respectively

TABLE 2. New Prague Annual Cropping Schemes

Acres	Crops*	Acres	Crops
196.7	C-G-3H	14	Pasture
37.5	C-G-3H	81	C-G-H-C-G
91.0	C-G-3H	2	H
144.2	Continuous Row	106.6	G-H-H-C-G
72.6	C-G-3H	111.5	C-C-G-H-H
15.0	Pasture	37.5	Continuous Corn
21.2	C-G-2H-C	4.7	Pasture
84.8	C-G-H-C-G	53.5	G-C-G-H-H
95.5	B-C-C-G-H	79	G-C-G-H-C
54.0	C-G-H-C-G	9	C-G-3H
67.5	C-C-G-H-C	22	Pasture
32.0	R-R-G-R-R	105	C-G-H-H-C
30.0	R-R-G-H-R	30.4	G-H-C-G-C
26.0	Pasture	17.4	H-C-G-H-H
105	Sweet Corn	8	Continuous Row
15.0	C-B-C-B-B	79	C-C-G-H-H
6.4	Pasture	21	C-G-H-H-C

Pasture= land usually not capable of being cultivated.
*C = Corn; G = Grain; H = Hay (Alfalfa mixture); B = Beans;
R = Row (Beans or Corn).

domly selected -- such was not the case. The 35 samples shown represent 100% of the information available from the County Agricultural Agent and the Soil Conservation Service District Office. Having spent considerable time in the New Prague area, it is the author's opinion that these estimates are quite reasonable, and agricultural patterns do not appreciably change for several tens of miles in any direction from New Prague. Table 3 shows the overall watershed land use patterns, and Table 4, developed from the data in Table 1 and Table 3, indicates the crop use and estimated fertilizer application of 1,240,000 lbs of nitrogen.

(3) Sewage Effluent Spreading: The data presented by Kardos (1967) indicates the tremendous potential of utilizing a waste as a resource.

(4) Feedlot Drainage: Feedlot drainage is a direct source of nutrient enrichment and the problem is increasing as a result of the increasing consumption of meats. Allred (1969) indicates that, using population equivalents based upon biochemical oxygen demand (BOD), a 200 cow dairy farm has a population equivalent to a city of 3,000, and on the same basis (BOD), a 250,000 bird farm has a population equivalent equal to a city of 25,000 people. Townshend, et al., (1969) published data on human population equivalents for farm animals as projected to 1975. Their estimates included Canadian data and U.S. data provided by R.C. Loehr. The 1975 estimate includes a projected change in feed. Using their data (Townshend, et al.) for nitrogen equivalents, rather than BOD equivalents, the 200 cow dairy farm equals a city of 2,400 people, and the 250,000 bird farm equals a city of 1,000,000 people.

Stewart, et al. (1967) indicate, as a result of their extensive study of subsurface water under various fields and corrals, that nitrates do percolate into the groundwaters,

TABLE 3. New Prague Watershed Land Use Pattern

Land Use	Area Sq. Mi.	% of Total
Total Watershed	23.3	100.
Total Urban and Major Roads	1.6	6.9
New Prague	1.1	4.7
Heidelburg	0.1	0.4
Major Roads	0.4	1.7
Total Rural	21.4	91.8
Cultivated to Crops	18.7	80.2
Pasture	1.0	4.3
Woodland and Wildlife	0.6	2.6
Farms Roads and Buildings	1.1	4.7
Total Surface Water	0.3	1.3
Lake Tietz	0.3	1.3
Stream Channels	0.019	0.08
Farm Land Tile Drained (69% of Crop and Pasture)	13.6	58.4

TABLE 4. Industrial Fertilizer Application for New Prague Watershed

Crop	Acres	Total Fertilizer-lbs N
Corn	4095	868,000
Beans and Row	1500	240,000
Small Grains	2645	132,000
Hay	3767	-
Pasture	592	-
TOTAL	12,600	1,240,000

but they state that more studies are required before "the significance and magnitude of this pollution can be assessed."

Evaluation of the nutrient contribution from feedlots in the New Prague watershed is somewhat simplified by the small size of the total herd population. Previously it was estimated that, on the basis of manure production, 110,000 lbs of nitrogen could be expected from the animal population. For simplicity, the feedlot and manure spreading sources are lumped into a single category for balance purposes.

(5) Septic Tank Effluent: It is estimated that within the watershed there are about 250 five-member family homes which are on septic tanks (The city of New Prague is on a sewer system). Using Polta's data, 27 lbs/yr of nitrogen are contributed by each five-member family discharging an average of 50 gal/cap-day of sewage (Polta 1969). This computes to 6,700 lbs of nitrogen added to the watershed by the 250 families. For the nitrogen balance, the source will be rounded to 10,000 lbs. Even at 10,000 lbs this source represents less than 0.5% of the total.

NITROGEN DEPLETION

Nitrogen depletion may be merely a loss of nitrogen from the basin, or it may result in an enrichment of surface waters. Depletions involving denitrification, harvest, animal uptake, wind eroded soil, and ammonia volatilization do not directly contribute to enrichment of surface waters. Products of denitrification and wind eroded soil may return as bulk precipitation, and animal uptake may result in excrement which enriches stream or surface impoundments. Depletion to groundwater may or may not contribute to surface water enrichment, depending upon whether the groundwater serves as surface-water baseflow or merely remains in groundwater storage. Subsurface drainage, soil erosion, surface runoff, and municipal or industrial effluent contribute directly to the nutrient enrichment and each will be discussed separately.

Non-Enrichment Losses

(1) Denitrification: Webber and Lane (1969) estimate 20 lbs/ac-yr lost annually through denitrification in soils cultivated with corn crops. This loss is for soil under a manure application, and at twice the application, denitrification doubled. Allison (1965) reports that 10 to 20% of the total mineral nitrogen in the soil is lost through denitrification and Broadbent and Clark (1965) report a loss of 10 to 15%. For the New Prague watershed, assuming 15% loss of the total nitrogen source, the depletion would be 350,000 lbs. Fifteen per cent loss of the applied fertilizer would represent a 186,000 lb depletion. If Webber and Lane's 20 lbs/ac were used to compute the annual loss for the 12,600 acres in agricultural crops, it would come to 252,000 lbs of nitrogen, or if the 20 lbs/ac loss were applied to the entire watershed, it would come to 298,000 lbs. A considerable amount of the total nitrogen supply is tied up in forms not subject to denitrification, so the 350,000 lbs is probably high. A "best guess" estimate of 250,000 lbs loss for the watershed was used for the nitrogen balance.

(2) Ammonia Volatilization: Harmsen and Kalenbrander (1965) report that ammonia volatilization losses are usually 5 to 20% of that ammonia which is applied as fertilizer. New Prague prevailing practice is to till the ammonia to a depth of six to eight inches. It was assumed that a maximum of 10% is lost by volatilization, and this was about 110,000 lbs (not all applied fertilizer nitrogen is in the ammonia form).

(3) Harvest Depletion: Considerable data have been published relative to crop yields and nutrient yield in the crop. These data which are not shown here, are comparable

with the New Prague yields shown in Table 5.

Oats and wheat are small grains which at a mean yield of 55 lbs/ac-yr on the 2646 acres in small grains yield about 150,000 lbs of nitrogen. The 4095 acres in corn yield about 630,000 lbs of nitrogen, the 1500 acres in beans and non-specific row crops yield about 140,000 lbs. The hay is only 20 to 30% alfalfa, and the 3767 acres in hay will yield approximately 300,000 lbs of nitrogen. The total harvest depletion then comes to about 1,220,000 lbs.

(4) Other Depletions: Such depletions as animal uptake and wind erosion are not well enough documented to be predictable. It can be readily seen, however, that livestock uptake is quite small for the New Prague watershed. The animals that contribute the 110,000 lbs of manure could weigh as much as 500,000 lbs wet weight. Thus if as much as 1% of the wet weight of all these animals were nitrogen, that is still only 5000 lbs. Even if 5000 lbs accurately represented the weight of nitrogen in the animals, this could only be depletion if the 500,000 lbs of animal represented annual growth of livestock.

Subsurface Drainage

Table 6 summarizes some of the published data on nitrogen concentrations and loadings in tile drain effluent. Tile drain data were analyzed for the New Prague watershed and the results of the analysis are as indicated in Table 7. The three areas representing acres drained are based upon different criteria: i.e., 15 acres results from an engineering criteria of drainage density equal to 400 feet of tile per acre drained; 28 acres is based on a 200 feet tile drain spacing; 49 acres is what the farmer thinks he is draining, a density of 123 feet of tile per acre drained. For total watershed, the length of tile drain are used rather than a loading per acre (see Johnson 1971a, 1971b for details of analysis).

TABLE 5. New Prague Crop Yields
(Hanson, 1970 and Leary, 1970)

Crop	bu/ac (T/ac)	Nutrients lb/ac N	P
Oats	65	61	12
Wheat	28.2	50	10
Corn	96	154	25
Soy Beans	24	90	9
Alfalfa	3.4 T/ac	153	14

TABLE 6. Nitrogen in Tile Drains

Ref	Location and Description	Conc mg/l	Load lb/ac-yr
1	San Joaquin, California irrigated and fertilized	44.5	-
1	San Joaquin, California irrigated and fertilized	23.0	-
1	San Joaquin, California irrigated and fertilized	37.0	-
1	San Joaquin, California unirrigated and noncropped	1.0	-
1	Yakima, Washington	-	33
1	United States intertilled crops	-	17.1
1	United States annual not tilled	-	32.5
1	United States bi and perennial	-	23.0
1	Wisconsin (Inorganic and organic) average	-	6.7
2	Yakima, Washington (Range 38-166)	-	81.

(1) Biggar and Corey (1969).
(2) Sylvester (1961).

TABLE 7. Nitrogen Loads as Computed for Three Assumed Drainage Areas of a Sampled Tile Drain Field

Nutrient Period	lb/ac-yr Assumed Acres Drained 15	28	49
Nitrogen			
1969	16	8.5	4.8
1970	8.7	4.6	2.7
Average	12	6.6	3.7

Based upon tile drain length, the total N output from subsurface drainage was about 200,000 lbs.

Runoff and Erosion

The surface runoff and erosion value of 264,000 lbs of nitrogen was derived entirely from integration of data collected at New Prague. It is interesting to note the 89% of this 1969 total nitrogen load occured during the spring runoff period of 53 days. Similar results were obtained for 1970 spring runoff.

NITROGEN BALANCE

Table 8 is a synoptic listing of the values derived for each of the various categories. The "Groundwater or Soil Storage" category is a sort of catch-all which was not directly measured, it was computed as the difference between the input and output. Data published by G. E. Smith (1967) indicated that in Missouri over a 17 year period about 13 lbs per acre-year of nitrate nitrogen accumulated in a ten foot soil column (this would represent about 200,000 lbs of nitrate at New Prague). The organic fraction of nitrogen would probably be greater in soil than the nitrate fraction, and a build up of total nitrogen in the soil column which may be on the order of, or even exceed, the 476,000 lbs of N indicated in Table 8, appears reasonable.

The closeness of the values for crop yield and commercial fertilizer application is an unfortunate coincidence most likely related to their general magnitude. The closeness is not an indication of accuracy, and it certainly is not an indication that the entire fertilizer supply was taken up by crops.

Feth (1967) indicates that sampling in the Mojave Desert provides data "strikingly similar in concentration and chemical type to bulk precipitation in the far different environment of Menlo Park, California, near the coast." It would appear that in a desert environment, free from fertilized agriculture, bulk precipitation may provide the major source of nitrogen compounds. It is evident from a review of the literature, that, from a quantitive viewpoint, little has been documented on a nitrogen cycle or balance in an arid environment.

TABLE 8. New Prague Watershed Soil Nitrogen Balance, 1969

	Total Nitrogen* lb/yr	%
SOURCES		
Bulk Precipitation	805,000	34.4
N - Fixation	175,000	7.5
Manure and Feedlot Drainage	110,000	4.7
Commercial Fertilizer	1,240,000	53.0
Septic Tank Effluent	10,000	0.4
TOTAL SOURCES	2,340,000	100.0
NON-ENRICHMENT DEPLETIONS		
Denitrification	250,000	10.7
Ammonia Volatilization	110,000	4.7
Crop Yield	1,220,000	52.1
To Groundwater or Soil Storage	476,000	20.4
ENRICHMENT DEPLETIONS		
Subsurface Drain	20,000	0.9
Surface Runoff and Erosion	264,000	11.2
TOTAL DEPLETIONS	2,340,000	100.0

*The number of significant figures shown are for mathematical completeness only and should not be construed to be an indication of accuracy.

BIBLIOGRAPHY

Alexander, M. 1965. Nitrification. In W. V. Bartholomew and F. E. Clark [ed] Soil Nitrogen. Agronomy 10, Amer. Soc. Agron., Madison, Wisconsin.

Allison, F. E. 1965. Evaluation of Incoming and Outgoing Processes that Affect Soil Nitrogen. In W. V. Bartholomew and F. E. Clark [ed] Soil Nitrogen. Agronomy 10, Amer. Soc. Agron., Madison, Wisconsin.

--- --- 1966. The Fate of Nitrogen Applied to Soils. Adv. Agron. 18:219-258.

Allred, E. R. 1969. Animal Waste Disposal Problems and Trends in Minnesota. In Water Pollution by Nutrients--Sources, Effects and Control. Water Resources Research Center Bulletin 13, University of Minnesota.

Bartholomew, W. V. 1965. Mineralization and Immobilization of Nitrogen in the Decomposition of Plant and Animal Residues. In W. V. Bartholomew and F. W. Clark [ed] Soil Nitrogen. Agronomy 10, Amer. Soc. Agron., Madison, Wisconsin.

Biggar, J. W. and R. B. Corey. 1969. Agricultural Drainage and Eutrophication. In Eutrophication: Causes, Consequences, Correctives. National Academy of Sciences, Washington, D. C.

Broadbent, F. E. and F. Clark. 1965. Denitrification. In W. V. Bartholomew and F. E. Clark [ed] Soil Nitrogen. Agronomy 10, Amer. Soc. Agron., Madison, Wisconsin.

Feth, J. H. 1966. Nitrogen Compounds in Natural Waters--A Review. Water Resources Research. 2:44-58.

--- --- 1967. Chemical Characteristics of Bulk Precipitation in the Mojave Desert Region, California. U.S. Geological Survey, Professional Paper 575C. pp C222-C227.

Hanson, L. 1970. Personal Communication.

Harmsen, G. W. and G. J. Kalenbrander. 1965. Soil Inorganic Nitrogen. In W. V. Bartholomew and F. E. Clark [ed], Soil Nitrogen. Agronomy 10, Amer. Soc. Agron., Madison, Wisconsin.

Jensen, H. L. 1965. Nonsymbiotic Nitrogen Fixation. In W. V. Bartholomew and F. E. Clark [ed], Soil Nitrogen. Agronomy 10, Amer. Soc. Agron., Madison, Wisconsin.

Johnson, J. D. 1971a. Development of a Mathematical Model to Predict the Role of Surface Runoff and Groundwater Flow in Overfertilization of Surface Waters. Unpublished doctoral dissertation.

--- --- 1971b. Development of a Mathematical Model to Predict the Role of Surface Runoff and Groundwater Flow in Overfertilization of Surface Waters. Water Resources Research Center Bulletin 35. University of Minnesota, Minneapolis, Minnesota. (In press).

Kardos, L. T. 1967. Waste Water Renovation by the Land--A Living Filter. In W. C. Brady [ed], Agriculture and the Quality of Our Environment. Amer. Ass. Adv. Sci. Mono. 85, Washington, D. C.

Leary, R. 1970. Personal Communication.

Loehr, R. C. 1968. Pollution Implications of Animal Wastes--A Forward Oriented Review. U. S. Department of the Interior, Red. Water Pollution Control Adm., Robert S. Kerr Water Research Center. Ada, Oklahoma.

Mackenthum, K. M. 1968. The Phosphorus Problem. J. Amer. Water Works Ass. 60:1047-1054.

Nommik, H. 1965. Ammonium Fixation and Other Reactions Involving a Nonenzymatic Immobilization of Mineral Nitrogen in Soil. In W. V. Bartholomew and F. E. Clark [ed], Soil Nitrogen. Agronomy 10, Amer. Soc. Agron., Madison, Wisconsin.

Nutman, P. S. 1965. Symbiotic Nitrogen Fixation. In W. V. Bartholomew and F. E. Clark [ed], Soil Nitrogen. Agronomy 10, Amer. Soc. Agron., Madison, Wisconsin.

Odum, E. P. 1959. Fundamentals of Ecology. W. B. Saunders Co., London.

Polta, R. C. 1969. Septic Tank Effluents. In Water Pollution by Nutrients--Sources, Effects and Control. Water Resources Research Center Bulletin 13. University of Minnesota, Minneapolis, Minnesota.

Reid, G. K. 1961. Ecology of Inland Waters and Estuaries. Reinhold Publishing Corp., New York.

Scarsbrook, C. E. 1965. Nitrogen Availability. In W. V. Bartholomew and F. E. Clark [ed], Soil Nitrogen. Agronomy 10, Amer. Soc. Agron., Madison, Wisconsin.

Smith, G. E. 1967. Fertilizer Nutrients as Contaminants in Water Supplies. In Agriculture and the Quality of Our Environment. Amer. Ass. Adv. Sci., Washington, D.C.

Stevenson, F. J. 1965. Origins and Distribution of Nitrogen in Soil. In W. B. Bartholomew and F. E. Clark [ed], Soil Nitrogen. Agronomy 10, Amer. Soc. Agron., Madison, Wisconsin.

Sylvester, R. O. 1961. Nutrient Content of Drainage Water from Forested, Urban and Agricultural Areas. In Algae and Metropolitan Wastes, U.S. Public Health Service, Robert A. Taft Sanit. Eng. Center, Cincinnati, Ohio.

Townshend, A. R. and K. A. Reichert. 1969. Status Report on Water Pollution Control Facilities for Farm Animal Wastes in the Province of Ontario. In Animal Waste Management, Cornell University Conference on Agricultural Waste Management. Syracuse, New York.

Tukey, H. B., Jr., and R. A. Mecklenburg. 1961. Leaching of Metabolites from Foliage and Subsequent Reabsorption and Redistribution of the Leachate in Plants. American Journal of Botany 51:737-742.

--- --- and J. V. Morgan. 1962. The Occurrence of Leaching from Above-Ground Plant Parts and the Nature of the Material Leached. XVIth International Horticulture Congress, Brussels, Belgium.

Vincent, J. M. 1965. Environmental Factors in the Fixation of Nitrogen by the Legume. In W. V. Bartholomew and F. E. Clark [ed], Soil Nitrogen. Agronomy 10, Amer. Soc. Agron., Madison, Wisconsin.

Waksman, S. A. 1952. Soil Microbiology. John Wiley and Sons, Inc.

Webber, L. R., and T. H. Lane. 1969. The Nitrogen Problem in the Land Disposal of Liquid Manure. In Animal Waste Management, Cornell University Conference on Agricultural Waste Management, Syracuse, New York.

SEASONAL EFFECTS ON SOIL DRYING AFTER IRRIGATION

B. A. Kimball and R. D. Jackson

U.S. Water Conservation Laboratory, Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture, Phoenix, Arizona 85040

The meteorological variables which characterize the different seasons of the year produce large changes in the rate of evaporation from exposed surfaces after irrigation. Erie, French, and Harris (1968) have published information depicting the seasonal evapotranspiration of water by crops in Arizona, and Cooley (1970) has computed seasonal evaporation rates from open water surfaces. For both types of surface, the amount of time elapsed since the last addition of water does not materially affect the rate of water loss (provided the crop has a full canopy and water is not withheld too long, of course). On the other hand, bare soil dries rapidly at the surface, and the evaporation rate from it depends upon both the meteorological variables that characterize the season of the year and the amount of time that has elapsed since the last irrigation or rain. We shall present data which illustrates how the evaporation rate from one soil, bare Adelanto loam in Phoenix, changes with season and with time since the last irrigation.

DESCRIPTION OF THE DATA

Ten years ago precision weighing lysimeters were installed in a field at the U.S. Water Conservation Laboratory in Phoenix, Arizona [Van Bavel and Myers (1962)]. The soil in the field and in the lysimeters is Adelanto loam. Eleven times during these last ten years, the lysimeters and the surrounding field were irrigated while the soil was bare, and the subsequent loss of water from the lysimeters was followed for one week or more. These irrigations and the subsequent drying cycles have been observed during almost every month of the year. We have assembled these soil drying data into some graphs which reveal seasonal effects on the drying of Adelanto loam.

DAILY EVAPORATION

In Fig. 1 are plotted the values of daily evaporation for the first day after irrigation against the time of year. As expected, the data exhibit a cosine-shaped curve with a maximum evaporation rate of about 9 mm/day in summer and a minimum of about 2 mm/day in winter. The dashed lines represent the range of daily evaporation from open water surfaces in the data compiled by Cooley (1970). The solid line is the potential daily evaporation we have computed from long-term monthly climatological data compiled by the National Weather Service at Sky Harbor Airport in Phoenix. We used Van Bavel's (1966) combination formula with a roughness length of 0.02 cm. One can see that generally the bare soil evaporated at somewhat more than the potential rate on the first day after irrigation during all seasons of year, and also that generally this rate fell within the range of open water evaporation rates reported by Cooley. The potential evaporation curve was computed from averages over all weather conditions, whereas the data are more representative of fair weather conditions since they are from drying periods of one week or longer. Thus, indeed, the data points should indicate evaporation rates higher than the average potential rate.

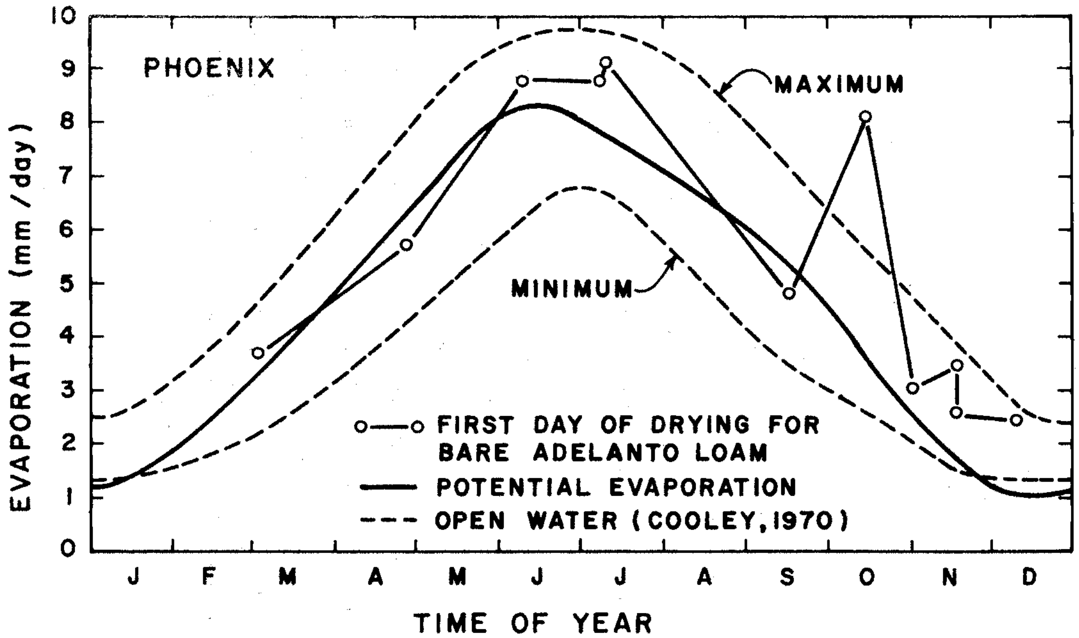


Fig. 1. Daily evaporation from bare Adelanto loam for the first day after an irrigation and from open water and potential evaporation versus time of year.

In Fig. 2 are plotted the values of daily evaporation for several days after irrigation against time of year. (Values obtained after a 7 July 1961 and a 9 July 1970 irrigation, and also after a 16 November 1961 and a 16 November 1969 irrigation have been averaged together so only nine drying periods appear in Fig. 2 rather than eleven.) In summer the daily evaporation decreased rapidly with the number of days since irrigation, going from 9 mm/day on the first day to 2 mm/day by the seventh. In winter, however, the evaporation rate was about 2 mm/day on the first day and it was still about 2 mm/day on the seventh. Thus, about one week after irrigation there were little or no changes in the evaporation rate with season, and the curve for seventh day evaporation is virtually a straight line. The curve for the 21st day evaporation also is virtually a straight line, showing about 0.75 mm/day of evaporation regardless of season.

There is much scatter in the data in Fig. 2, however, and this distorts the clarity of the seasonal patterns of daily evaporation. Note that the third day of evaporation in March was particularly high, a consequence of abnormally high winds. Thus the day-to-day variations in weather evidently exerted significant influences which are superimposed on the seasonal trends. Just as the seasonal effects disappeared about a week after irrigation, so the day-to-day variation decreased to a rather small magnitude. In winter, however, the relative effects of day-to-day variations of weather were rather high, as much as 100%, because the mean evaporation rate was so small.

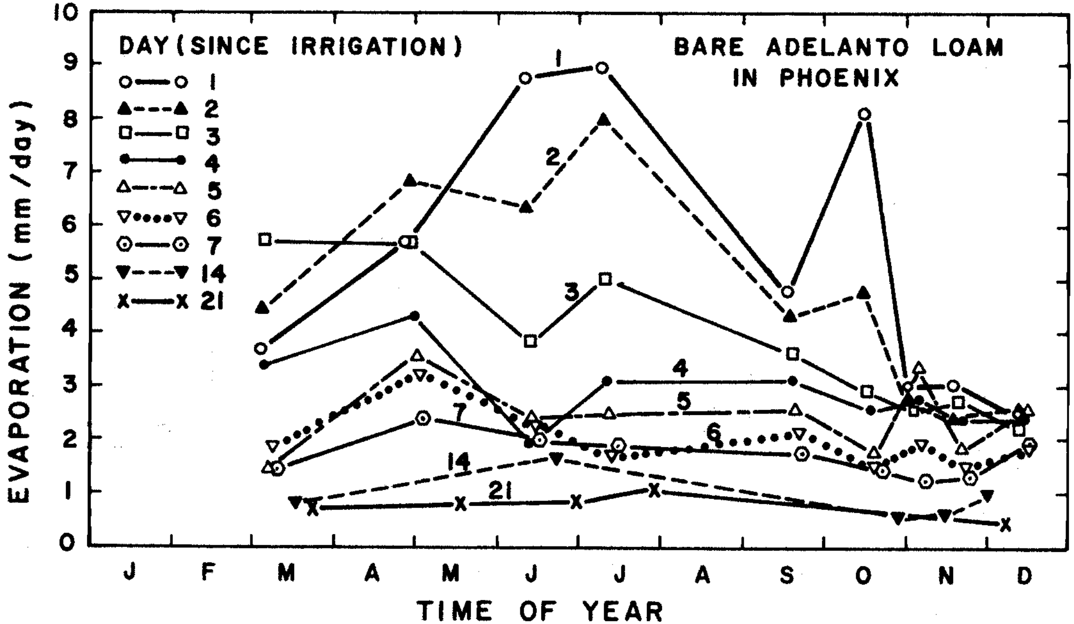


Fig. 2. Daily evaporation for several individual days following irrigation of bare Adelanto loam versus time of year.

CUMULATIVE EVAPORATION

In Fig. 3 cumulative daily evaporation has been plotted against the number of days since irrigation for several periods of drying occurring during several different months of the year. As expected, the curves for the summer months have the largest initial slopes, those for the winter months have the smallest, and those for the spring and fall months have intermediate. After about a week all the curves have essentially similar slopes - again illustrating the dampening of the seasonal effects on daily evaporation after about a week of drying. Total evaporation during the two-week period was nearly twice as much for the summer months as for the winter months. For the first three days following irrigation nearly four times as much water was lost during summer months as winter months. We note, too, that there is relatively little crossing of the curves. Thus, the total amount of water lost for the summer months was always greater than the total amount lost in winter months, at least for the time period to which we can safely extrapolate these data.

THEORETICAL CONSIDERATIONS

Recently, Black et al. (1969) attempted to use a square root relationship developed by Gardner (1959) to describe cumulative evaporation from Plainfield sand under summertime conditions in Wisconsin. They empirically fitted a constant of proportionality to relate cumulative evaporation to the square root of time. By replotting the data from Fig. 3 on a square root of time scale in Fig. 4, one can see that all of the curves are considerably straightened. However, they are by no means straight, and they are all different. No single constant of proportionality will describe them because any constant would have

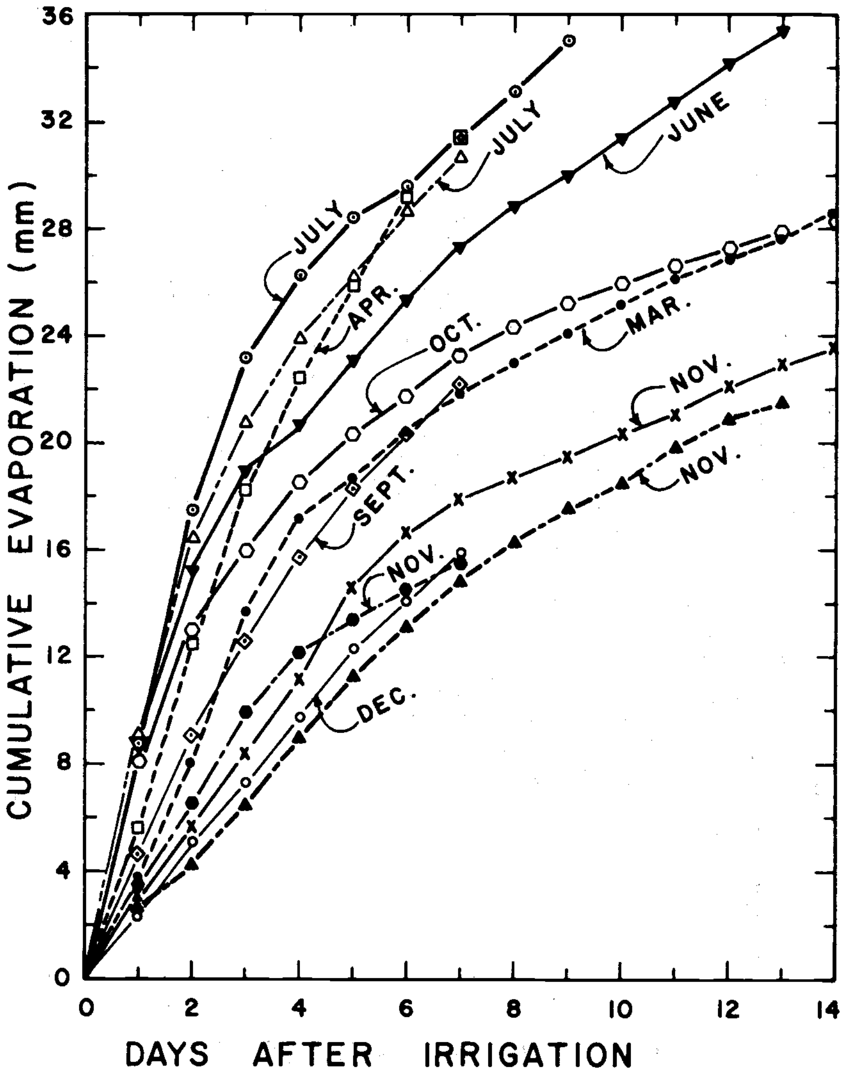


Fig. 3. Cumulative daily evaporation from bare Adelanto loam versus time after irrigation for several periods of drying occurring during several different months of the year.

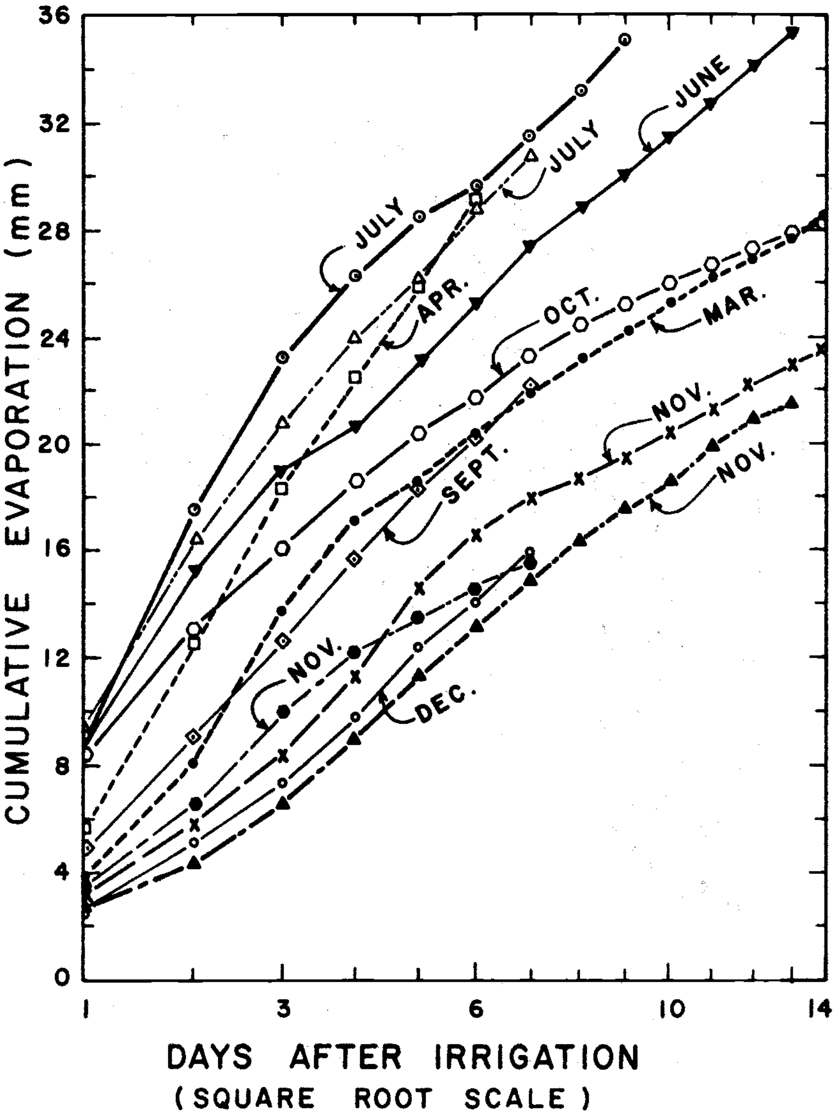


Fig. 4. Cumulative daily evaporation from bare Adelanto loam versus time after irrigation on a square root scale for several periods of drying occurring during several different months of the year.

to be a function of the season of the year.

It is generally accepted that a soil dries in three stages, as discussed by Lemon (1956). During the first stage, water is lost rapidly while capillary flow to the surface is able to meet the evaporative demand of the atmosphere. In the second stage, rate of loss declines rapidly because the soil moisture content has become so low that the intrinsic hydraulic properties of the soil govern the rate of moisture flow to the surface. Atmospheric conditions no longer are as important. The third stage is characterized by extremely low rates of moisture loss and is governed by adsorptive forces acting over molecular distances at liquid-solid interfaces.

In most laboratory studies of soil drying, atmospheric conditions are relatively constant, and consequently, stage I can easily be distinguished from stage II [Gardner and Hillel (1962), Fritton, et al. (1967), Hanks et al. (1967), Gardner and Gardner (1969), and Gardner et al. (1970)]. During stage I, the cumulative evaporation curves are straight lines, and they abruptly become curvilinear with decreasing slope at the onset of stage II. Gardner and Hillel (1962) have developed an equation to predict the time of the onset of second stage drying and a second equation to compute the actual rate of evaporation during the second stage. Their equations agreed closely with experimental results from soil columns under laboratory conditions.

The curves in Fig. 3, however, were obtained under field conditions, and they are qualitatively different from those obtained in the laboratory. One cannot ascertain any particular time at which there was a transition from a stage I to a stage II. In all the laboratory data, the amount of water lost during stage I increased as the initial evaporation rate was decreased. In

Fig. 3, however, the greatest curvature (indicating a transition from stage I to stage II?) occurs for the summer months after more than 20 mm of water evaporated. For the winter months, which have the lower initial evaporation rates, the greatest curvature occurs after only 14 mm evaporated. We attempted to apply the equations of Gardner and Hillel, but found little agreement.

There may be several reasons why the data in Fig. 3 obtained under field conditions do not exhibit distinct stages and do not obey the equations of Gardner and Hillel (1962). For instance, the initial moisture distribution and subsequent redistribution below an initial depth of wetting could have affected the evaporation rate [Gardner et al. (1970)]. However, we think that the most important reason for disagreement is that there are wide variations in temperature and other meteorological parameters in the field which were not simulated in the laboratory studies. These variations cause temperature gradients in the soil which significantly affect the evaporation process.

The diurnal variation of these meteorological parameters produces a diurnal variation in the evaporation rate from bare soil. In Fig. 5 the hourly evaporation from bare Adelanto loam is plotted against time of day for the 2nd, 9th, 16th, 23rd, and 37th days after irrigation. The hourly evaporation rate from an insulated open water tank is also plotted for reference. The hourly evaporation rate at noon from the bare soil decreased progressively with time after irrigation. However, even 37 days after irrigation there was still a definite diurnal variation in evaporation rate. Evidently, atmospheric effects are far more important in stage II drying than has generally been appreciated.

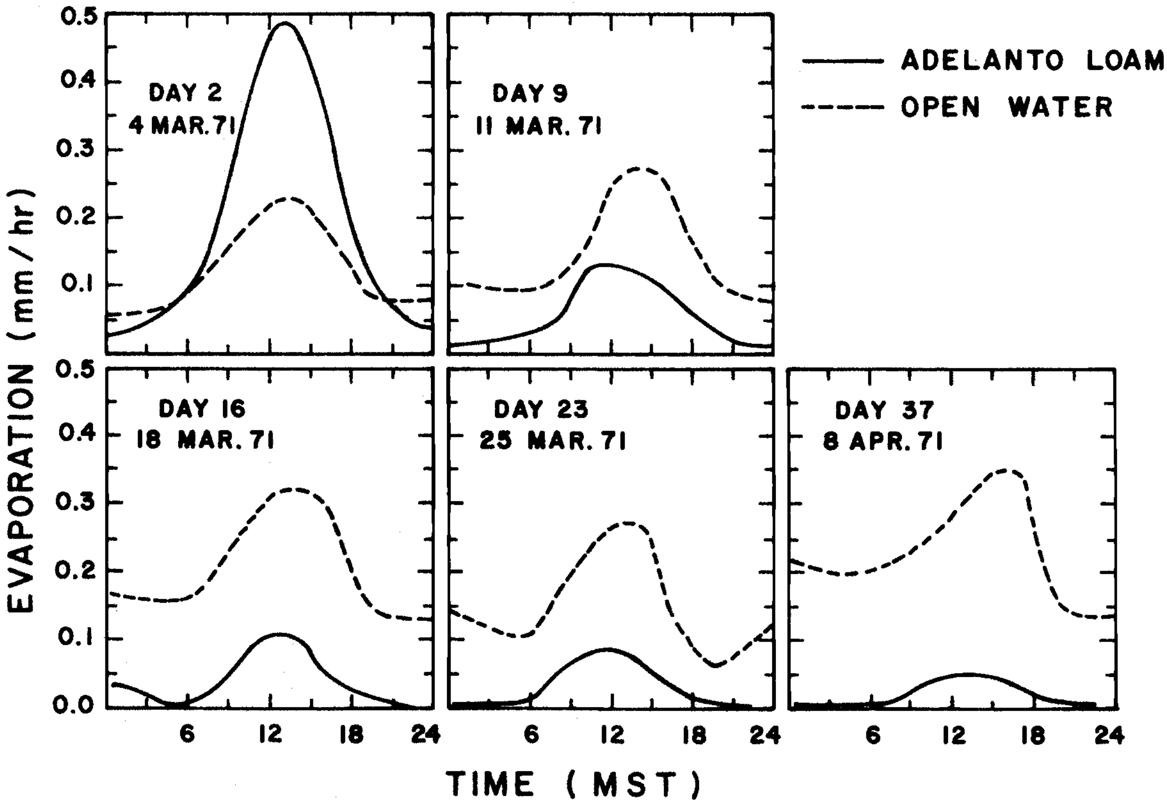


Fig. 5. Hourly evaporation from Adelanto loam and from open water versus time of day for five individual days following irrigation of the Adelanto loam.

SUMMARY

Lysimeter measurements of evaporation from bare Adelanto loam in Phoenix have been obtained during all seasons of the year. These data show that the evaporation rate on the first day of drying after irrigation is about 9 mm/day in summer and 2 mm/day in winter. By the seventh day of drying seasonal effects virtually disappear, and the evaporation rate is about 2 mm/day in both summer and winter. By 21 days it is about 0.75 mm/day in both summer and winter.

The individual drying curves were qualitatively different from the drying curves commonly obtained in the laboratory under isothermal conditions. It is suggested that the diurnal variations in temperature and other meteorological parameters have caused the difference, and data are presented which illustrate a diurnal fluctuation in evaporation rate still persisting on the 37th day after irrigation.

ACKNOWLEDGEMENT

Some of the data was collected and summarized in U.S. Water Conservation Laboratory Annual Reports by Dr. C. H. M. van Bavel.

LITERATURE CITED

Black, T. A., W. R. Gardner, and G. W. Thurtell, The prediction of evaporation, drainage, and soil water storage for a bare soil, Soil Sci. Soc. Amer. Proc. 33(5), 655-660, 1969.

Cooley, K. R., Evaporation from open water surfaces in Arizona, University of Arizona, Agricultural Experiment Station and Cooperative Extension Service, Folder 159, 1970.

Erie, L. J., O. F. French, and K. Harris, Consumptive use of water by crops in Arizona, University of Arizona, Agricultural Experiment Station, Technical Bulletin 169, 46 pp., 1968.

Fritton, D. D., D. Kirkham, and R. H. Shaw, Soil water and chloride redistribution under various evaporation potentials, Soil Sci. Soc. Amer. Proc. 31(5), 599-603, 1967.

Gardner, H. R., and W. R. Gardner, Relation of water application to evaporation and storage of soil water, Soil Sci. Soc. Amer. Proc. 33(2), 192-196, 1969.

Gardner, W. R., Solutions of the flow equation for the drying of soils and other porous media, Soil Sci. Soc. Amer. Proc. 23, 183-187, 1959.

Gardner, W. R., and D. I. Hillel, The relation of external evaporative conditions to the drying of soils, J. Geophys. Res. 67(11), 4319-4325, 1962.

Gardner, W. R., D. Hillel, and Y. Benyamini, Post-irrigation movement of soil water 2. Simultaneous redistribution and evaporation, Water Resources Res. 6(4), 1148-1153, 1970.

Hanks, R. J., H. R. Gardner, and M. L. Fairbourn, Evaporation of water from soils as influenced by drying with wind or radiation, Soil Sci. Soc. Amer. Proc. 31(5), 593-598, 1967.

Lemon, E. R., The potentialities for decreasing soil moisture evaporation loss, Soil Sci. Soc. Amer. Proc. 20(1), 120-125, 1956.

Van Bavel, C. H. M., Potential evaporation: the combination concept and its experimental verification, Water Resources Res. 2(3), 455-467, 1966.

Van Bavel, C. H. M., and L. E. Myers, An automatic weighing lysimeter, Agric. Eng. 43(10):580-583, 586-588, 1962.

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

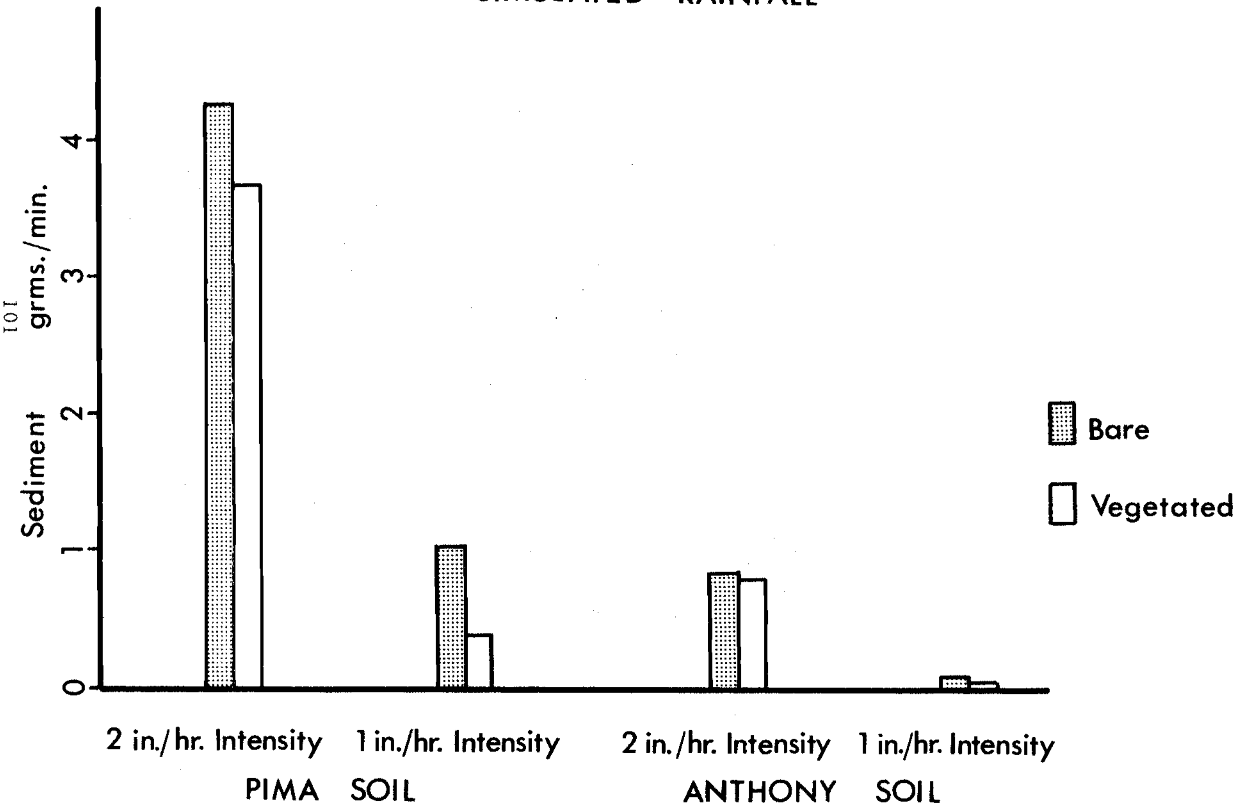


TABLE 1

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.

REFERENCES

Booth, W. E., Algae as pioneers in plant succession and their importance in erosion control, Ecology, (22), 38-46, 1941.

Faust, W. F., The effect of algal-mold crusts on the hydrologic processes of infiltration, runoff, and soil erosion under simulated rainfall conditions, Masters thesis, University of Arizona, Tucson, Arizona, 1970.

Fletcher, J. E. and W. P. Martin, Some effects of algae and molds in the rain crusts of desert soils, Ecology, (29), 95-99, 1948.

Osborn, B. O., Range cover tames the raindrop, Soil Conservation, (16), 195-197, 1950.

EFFECTS OF FIRE ON WATER INFILTRATION RATES IN A PONDEROSA PINE STAND

Malcolm J. Zwolinski
University of Arizona, Tucson

INTRODUCTION

One of the more important ways in which water supplies can be maintained and, in some cases increased substantially, is through the proper management of watersheds or land areas producing water. Attention is being focused, in particular, on land areas supporting forest vegetation, and, specifically in Arizona, on the ponderosa pine type. Watershed studies have shown that these forested areas, which are normally limited to regions of high rain and snow fall, are best suited for intensive water yield management.

There are, however, some forest management practices which may affect the water yield from a forested watershed. The importance of the pine forest as a timber and water producing area has led to increased protection from wildfire. This has resulted in dense stand growth with increased destructive fire potential and transpirational water loss. In Arizona, as in many areas of the South and West, prescribed burning has been used to effectively reduce these fuel hazards in the forest. For example, 400,000 acres of ponderosa pine on the Fort Apache Indian Reservation, all of which lie in the Salt River Watershed, are being prescribed burned periodically to reduce surface fuels and raise crown levels. With periodic treatment by fire in this manner, a forest stand becomes open and parklike with a much reduced fuel volume.

Although these prescribed burns frequently accomplish their management objectives, concern has been expressed about the possible side effects of such treatments. Specifically, questions have been raised relating to atmospheric pollution by smoke particles and to the effects on water infiltration and water yield. The brief discussion in this paper will be limited to the effects on water infiltration rates.

FIELD PROCEDURES

A study was conducted on the Fort Apache Indian Reservation in east central Arizona at an elevation of approximately 7,600 feet above sea level. Research sites were located within a half square mile area 5 1/2 miles east of McNary on the south side of State Highway 73. Although the study sites and surrounding area were relatively flat there was an overall exposure to the south and southwest toward the North Fork of the White River.

Ponderosa pine (*Pinus ponderosa* Laws.) was the dominant tree species in the study area with some occasional deciduous white oak (Gambel oak - *Quercus gambelii* Nutt.). Average stocking density was found to be about 1,500 trees per acre with a mean basal area of nearly 160 square feet per acre.

Soils in this region are silt loam in texture derived from a mixture of volcanic cinders and basalt slag. Examination of profiles exposed in the study area provided enough evidence to classify the soils in the Sponseller series.

The study was designed to evaluate the influence of burning treatments on water infiltration capacities. These treatments (control, light burn, and heavy burn) were replicated on four sites. Light burn treatments were made on areas approximately 10 feet square by igniting an edge of the plot and allowing the fire to move across against the wind. This light intensity burn closely approximated a typical prescribed burn. A heavy burn treatment plot of similar size was ignited simultaneously from all sides and the fire allowed to reach maximum intensity in the plot center.

Seven fusion pyrometers were used to measure the heat generated by each burning treatment. These pyrometers consisted of pure organic compounds, which had definite melting points, painted on small sheets of mica. When inserted vertically into the soil with a flat putty knife, the temperature distribution of the top few inches of soil during burning could be determined by observing the extent of melting of each compound. Surface soil temperatures for the light burn treatments did not exceed 200° F. Maximum temperature at the soil surface for heavy burns ranged from 350° F. to 550° F.

After burning, an infiltrometer plot, one by 2 1/2 feet in size, was installed in the center of each treatment area on each site. A modified North Fork sprinkling type infiltrometer with constant head tank was utilized to conduct infiltration measurements. The twelve infiltrometer plots remained in place for over two years through two overwintering periods. Two infiltration runs were conducted on each plot in the late summer of 1963, and three series of runs were made in both the summers of 1964 and 1965. Infiltration curves were plotted for each run from runoff data programmed into a computer and an incremental digital plotter. Infiltration capacity values were obtained directly from these curves.

RESULTS AND CONCLUSION

Results showed light and heavy burns produced highly significant decreases in infiltration capacities immediately following burning. However, no statistically significant differences due to burning were detected between heavy burn and light burn treatments and controls during the second and third summers.

The restoration of infiltration capacities to nearly normal conditions after an overwintering period can be attributed to freezing and thawing conditions. It was noted in the early spring of 1964 and again in 1965 that the soils on the study area were more loosely textured and porous indicating the effects of frost action. Minimum temperatures during the winter months in this area are sufficiently low to cause freezing and thawing.

Increases in soil pH, carbon, and total nitrogen percentages for the surface two inches of soil were detected immediately following both light and heavy burning treatments. A slight increase in cation exchange capacity was also noted. These increases were still evident two years after treatment but to a lesser extent.

A significant increase in soil bulk density was obtained following heavy burning treatment but not following light burning. This increase, however, was not detected after the first overwintering period. Surface temperatures indicated that the heat generated by the heavy burn treatment was adequate to consume the organic material incorporated in the surface few millimeters of soil. This removal of organic material probably caused a breakdown in soil structure resulting in a more compacted surface soil. Consequently, bulk density samples of the surface one inch of soil would actually include more mineral soil, resulting in a higher bulk density value.

Late fall prescribed burning programs conducted on the Fort Apache Indian Reservation, when followed by an overwintering period with freezing and thawing conditions, therefore, seem to have little or no detrimental effect on infiltration rates.

Another interesting facet of water infiltration into Arizona forest soils was detected during the analyses of study data. Examination of the 96 infiltration curves plotted from the field data showed that 74 had a prominent depression approximately 5 to 15 minutes after the start of water application. This indicated that the infiltration rate reached a minimum value and then increased before a constant capacity was maintained.

The best explanation for this dip in the infiltration curve is soil non-wettability, sometimes known as a water-repellent or hydrophobic soil condition. It has been commonly observed that extremely dry surface soils will temporarily resist wetting at the start of rainfall but will transmit water normally after being moistened. This initial resistance to wetting may be caused by the formation of impenetrable air films at the water-soil interface (Krammes and DeBano, 1965).

Water-repellent soils have received increasing attention in recent years, particularly since they seem to be much more widespread than originally suspected. These soils may have widespread implications for watershed management. They can be a serious problem on steep slopes, where they reduce infiltration of rainwater and cause erosion. But they may also be an asset, for example, in arid regions, where soils might be artifically waterproofed to obtain more water (DeBano, 1969).

The identity of hydrophobic substances in soils responsible for water repellancy have not been established conclusively. It is suspected that oils and resins from organic plant remains may play an important role. The coniferous litter cover and acidic surface soil found in the study area could promote such a condition. Some research has also been published indicating that fire may accentuate a hydrophobic soil condition.

During the past two summers infiltration determinations have been made on ponderosa pine soils near Flagstaff and in the Santa Catalina Mountains northeast of Tucson. Preliminary results show the presence of a dip in the infiltration curves for these two locations which strongly indicates a water repellent-soil condition. Additional field infiltration studies are planned to investigate further the hydrologic importance of this phenomenon.

DeBano, Leonard F. 1969. Water repellent soils: a worldwide concern in management of soil and vegetation. Agric. Sci. Rev. 7(2): 11-18.

Krammes, J.S., and L. F. DeBano. 1965. Soil wettability: a neglected factor in watershed management. Water Resources Res. 1(2): 283-286.

THE USE OF A REALISTIC RAINFALL SIMULATOR TO DETERMINE RELATIVE INFILTRATION RATES OF CONTRIBUTING WATERSHEDS TO THE LOWER GILA BELOW PAINTED ROCK DAM

C. B. CLUFF
Water Resources Research Center, University of Arizona

D. G. BOYER
Hydrology and Water Resources, University of Arizona

INTRODUCTION

A rotating disk rainfall simulator developed at the Water Resources Research Center, The University of Arizona, was used in determining relative infiltration rates on approximately 7,000 mi^2 of semiarid subwatersheds of the Lower Gila River in southwestern Arizona. The location of this study area is shown in Figure 1. This hydrologic study was made as a part of the Corps of Army Engineers Environmental Impact Study, in which the senior author served as a consultant.

The unique features of the simulator used will be presented in order to satisfy the claim that it does produce realistic rainfall.

A comparative examination of Gila River flow records at Gillespie Dam approximately 37 miles upstream from Painted Rock Dam, and at the Dome gaging station eight miles above the confluence of the Gila with the Colorado River, indicated that all major flows recorded at Dome gaging station since 1920 resulted from runoff above Gillespie gaging station. These findings have been reported in the *Hydrology Study for the Gila River Below Painted Rock Dam* [1970]. The highest flow at Dome originating from the Lower Basin below Painted Rock Dam was 4820 cfs [*Water Resources Data for Arizona*, 1963] on Sept. 18, 1963. This flow originated

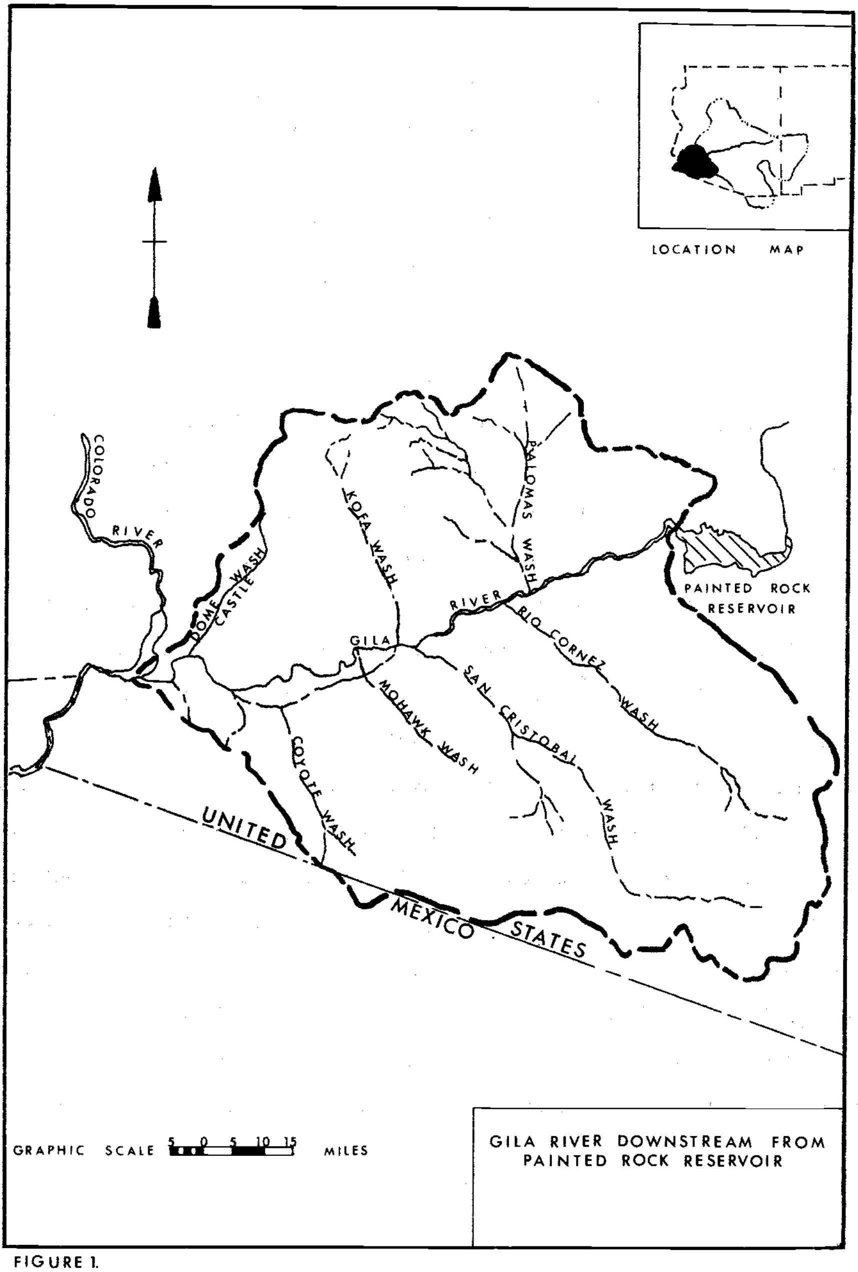

LOCATION MAP
COLORADO
RIVER
DOME
CASTLE
WASH
KOFA WASH
PALOMAS WASH
PAINTED ROCK
RESERVOIR
GILA
RIVER
RIO CORNEZ
WASH
SAN CRISTOBAL
WASH
MOHAWK WASH
COYOTE WASH
UNITED
MEXICO
STATES
GRAPHIC SCALE
5 0 5 10 15
MILES
GILA RIVER DOWNSTREAM FROM
PAINTED ROCK RESERVOIR

FIGURE 1.

from the Castle Dome Watershed. As a result of these observations, the rainfall simulator was used in an attempt to determine why so few floods had occurred from the Gila River Watershed below Painted Rock Dam.

The rainfall simulator was used on reconstituted samples taken from different soil types in the Lower Gila Watershed. The use of the simulator in this manner was not intended to quantify infiltration rates such that they could be used directly in the unit hydrograph for determining peak flows but rather to qualify the relative differences in infiltration rates in the Lower Gila subwatersheds to determine the flood threat indirectly. Funds were not available to take the simulator into the field, hence soil samples had to be taken to the simulator.

ROTATING DISK RAINFALL SIMULATOR

Rainfall simulators used in the past can be divided into two basic types, drip simulators and nozzle simulators. Drip simulators include those that use hanging yarn, glass tubing, hypodermic needles, etc., to form small tips from which drops fall by gravity. The main advantage of drip simulators is in their ability to produce a combination of relatively large drops at a low rate of application. However, impact velocities approaching those of natural rain cannot be achieved unless the drops fall more than 30 feet above the soil [*Mutchler and Hermsmerer*, 1965; *Gunn and Kinzer*, 1949]. Because of this height requirement the drip simulators are not practical for field investigations.

Nozzle simulators produce a drop distribution that includes a large number of drop sizes. If the nozzle is directed downward the pressure can be regulated to give an impact velocity similar to the terminal velocity of raindrops. Increased pressure, however, reduces the size of drops. Thus, in order to obtain realistic sized drops of high velocities, large orifice openings in the nozzles are required, causing excessive application rates. This then is the paradox of the nozzle-type simulator. An attempt to use large nozzles and reduce the intensity has been made in three basic ways: (A) to spray the nozzle over a large area by turning it upward, such as the Type F simulator; (B) to physically move the nozzle back and forth across a plot of suitable size, such as the rainulator developed by *Meyers and McCune* [1958]; or (C) to physically remove a portion of the water from the high capacity nozzle to obtain realistic intensities, as with the rotating disk rainfall simulator first developed as a laboratory model by *Morin, Goldberg, and Seginer* [1967].

During 1968-70, J. Morin, while employed by the Water Resources Research Center, The University of Arizona, developed a field model rainfall simulator based on his earlier laboratory model. This development was a part of a Water Harvesting Research Project sponsored by the Office of Water Resources Research, U. S. Department of the Interior. This field model will be designated as the Rotadisk Rainulator.

The Rotadisk Rainulator utilizes a full-cone-spray type nozzle which is similar in principle to those used by *Bertrand and Parr* [1961], but much larger in capacity. The best nozzle was found to be the Spraying Systems Company Fulljet 1-1/2H30. This nozzle, when elevated 6 feet and operated at pressure of 0.6 atmosphere, will produce an intensity of approximately 60 inches per hour. In order to reduce this intensity to a more realistic value, a slotted metal disk is rotated on a vertical axis beneath the nozzle (Figure 2). Drops from the nozzle reach the experimental plot only when the aperture is under the nozzle. In other positions the water is thrown toward the circumference of the revolving disk, where

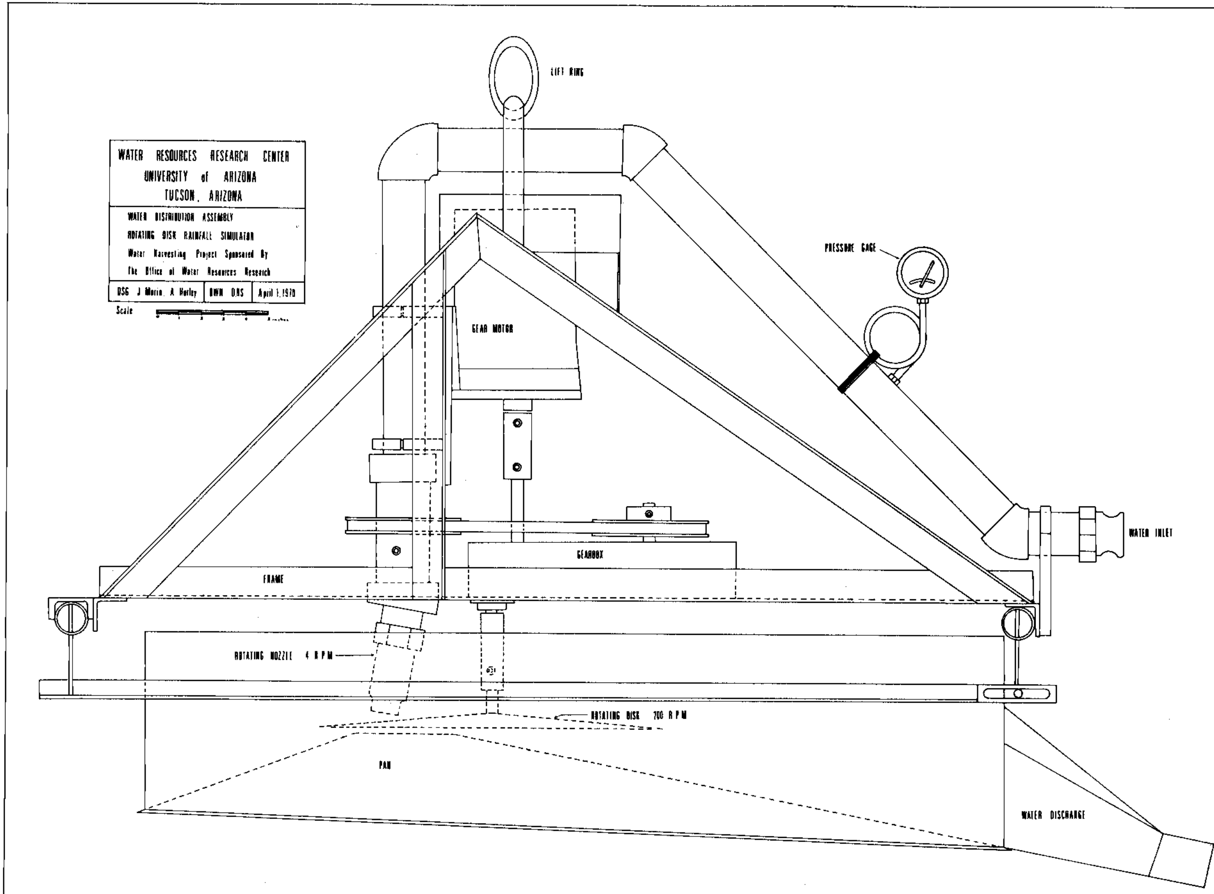

WATER RESOURCES RESEARCH CENTER
UNIVERSITY of ARIZONA
TUCSON, ARIZONA
WATER DISTRIBUTION ASSEMBLY
ROTATING DISK RAINFALL SIMULATOR
Water Harvesting Project Sponsored By
The Office of Water Resources Research
DSG J Morin. A Harley
DWN DRS
April 1, 1970
Scale
LIFT RING
PRESSURE GAGE
GEAR MOTOR
WATER INLET
GEARBOX
FRAME
ROTATING NOZZLE 4 R P M
ROTATING DISK 200 R P M
PAN
WATER DISCHARGE

FIGURE 2.

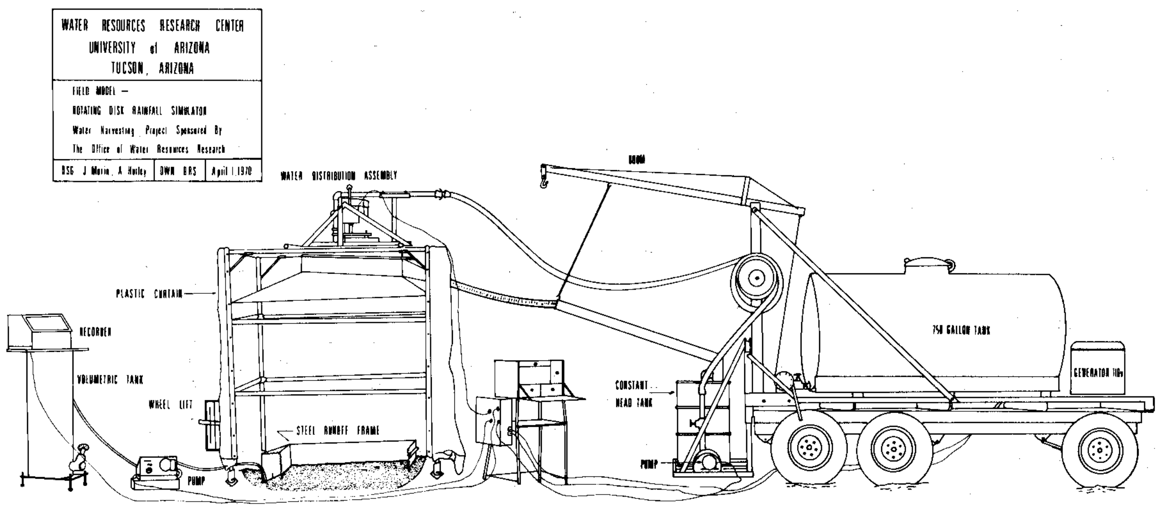
it is drained away by means of a collector pan. The excess water is returned from the pan through a storage tank to the supply pump for reuse. The nozzle on the field model rotates at 4 rpm, which is an improvement over the original laboratory model where the pan containing the soil was rotated. The complete field assembly constructed at The University of Arizona is shown in Figure 3.

The unique feature of the rotating disk rainfall simulator is the rotation of disks with various size openings that makes it possible to produce intensities from close to zero up to the full nozzle capacity. Disks can be changed in less than one minute, making it possible to study the effect on infiltration rates of a series of intensities, such as occur in natural storms.

The disks are shaped to a shallow cone with five-degree side slopes. They are 15 inches in diameter and constructed of 0.020 inch brass sheets. Disks with 5, 10, 15, 30, and 40-degree aperture angles were prepared. Corresponding intensities range from 0.67 in/hr to 6.00 in/hr, when the height is set at 6 feet and the nozzle is rotating at a 10-degree angle from the vertical. The cocking of the nozzle 10 degrees to one side is also an improvement over the original laboratory model, in that better uniformity can be obtained over a larger area. With these improvements the spacial coefficient of variation over a 4.5 ft square plot for the 2.00 in/hr intensity is 9.1 percent.

The rotation of the disk on the field model is fixed at 200 rpm which produces a rain that is visually continuous. There is some pulsation, but it is not much more than would be experienced during an intense natural rainstorm.

The simulator is portable, so that it can be taken into the field to determine the infiltration capacity of the 4.5 ft square plots. Rainfall intensity is checked periodically by covering the surface of the soil in the runoff plot with



WATER RESOURCES RESEARCH CENTER
UNIVERSITY of ARIZONA
TUCSON, ARIZONA
FIELD MODEL —
ROTATING DISK RAINFALL SIMULATOR
Water Harvesting Project Sponsored By
The Office of Water Resources Research
DSG J Morin, A Hurley
DWN BRS
April 1, 1970
WATER DISTRIBUTION ASSEMBLY
BOOM
PLASTIC CURTAIN
RECORDER
VOLUMETRIC TANK
WHEEL LIFT
STEEL RUNOFF FRAME
PUMP
CONSTANT HEAD TANK
PUMP
750 GALLON TANK
GENERATOR 110v

FIGURE 3.

plastic. If care is taken to keep the height of the nozzle at a constant height of 6 feet and if the plot is correctly positioned, the variation in rainfall intensity with time is very small. The coefficient of variation for a given rainfall intensity over nine months of intensive use was found to be approximately 0.8 percent. The reason the uniformity is so good is primarily because the large opening in the nozzle prevents any variation due to plugging.

COMPARISON OF RAINFALL CHARACTERISTICS OF ROTADISK RAINULATOR WITH NATURAL RAINFALL

Rainfall simulator data in the past characteristically have been used primarily for qualitative determinations [*Meyer*, 1965]. Some investigators have tried unsuccessfully to find a good correlation between infiltration rates determined using a simulator, and those determined from hydrograph analysis [*Crawford and Linsley*, 1966]. This is caused in part by the failure of most simulators to adequately duplicate the characteristics of natural rainfall.

Before raindrop characteristics were known, a rainfall simulator that applied both the amount and intensity of a design storm was considered adequate. With increased knowledge of raindrop characteristics came an appreciation of the fact that simulated rainfall should also have a drop size distribution very similar to natural rainfall, with all drops falling at their terminal velocities. This has proven to be absolutely necessary if there is any exposed surface in the plot area covered by the simulator. In both erosion studies and infiltration studies the failure to adequately duplicate drop size distribution and the terminal velocity of natural rainfall can result in gross errors. If there are no exposed surfaces, such as in a dense grass cover, drop size distribution and kinetic energy of the simulator are not important. Under this condition the important factors are the intensity and uniformity of application over the plot. According to a literature survey by *Meyer* [1965], the rainfall parameters which are important in both the erosion of soil and the infiltration rate on exposed surfaces include (A) kinetic energy ($1/2MV^2$), (B) momentum (MV), (C) kinetic energy per unit of drop-impact area ($1/2MV^2/A_d$), and (D) interactions of these variables with rainfall intensity.

A comparison between some of the most widely used simulators and natural rainfall was made by *Meyers* [1965]. This comparison expressed as a percent of natural rainfall as determined by *Laws and Parsons* [1943] is given in Table 1, together with the same data for the Rotadisk Rainulator. The Rotadisk Rainulator provides essentially the same kinetic energy and momentum per unit of rainfall as natural rainfall of 2.0 in/hr. For intensities less than 2.0 in/hr it gives slightly higher kinetic energy, and for intensities higher than 2.0 in/hr it gives slightly lower kinetic energy than natural rainfall as reported by *Laws and Parsons* [1943]. For all intensities above approximately 1.0 in/hr the Rotadisk Rainulator comes much closer to duplicating natural rainfall than has been achieved by other types of rainfall simulators.

THE USE OF THE ROTADISK RAINULATOR ON ACRE PLOTS AT ATTERBURY EXPERIMENTAL WATERSHED

In the spring of 1970 the Rotadisk Rainulator was used to determine the infiltration rate on two one-acre plots, one of which had been treated with sodium chloride in order to increase runoff. These plots are on the Atterbury Experimental Watershed located just east of Tucson. A total of eight runs was made on each of the acre plots, which are covered by a moderate growth of creosote bushes

TABLE 1. COMPARISON BETWEEN VARIOUS RAINFALL SIMULATORS AND NATURAL RAINFALL OF 2.0 INCHES PER HOUR

(The performance of the simulators relative to that of natural rainfall as based on various parameters is presented in percents. After *Meyer* [1965] except for the Rotadisk Rainulator.)

Parameter	Rainfall Simulator			
	Type C	Type F	Purdue Rainulator	Rotadisk Rainulator
Kinetic energy per unit of rainfall ($\alpha\Sigma(pV^2)$)	44	56	77	100
Momentun per unit of rainfall ($\alpha\Sigma(pV)$)	68	76	87	99
Total kinetic energy per unit of total drop impact area ($\alpha\Sigma(pV^2)/\Sigma(p/D)$)	82	72	62	86
Total momentum per unit of total drop impact area ($\alpha\Sigma(pV)/\Sigma)p/D)$)	126	98	70	85
Kinetic energy per unit of drop impact area (by increments) ($\alpha\Sigma(pDV^2)$)	65	70	63	110
Momentum per unit of drop impact area (by increments) ($\alpha\Sigma(pDV)$)	105	97	72	107

α, proportionality factor.

p, portion by weight in a given drop size group

V, terminal velocity

D, drop diameter

Type C, produces a nearly uniform drop size which is much larger than most raindrops. The drops fall from zero velocity for a distance of only 4.3 feet.

Type F, produces a drop-size distribution larger than intense natural rainfall. The drops fall from zero velocity for a distance of only 9 feet.

Rainulator, produces a drop-size distribution slightly smaller than intense natural rainfall. Drop velocities are near terminal velocities except for large drop sizes.

Rotating disk simulator, Nozzle 1½H30; pressure 0.6 atm; angular velocity 30 rpm; aperture angle 10 deg. To obtain 2.0 in/hr with these characteristics an aperture angle of 14 deg is required.

and cacti native to the southwest. The average terminal infiltration rate was found to be 0.29 in/hr on the treated plot and 0.59 in/hr on the control. Owing to the careful selection of infiltration sites, these averages are considered to be weighted averages and therefore representative of the infiltration rates over each of the respective plots. Within a month after the infiltration runs were made using the rainfall simulator, a natural storm occurred in which the rainfall intensity was very uniform for approximately 50 minutes at a rate of 0.37 in/hr. This rainfall intensity produced a fairly constant runoff rate from the treated plot of 0.05 in/hr as determined from the resulting hydrograph. The difference of 0.32 in/hr between these two values represents the natural infiltration rate. The difference between the infiltration rate determined by the simulator and that determined from a natural storm is insignificant in view of the variability involved in determining either rate.

The untreated plot, whose infiltration rate had been determined by the simulator to be 0.59 in/hr, yielded negligible amounts of runoff from the same storm. Therefore, the infiltration based on this natural storm could not be determined. Approximately one week later, during an extended storm period in which 0.87 inches of low intensity rain was obtained, a relatively high intensity shower of approximately 0.57 in/hr occurred for five minutes. This shower produced a flow of approximately 0.01 in/hr on the untreated plot. Thus the infiltration rate as determined from this storm would be 0.56 in/hr. Although the accuracy ot this calculation is not as good as that made on the treated plot during the earlier storm, the results do indicate that the infiltration rate as determined by the rainfall simulator in the field is realistic.

THE USE OF THE ROTADISK RAINULATOR ON SAMPLES FROM THE LOWER GILA WATERSHED

A helicopter tour of some of the lower watersheds was made on July 24, 1970 and was supported with limited ground surveys. These surveys showed that large areas of the sub-watershed consisted of similar soil types. The line of demarcation between older and more recent alluvial soil types is in most cases very distinct. Table 2 gives the location of the sampling point and the principal sub-watersheds in which the samples were located. In general, the soil samples taken were representative of the major portions of the watershed in which they were located. The exceptions are noted in Table 2.

A soil analysis was made of each sample in addition to filling a 4" x 12" x 18" pan. These soil-filled pans were then placed under the rainfall simulator. Runoff was collected in graduated cylinders which were photographed every 30 seconds to determine the runoff rate. The results of these infiltration runs and soil analyses are shown in Table 3. Two infiltration runs were made six weeks apart. The length of the run was restricted by the water-holding capacity of the soil. In less than 26 minutes, because of its high infiltration rate, San Cristobal soil was completely saturated. The two infiltration rates made on each soil sample six weeks apart were very close. Only the Kofa samples showed a significant reduction. There were considerable variations in infiltration rates of the soils tested. The reasons for these differences is apparent when the mechanical analysis and exchangeable sodium percentage are compared.

According to the soil classification the Picacho and Castle Dome soils are classified in the Harqua series and are older alluvium soils than are Anthony, Gila, Vienton and Pima series. The Mohave is also an older alluvium soil series, differing only from Harqua series in that it has a lower exchangeable sodium con-

TABLE 2. LOCATION OF SOIL SAMPLES TAKEN FROM PRINCIPAL SUB-WATERSHEDS OF THE GILA RIVER BELOW PAINTED ROCK DAM, JULY 24, 1970

Sub-Watershed	Location	Remarks
Picacho* ($43\ mi^2$)	Two miles west of All American Canal on Picacho Peak Road.	Sample was typical of soil on watershed.
Castle Dome[1] ($410\ mi^2$)	Sampled in R19W, T5S, near the southwest corner of the Kofa Game Refuge, near mountains.	Sample representative of large part of watershed.
Castle Dome[2] ($410\ mi^2$)	Sample taken in Sec. 12, R21W, T7S, near U.S. 95.	Soil typical of large part of the lower watershed.
Kofa ($575\ mi^2$)	Sampled in Sec. 33, R16W, T3S, approximately 20 miles above the confluence with the Gila River.	Representative of bottom land between stream channels.
Palomas ($1260\ mi^2$)	Sampled in Sec. 11, R3W, T6S, located west of Hoodo Wash.	Sample was representative of fairly large area between Palomas Wash area and Kofa Wash area. It is not representative of entire Palomas Wash area.
Ligurta ($30\ mi^2$)	Sample taken in Sec. 3, R20W, T9S, about 200 yards south of the new freeway.	Representative of large area of the watershed.
Coyote ($450\ mi^2$)	Sample taken in Sec. 13 or 24 of R18W, T98, approximately 3 miles south of highway.	Appeared to be representative of lower portion of Coyote Wash area.
San Cristobal -Mohawk ($2520\ mi^2$)	Sample taken in Sec. 2, T9S, R13W, approximately 12 miles from the confluence with the Gila River.	Appeared to be representative of large area in the lower portions of San Cristobal and Mohawk and Rio Cornez basins.
Rio Cornez ($1410\ mi^2$)	Sample taken in Sec. 34, R6W, T9S, approximately 16 miles south of Gila Bend near Highway 85.	Typical of large area in upper Rio Cornez Wash.

*A 43-square mile watershed located in California just west of Yuma. This watershed, which had a recorded flood peak of 37,000 cfs in 1937, was included for comparative purposes.

TABLE 3. ANALYSIS OF SOIL SAMPLES TAKEN FROM PRINCIPAL SUB-WATERSHEDS OF GILA RIVER BELOW PAINTED ROCK DAM, JULY 24, 1970

Sub-Watershed[1]	Mechanical Analysis (percent)			Soluble Salts in Saturation Extract (ppm)	Exchange-able Sodium (percent)	Infil. rate after 20 mins (9-24-70)[2]	Infil. rate after 26 mins (11-7-70)	Soil Classification[5]
	Sand	Silt	Clay					
Picacho[3]	52.4	27.4	20.2	8820	16.7	0.63	0.68	Harqua Sandy Clay Loam
Castle Dome 1	21.8	60.2	18.0	5411	19.6	0.86	0.92	Harqua Gravely Silt Loam
Castle Dome 2	47.5	33.7	18.8	9450	13.0	--	--	Harqua Gravely Loam
Kofa	50.0	42.8	7.2	1498	1.9	2.75	2.11	Gila Loam
Palomas	75.2	17.2	7.6	212	1.0	--	--	Anthony Sandy Loam
Ligurta	60.5	19.9	19.6	4221	5.9	--	--	Mohave Sandy Clay Loam
Coyote	74.7	17.3	8.0	25,025	33.9	1.04	1.08	Anthony Sandy Loam (Saline-Alkali)
San Cristobal	86.5	9.1	4.4	2435	6.4	>3.80[4]	>3.80[4]	Vienton Loamy Sand
Rio Cornez	58.0	38.2	3.8	1365	1.1	--	--	Anthony Sandy Loam
Atterbury[3]	61.7	21.1	17.2	332	5.1	--	1.51	Pima Sandy Loam

[1]For locations see Table 4.

[2]Infiltration rates were made on disturbed but recompacted samples with the rainfall simulator. Rate is in inches/hour.

[3]Analyses of soils from the Picacho, and the Atterbury Experimental Watershed near Tucson, are included for comparison.

[4]Infiltration rate exceeded applied rainfall rate of 3.80 inches/hour.

[5]Classification made by Y. H. Haven, Soil Correlation Specialist, U. S. Soil Conservation Service, Tucson, Arizona.

tent.

An important soil property sometimes overlooked by hydrologists is the Exchangeable Sodium Percentage (ESP). This factor, together with the percentage of clay, is helpful in estimating relative infiltration rates. If more comparative data were available between infiltration rates and chemical analyses of soil, the soil properties could be used even more effectively to predict runoff.

While the clay and silt content of the lower Coyote Watershed is much lower than that of the Picacho and Castle Dome Watersheds, the ESP is very high. This tends to disperse the available clay and produce a relatively low infiltration rate as compared with the Kofa sample with approximately the same clay content. Soils from the San Cristobal Watershed have a moderate value of ESP but very little clay for the sodium to disperse, hence they have a relatively high infiltration rate.

The Picacho Watershed, because of its recorded peak, was included in the analysis for comparative purposes. From the mechanical analysis one would expect similar infiltration rates to that of Castle Dome and Ligurta; however, there was enough difference in clay content to cause a lower infiltration rate. Castle Dome Watershed also has dense single-layer gravel cover, which would cause the infiltration rate to be higher than at Picacho. This difference in surface gravel could not be duplicated in the rainfall simulation tests. If the simulator were taken to the field the effect of the gravel cover could be properly evaluated.

A sample of soil adjacent to the acre plots at Atterbury was placed in a 4" x 12" x 18" pan and included in the infiltration run made on November 7, 1970. (See Table 2.) This was done in order to determine the difference between using a recompacted sample in a small pan and taking the simulator to the field. The average infiltration rate found using the rainfall simulator in the field on an untreated soil, as indicated earlier, was 0.59 in/hr. Thus, the infiltration rate of the recompacted soil in the small pan was approximately 2.5 times the rate in the field. Additional correlation is needed but apparently the infiltration rate of the recompacted sample would be much higher than that obtained when the simulator is used in the field. Therefore the infiltration rates obtained from recompacted soil samples, while suitable for use as a guide for comparative purposes, should not be used directly as being representative of the actual infiltration capacity.

The infiltration rates of the recompacted soil samples supported visual observations of stream channels in ranking the watersheds according to their ability to produce substantial runoff. In making these observations, consideration was also given to the stream gradient.

Picacho Wash has well-defined main channels, indicating substantial runoff from the relatively small watershed. The large number of stream channels is evidence that the infiltration rate of Castle Dome is low enough to produce substantial runoff. Because of slightly flatter gradients than Picacho, the minor channels do not combine into large major channels, except near the lower end of the watershed. This fact would reduce flood flows even if the infiltration rates were the same.

Coyote Wash area shows more evidence of flow than the Kofa Wash area, but less than the Castle Dome Wash area. Numerous small channels exist, indicating substantial runoff.

San Cristobal, Mohawk and Rio Cornez Wash areas show much less evidence of runoff, particularly in the areas away from the mountains. In Mohawk Valley stream channels disappear as they approach a 15-mile-long sand dune area extending along the west side of the Mohawk Mountains. In both the lower portions of San Cristobal and Rio Cornez, main stream channels are nonexistent, even though stream gradients are steeper than 10 feet per mile. In comparison, the gradient of the main channel of the Gila River through the Wellton-Mohawk area is 5 feet per mile. Because of the lack of channels, large areas would have to be covered with sheet flow in order for any substantial amounts of water to reach the confluence with the Gila River.

Palomas Wash Area, as indicated on Table 2, was not properly represented by the soil sample taken. This subwatershed does appear to be a heavy producer. Five drainage channels, extending to the Gila River, each of which are several times larger than the channels from the lower portions of Rio Cornez and San Cristobal, give evidence that the runoff is substantial. During the historical record the broad channel of the Gila River has dissipated any flood flows from this area so that they are insignificant by the time they reach the Dome gaging station.

SUMMARY

Infiltration rates determined using the Rotadisk Rainulator on recompacted samples support the soil analysis and visual surveys in ranking the subwatersheds of the lower Gila in terms of flood threat. This indirect approach was used because rainfall-runoff data on most of the lower Gila subwatersheds or from "similar" watersheds are not available. The rankings revealed that over 50 percent of the subwatersheds have infiltration rates more than five times as high as those of Picacho Wash. With the substantial differences in infiltration rates and other hydrologic considerations, it is highly unlikely that the Mohawk, San Cristobal and Rio Cornez subwatersheds have or will produce flood peaks comparable with the high flood peaks of Picacho Wash, even though these watersheds are much larger. Castle Dome, Coyote, Kofa and Palomas Watersheds would be ranked between Picacho and Mohawk-San Cristobal-Rio Cornez Watersheds in flood producing capability. Any future hydrologic studies in the area should reflect these large differences in infiltration rates of individual watersheds. These rankings support the flood frequency analysis which indicates the flood threat from subwatersheds along the lower Gila is much lower than previously had been projected.

Additional soil samples and infiltration data using the recompacted samples should greatly strengthen the above arguments. However, the results at Atterbury Experimental Watershed indicate that it should be possible to determine the actual infiltration capacities of different soil and vegetative types with reasonable accuracy when the Rotadisk Rainulator is taken into the field. This information would be even more valuable to hydrologists than data from the recompacted samples.

REFERENCES

Bertrand, A. R. and J. F. Parr, "Design and Operation of the Purdue Sprinkling Infiltrometer", Purdue University Agric. Expt. Sta. Res. Bull., 723, 15 p., 1961.

Crawford, N. H. and R. K. Linsley, "Digital Simulation in Hydrology: Stanford Watershed Model IV, "Department of Civil Engineering, Stanford University, Technical Report No. 39, 1966.

Gunn, R. and Q. D. Kinzer, "The Terminal Velocity of Fall For Water Droplets in Stagnant Air", J. Met. 6:(4), 243-248, 1949.

"Hydrology Study for the Gila River Below Painted Rock Dam", Office of Arid Lands, School of Earth Sciences, University of Arizona, October, 1970.

Laws, J. O. and D. A. Parsons, "The Relation of Raindrop Size to Intensity", Trans. Am. Geophys. Un. 24: 452-459, 1943.

Meyer, L. D., "Simulation of Rainfall for Soil Erosion Research", Trans. of the ASAE, 8:(1), 63-65, 1965.

Meyer, L. D. and D. L. McCune, "Rainfall Simulator for Runoff Plots", Agricultural Engineering, October, 1958.

Morin, J., D. Goldberg and I. Seginer, "A Rainfall Simulator with a Rotating Disk," Trans. of the ASAE, 10:(1), 74-49, 1967.

Mutchler, C. K. and L. F. Hermsmerer, "A Review of Rainfall Simulators," Trans. of the ASAE, 8:(1), 67-68, 1965.

"Water Resources Data for Arizona, Part 1. Surface Water Records", United States Department of the Interior, Geological Survey, 1963.

MULCHING TECHNIQUES FOR ARID LANDS VEGETABLE PRODUCTION

R. W. Peebles and Norman F. Oebker

University of Arizona, Tucson, Arizona 85721

INTRODUCTION

This project was initiated by the Food and Agriculture Organization of the United Nations to test the use of plastic aprons as a mulch to grow horticultural crops on a minimal supply of water. Scarcity of water and high evaporation losses under arid land conditions make vegetable production impossible using traditional cultivation practices. For reducing evaporation losses from the soil, a variety of mulches, including gravel and plastic, has been demonstrated (Courter et al., 1969). Fairbourn and Kemper (1970) investigated the use of gravel for tomato production under dry conditions. Adams (1965) reports on the use of a gravel mulch for grain sorghum. Plastic aprons have been used in Spain and Mexico as a means of establishing seedlings in reforestation projects.

Traditionally, mulching has been regarded as an evaporation inhibitor. In this study the water harvesting properties were considered. Plastic aprons were compared with gravel mulch and bare soil.

The use of mulches in vegetable production is intended primarily for family gardens as a means of supplementing existing diets in developing countries. Larger scale commercial production of vegetables can benefit also from the findings of this work.

PROCEDURE

The plastic aprons were supplied by F.A.O. They are made of vinyl, six mils in thickness and are approximately one meter square. Plots were prepared for individual plants by excavating a shallow basin using a vee-shaped sweep on a posthole digger attached to a tractor. The basins were about three feet in diameter with 5 percent side slopes. It took about two hours to dig 200 basins. Following each planting, the plastic and gravel were taken up, the land plowed, and the plots re-established.

The plastic aprons were anchored by covering the edges with soil at the rim of the basin. The aprons are constructed with holes in the center or bottom of the cone. These holes are covered with an attached piece of plastic in such a way that the rainwater is funneled beneath the plastic apron, but evaporation is inhibited due to the cover over the holes. A light gray gravel varying in size from 3/16 to 5/8 inches was used on the gravel plots. It was applied to a depth of about 1.5 inches.

Rainwater collected from a one-half acre gravelled plastic catchment (Cluff, 1967) and stored in a butyl covered tank was used to supplement the natural rainfall collected on the plots. It was of high quality. A representative chemical analysis is given in Table 1.

Table 1

Typical Chemical Analysis of Water Used in FAO Mulch Project
(In parts per million)

TDS	Ca	Mg	Na	Cl	SO_4	CO_2	HCO_2	FP	NO_3	N	B
138	13	1	27	8	40	0	44	-	5	3.1	-

This auxilliary water was applied from a hand carried container in increments of one quart, two quarts and one gallon. This is the method that would be used on small-scale garden plots. For large-scale, commercial operations, a trickle irrigation system could be used. The F.A.O. is currently investigating a plastic apron with tubing on the underside to supply water in this manner (R. P. Chatelanat, personal communication).

Soil moisture values were determined by calibrating the moisture block. For the soil type (Anthony), moisture tension of 15 bars corresponds to a moisture content of about 10 percent by weight, while saturation moisture content is about 20 percent by weight.

Three squash plantings were made: in the fall of 1969, in the spring of 1970, and in the fall of 1970. In the fall of 1969 the plants were established on essentially dry soil. Gravimetric soil samples taken in the upper 12 cm showed the soil moisture to be about 5 percent by weight. This is well above 15 bars suction, so it can be assumed that the initial soil moisture was too low to contribute any water to the plants. All plastic aprons used were of a light green color. This color faded so that the plastic was essentially white at the end of the fall, 1970, planting. At this time five treatments were used: gravel and plastic mulch with two levels of water application each and bare soil. Ten plots were allocated for each treatment, and there were four replications of each set of treatments.

Gypsum moisture blocks were installed on randomly located plots of each treatment type. These were placed at two locations: One directly beneath the plant, and the other at the edge of the plot. Four blocks were placed in the soil at each location at depths of 2, 6, 12 and 18 inches. The blocks were used to monitor soil moisture, both as a means of deciding when to water and to observe moisture changes in the soil profile.

Cucurbita pepo cv. 'Yellow Straightneck' summer squash was planted and watered immediately with one gallon of water which is equivalent to .15 inches of rainfall on mulched area. This equivalence was also used for the bare soil and gravel plots to facilitate comparison. Originally, all plants were to be well watered to get them established. Then the watering was to be carried out only on certain plants (Level II watering schedule); the others were to be supplied by rainfall only (Level I watering schedule). A very dry fall in 1969 necessitated some watering of the plants that were to be left unwatered. Despite this there were many casualities on the bare plots. The higher level of water application was intended to maintain vigorous growth. Even at this high level the growth on the bare plots was marginal. The watering schedule for this planting is shown in Table 2. The growing season was terminated by a frost which occurred when the plants were just approaching full production.

In the spring of 1970 no results were obtained. This was due to disease which killed most of the squash and a very heavy rain toward the end of the growing season during which the plants were completely flooded.

In the fall of 1970 heavy rains saturated the soil just prior to digging the plots. All plots were covered with white plastic initially, plants were started, and the plastic was removed selectively to establish the bare and gravel mulched plots. Another heavy rain occurred just after planting, and it was decided to give all plants the same amount of water for the remainder of the growing season. The watering schedule is shown in Table 3. Again, the growing season was terminated prematurely by frost. However, the yielding period was longer than in 1969. This accounts for the larger yields. For this planting three treatments were used: plastic, bare soil and gravel. Ten plots were allocated to each treatment with four replications. Moisture blocks

Table 2

Application of Water in Inches*
Fall, 1969

	Plastic Covered		Gravel Covered	Bare Soil	
Date 1969	Level 1	Level 2	Level 2	Level 1	Level 2
Sept. 11	.15	.15	.15	.15	.15
Sept. 16				.075	.075
Sept. 18	.075	.075	.075	.150	.150
Sept. 19	.15	.15	.15	.15	.15
Sept. 23			.15	.15	.15
Sept. 24	.15	.15			
Sept. 27			.075	.075	.075
Oct. 1		.075	.150		.150
Oct. 6			.075		.150
Oct. 11	.075	.075	.075	.15	.15
Oct. 18		.150	.150		.150
Oct. 21	.17	.17	.17	.17	.17
Oct. 25		.15	.15		.15
Oct. 28	.04	.04	.04	.04	.04
Nov. 9**	.44	.44	.44	.44	.44
Nov. 15**	.15	.15	.15	.15	.15
Total Water in inches	1.36	1.77	1.92	1.55	2.15
in gallons	9.1	11.8	12.1	10.3	14.3

*Water application in inches was determined using the area of the plastic apron. The conversion factor was: 1 gallon = .15 inches of rain. This relation was used also for gravel and bare soil plots. Levels refer to intensity of water application; Level 2 is greater than Level 1.

**Rainfall of given amount occurred.

Table 3

Application of Water in Inches*
Fall 1970

Date 1970	All plots
Sept. 2	.04
Sept. 3**	1.92
Sept. 4**	.22
Sept. 5**	1.61
Sept. 6**	.02
Sept. 12**	.36
Oct. 1**	.02
Oct. 3**	.14
Oct. 20	.07
Oct. 26	.15
Nov. 2	.15
Total Water in inches	4.74
in gallons	31.6

*Water application in inches was determined using the area of the plastic apron. The conversion factor was: 1 gallon = .15 inches of rain. This relation was used also for gravel and bare soil plots.

**Rainfall of given amount occurred.

were installed as in the fall of 1969. In addition, thermistors were placed adjacent to each moisture block beneath the plant to monitor soil temperature changes.

RESULTS

Results indicate the value of gravel and plastic mulches in conserving water for growth of horticultural crops.

Plants with the plastic mulch required slightly less water than the plants with the gravel mulch. Prior to the frost in the fall of 1969, the plastic-apron-covered plots required only 12 gallons of water or 1.8 inches of water. It was much easier to achieve germination on the plots where the mulches were used. The effectiveness of the gravel might be enhanced by using a smaller particle size or increasing total gravel applied. Table 4 shows squash production for the 1969 and 1970 fall plantings. Plastic and gravel plots yielded significantly better than bare plots.

Table 4

Squash Yield* for Treatments Used in FAO Plantings, 1969 and 1970.

	Plastic Covered Fruit		Gravel Covered Fruit		Bare Soil Fruit	
	No.	Wt.(gms.)	No.	Wt.(gms.)	No.	Wt.(gms.)
Fall 1969						
Level 1	18.5	1560	--	--	0	--
Level 2	33.0	2529	8.2	534	0	--
Fall 1970						
Level 1	34.5	7718	27.7	6311	22.2	4367

*Average number and weight of fruit produced by five plants.

Temperatures were measured primarily to determine if soil temperature differences existed between treatments. During the day high specific moisture content (high thermal conductivity) and lack of evaporation under the mulches would be expected to result in higher temperatures. The question arises--does the temperature under the mulches remain higher during the entire 24-hour period? Readings at a depth of 6 inches taken at 9 a.m. show temperatures one or two degrees higher beneath the mulches as compared to bare soil. This difference increases a degree or two during the afternoon. This suggests that temperatures under the mulches remain higher throughout a 24-hour period. Higher temperatures under the gravel mulch and plastic aprons are favorable to more rapid germination and growth in the spring. However, too high soil temperatures would be detrimental.

The most interesting observation was that water condensed in droplets on the underside of the plastic aprons. Because of the slight incline toward the center of the basin and a rough basin surface causing the plastic to be elevated above ground surface, these droplets would move toward the plant. Thus, it appears that a mechanism operates under the plastic apron which tends to concentrate water around the plant. Some of the moisture block readings suggested this also. The block at a depth of two inches was wetter than the three deeper blocks after two days of not having watered the plant. Consequently, the plastic apron can be regarded as a small-scale water harvesting mechanism which concentrates evaporated water as well as water that is applied or falls in the form of rain.

CONCLUSION

The use of plastic aprons and gravel mulch appears to be a worthwhile method of conserving water in crop production. The plastic apron has the additional advantage in that it also collects and diverts rainfall to the plant. Where the mulch is to be supplied without cost to the farmer, plastic represents the most convenient material from an application point of view. The vinyl used in the tests lasted only two seasons, but more durable materials are being evaluated. The capital investment required to obtain a gravel mulch would be relatively low. This would be an advantage in developing countries where capital is scarce. Since gravel is unaffected by ultraviolet induced oxidation, it has an unlimited life providing the gravel particles are large enough so that they can be regenerated by screening. This regeneration would be needed following each planting to assure an effective mulch.

REFERENCES

Adams, J. E., Effect of mulches on soil temperature and grain sorghum development, Agricultural Journal, 57, 471-74, 1965.

Cluff, C. B., Water harvesting plan for livestock or home, Progressive Agriculture in Arizona, 19 (3), 6-8, 1967.

Courter, J. W., H. S. Hopen, and J. S. Vandermark, Mulching vegetables, Illinois Extension Circular 1009, 1969.

Fairbourn, Merle L., and W. D. Kemper, Gravel mulches for dryland tomato production, Colorado Rancher and Farmer, Denver, 1970.

FIELD MEASUREMENTS OF SOIL-WATER CONTENT AND SOIL-WATER PRESSURE

R. J. Reginato and R. D. Jackson

U. S. Water Conservation Laboratory, Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, Phoenix, Arizona 85040

Accurate and frequent measurements of soil-water content and soil-water pressure are necessary for studies concerning the movement of water in field soils--such as during infiltration, and redistribution. Knowledge of the dynamic water content-pressure potential relationship within the soil profile is useful in determining the importance of hysteresis under natural conditions.

Continuous monitoring of water content in the field is now possible using recently developed gamma-ray transmission equipment which allows water content measurements in 1-cm-thick soil layers with an error of 0.009 gram per gram [Reginato and Jackson, 1971]. Soil-water pressure can be measured in these layers with small ceramic tensiometers connected to sensitive pressure transducers with an error of 1 to 2 cm water [Watson, 1965].

This paper describes the equipment and procedures used to determine water content and pressure potential continuously in the top 10 cm of a field soil over a 2-week period following an irrigation. Data for 4 days during this 2-week period for one soil depth demonstrate the type of information obtainable by this method.

EQUIPMENT

Nuclear Equipment

The nuclear equipment used was described previously [Reginato and Stout, 1970]. Briefly, the equipment consisted of a high-voltage power supply, amplifier, scaler and timer, spectrum stabilizer, and single-channel pulse analyzer which was set to monitor transmitted gamma photons in the energy range of 0.644 to 0.680 Mev. This equipment was housed in an air-conditioned building about 50 m from the measurement site.

A 5-mCi source of ^{137}Cs was positioned 20 cm from the scintillation detector. The crystal, 1 cm thick and 3.8 cm in diameter, was mounted on a photomultiplier tube with built-on voltage divider. The source and detector assemblies were connected to a mounting plate, which was raised and lowered by a gear rack and gear motor. A tripod, which held the motor 2.5 m above the soil surface, was positioned over vertical access tubes within which the source and detector moved when the soil profile was scanned.

A controller device was designed and constructed to automatically and repeatedly position the source detector assembly at various depths within the soil profile. This device positioned the source and detector assembly at a depth, remained at this depth until the count and the location or depth of probes were recorded, moved the assembly to the next location, measured, and recorded again. After measuring and recording at the final depth, the assembly was automatically repositioned at the first location, and the measurement sequence repeated. The soil profile was continually scanned in 1-cm increments starting at the 0- to 1-cm soil depth, such that each layer was measured every 15 minutes.

Tensiometer Assembly

Tensiometers were constructed from double-bore porous ceramic tubes with a bubbling pressure of approximately 1.4 bars. A piece of tygon tubing connecting the two holes at one end of the ceramic tube was epoxied in place. Two 30-cm lengths of 18-gauge stainless steel tubing were inserted into the holes in the other end of the ceramic tube and epoxied in place. The ceramic tensiometers, 4- to 5-cm o.d. and 10-cm long, were inserted horizontally from a hole dug adjacent to the measurement site with just the stainless steel tubes extending from the soil. A bidirectional pressure transducer was attached with a small piece of tygon tubing to one of the stainless steel tubes coming from the tensiometer. Air was flushed from the system by opening the vent port of the pressure transducer and forcing de-aerated water into the open stainless steel tube through the ceramic tensiometer and back out through the transducer. The free end of the stainless steel tubing was then closed off with a small piece of plastic tubing and hose clamp. The tensiometers were installed 1.5, 2.5, 3.5, 5.5, 7.5, and 9.5 cm from the soil surface. The pressure transducers were placed in a watertight container in the hole adjacent to the measurement site, and voltages from the transducers were recorded on a digital data-logging system every 30 minutes. This tensiometer installation was located about 3 m from the gamma-ray transmission site.

PROCEDURES

Gamma-Ray Transmission

To calibrate the gamma site, it was assumed that the soil profile was horizontally homogeneous. Gravimetric samples were taken vertically in 1-cm increments to obtain a profile of gravimetric water content versus depth.

With this information and concurrent measurements of the count rate through the 1-cm increments, the bulk density profile for the experimental site was calculated using [Reginato and Jackson, 1971]:

$$\rho_s = \frac{\ell n\ (I_o/I)}{x\mu_w\ (0.93 + \theta_w)} \quad . \tag{1}$$

Subsequent scanning of the soil profile with the gamma apparatus allowed soil-water content data to be obtained as a function of depth and time. Gravimetric water contents were calculated using:

$$\theta_w = \frac{\ell n\ (I_o/I)}{x\mu_w\rho_s} - 0.93 \tag{2}$$

and volumetric water contents were obtained by multiplying equation (1) by equation (2). It was assumed that the bulk density at each measurement depth remained constant.

The volumetric water content was calculated for every 15 minutes for each depth. Two techniques were used to smooth the data. First was a numerical-averaging procedure, using the data from the two measuring periods prior to and following the specific measuring period of interest. This technique helped to reduce the scatter due to errors in random emission of the gamma-ray source. Second was to plot these values of water content as a function of time, and to draw a smooth curve through points to obtain the average water content change with time for each depth of interest.

Tensiometers

The voltage output from each of the six tensiometers was recorded every 30 minutes. These data were subsequently converted to millibars pressure from a calibration obtained in the laboratory. The pressure potential was then plotted as a function of time. No smoothing was required.

RESULTS AND DISCUSSION

Volumetric water content and pressure potential for the 1- to 2-cm soil depth are shown in Fig. 1. Data collection began 20 hours after the site was flooded with 10 cm of water, and data for the following 4 days are presented. Climatic conditions during this period were characterized by clear skies, low winds, and air temperatures ranging from -1 to 20 C.

Several points are immediately obvious. First is the rapid loss of water from early morning to early afternoon each day. Second is the gain in water during the mid afternoon and evening. Third is the diminishing amplitude of this diurnal change with time after irrigation. Fourth is the relatively uniform reduction in the average water content during these four days.

The highest water content was measured each day just before sunrise. Water content (about 0.01 $cm^3\ cm^{-3}\ hr^{-1}$) declined rapidly until 1300-1500 hours, which coincides with the time of maximum air temperature. Water then started to accumulate in the 1- to 2-cm soil layer until the next sunrise at an average rate of 0.003 $cm^3\ cm^{-3}\ hr^{-1}$. The net result of the depletion and accumulation of water was an average loss in volumetric water content of 0.02 $cm^3\ cm^{-3}\ day^{-1}$ during this 4-day period.

Pressure potential is plotted against time in Fig. 1 for the same 4-day period. The pressure potential, obtained from a tensiometer located at a depth of 1.5 cm, decreases most rapidly as the water content declines, but not exactly in phase as one might expect. Also, the increase in pressure during the night levels off for a long period as opposed to the sharp peak of the water content curve. This time lag difference between water content and pressure may be due to hysteresis, difference between the soil conditions at the tensiometer and gamma rig sites, or, more likely, temperature effects on the pressure transducer.

Temperature effects in a tensiometer-pressure transducer system have been discussed by Watson and Jackson [1967]. Their work was confined to a laboratory in which the period of the temperature fluctuation was on the order of 4 minutes. The temperature effect decreased with increasing conductance of the ceramic and with increasing period of the temperature fluctuation. The laboratory data indicated that temperature effects would be minimal under field conditions. However, the experiments reported here, and subsequent experiments indicate that temperature does affect the measurement of soil-water pressure in field situations. Further research is needed to quantify the effect and to develop means of circumventing it.

From Fig. 1 and data taken after this 4-day period, a moisture characteristic curve was constructed and is shown in Fig. 2. No hysteresis is apparent. The error in volumetric water content determinations is approximately $\pm$ 0.015 $cm^3\ cm^{-3}$.

SUMMARY AND CONCLUSIONS

Soil-water content and pressure in the top 10 cm of a field soil profile were measured continuously for a 2-week period following an irrigation. Water contents were determined in 1-cm soil increments with a gamma-ray transmission technique using a 15-minute scanning interval. Soil-water pressure was measured every 30 minutes at six depths in the top 10 cm of soil with a tensiometer-pressure transducer system.

There were larger diurnal changes in water content than in pressure potential. This may have been due to temperature effects on the pressure-measuring system. A moisture characteristic curve was constructed from these data.

Continuous measurements of soil-water content and soil-water pressure are necessary to describe in more detail the patterns of soil drying following irrigation. Knowing explicitly the drying patterns in the soil profile may lead to a better evaluation of the effectiveness of applied and naturally occurring mulches to conserve water.

REFERENCES

Reginato, R. J., and R. D. Jackson, Field measurement of soil-water content by gamma-ray transmission compensated for temperature fluctuations, Soil Sci. Soc. Am. Proc. 1971. (in press).

Reginato, R. J., and K. Stout, Temperature stabilization of gamma-ray transmission equipment, Soil Sci. Soc. Amer. Proc. 34(1), 152-153, 1970.

Watson, K. K., Some operating characteristics of a rapid response tensiometer system, Water Resources Research, 1, 577-586, 1965.

Watson, K. K., and R. D. Jackson, Temperature effects in a tensiometer-pressure transducer system. Soil Sci. Soc. Amer. Proc. 31(2), 156-160, 1967.

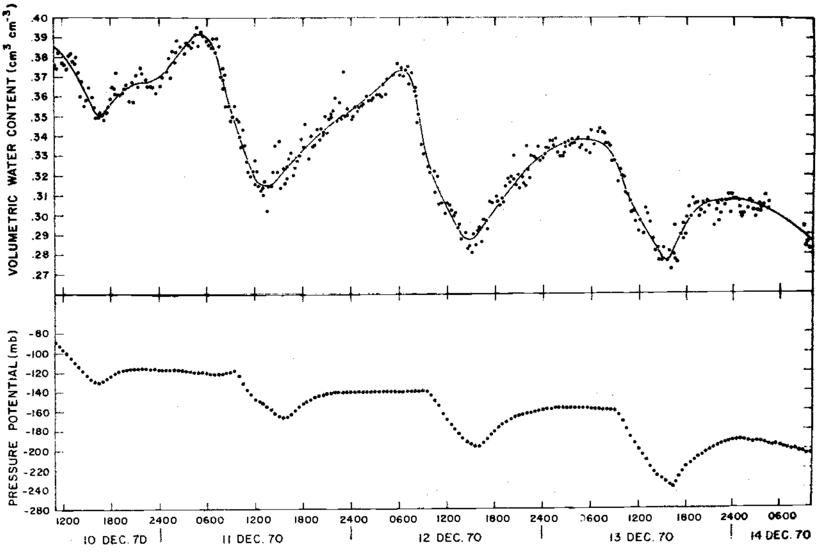


Figure 1. Volumetric water content and pressure potential in the 1- to 2-cm soil depth starting 20 hours after irrigation with 10 cm of water.

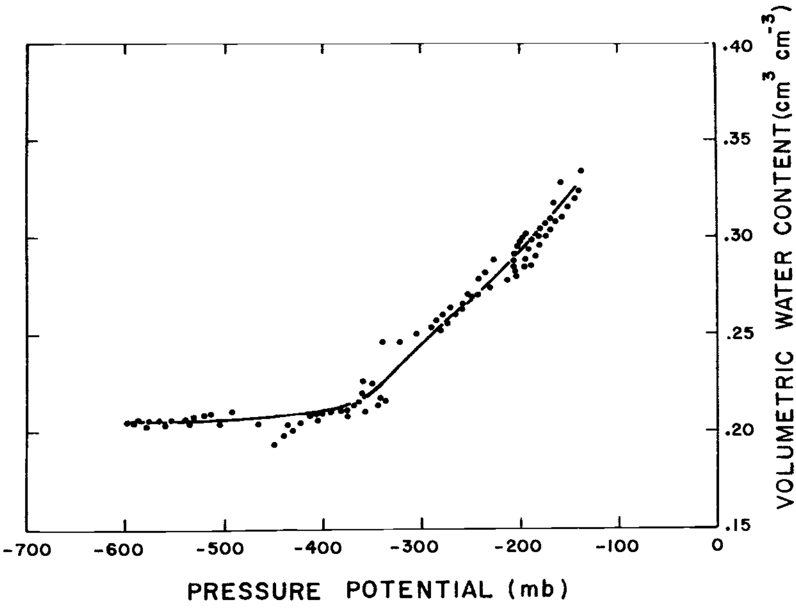


Figure 2. Moisture characteristic curve obtained from volumetric water content-pressure potential data taken from 1200 on 10 December 1970 to 1200 on 24 December 1970, MST.

CONDITIONAL STREAMFLOW PROBABILITY DISTRIBUTIONS

T. G. ROEFS

Hydrology & Water Resources, University of Arizona

D. M. CLAINOS

Hydrology & Water Resources, University of Arizona

INTRODUCTION

Monthly streamflows or streamflows for shorter time periods are, in most parts of the world, conditionally dependent. This fact must be taken into account in planning and operation studies for surface water reservoirs. This paper describes alternate ways that conditional streamflow dependencies may be taken into account in different kinds of studies and the ways that the congruence of those means can be most nearly guaranteed.

MOTIVATION

Under U. S. Office of Water Resources Research Grant # A-0240ARIZ "Decision Analysis in Water Resources Management" studies of the interaction between planning, commitment, and operation decisions were undertaken. Examples of these various kinds of decisions are: planning--where, how large, and when to build a reservoir; commitment--at what levels should contracts for system outputs be specified; operation--how much water should be released given current storage and inflow during the antecendent month.

All of these questions have been studied using simulation and optimization techniques. Among others, *Meier and Beightler* [1967] and *McLaughlin* [1967] have used optimization routines to study planning questions. *Hall and Roefs* [1966] have used optimization routines for commitment problems. *Butcher* [1968] and *Loucks* [1969] have used optimization routines to study operation rule determination problems. *Young* [1966] used a combination of simulation and optimization routines to study operation rule determination. On the other hand, *Hufschmidt and Fiering* [1966] and *U. S. Corps of Engineers* [1971], along with many others, have used simulation routines to study the whole spectrum of problems. These studies most closely resemble current agency practice although they differ in that stochastic streamflow synthesis routines are used. *Loucks* [1969] has successfully studied a combined problem in which two iteratively linked optimization routines were used to study the problem cited. The nature of the algorithms he used were such that only 10 X 10 matrices could be used to represent streamflow dependencies.

It can be shown [*Roefs*, 1968] that it is probably most computationally efficient to use simulation routines for decisions of low dimensions; i.e., planning and commitment, and optimization routines for the highly dimensional operation rule decisions.

THE PROBLEM

The choice of a combination of simulation and optimization routines creates the problem. One uses an essentially continuous representation of streamflow dependencies in simulation routines and an essentially discrete representation in the direct stochastic optimization routines. Since we are to compare the planning result of using the operation rule derived from the direct stochastic optimization with the planning result from using an arbitrary operation rule by means of a simulation routine employing stochastic streamflow synthesis routines, the means of representing the streamflow dependencies must be as nearly congruent as possible.

The stochastic streamflow synthesis routine selected was the one developed by the *U. S. Corps of Engineers* [1971]. Selection of this routine does not mean that we think it is, necessarily, the best routine that can ever be developed but that it is the best that is currently available. Information pursuant to the development of an alternative routine is, in fact, presented in this symposium [*Baran, Kisiel and Duckstein*, 1971]. The routine consists of two parts: streamflow probability distribution and dependency analysis and a streamflow generation using the relationships developed. If the representation of inter-station dependencies is disregarded the steps are:

1. add a small increment (1% of average flow for each month) to each streamflow;
2. take the common logarithm of the result;
3. for each monthly logarithmic vector compute the mean, standard deviation and skew factor; the skew factor is given by

$$g = \frac{N\sum_{i=1}^{N}(X_i-\bar{X})^3}{(N-1)(N-2)S^3}$$

where X_i is the result of step 2, S is the standard deviation, and N is the number of observations;

4. the standardized gamma deviate is given by

$$y = \frac{X_i - \bar{X}}{S}$$

where $\bar{X}$ is the computed sample mean;

5. the result of step 4 is transformed to a normal deviate using the transform:

$$k = \frac{6}{g}\{[(\frac{gy}{2})+1]^{1/3}-1\} + \frac{g}{6}$$

where g and y are as previously defined;

6. the correlation coefficient, r, is computed between the normal deviates for adjacent months;

7. a uniform (0,1) random number if generated;

8. the uniform random number is transformed to a standard normal deviate;

9. the relationship

$$k_{t+1} = rk_t + (1-r^2)^{1/2}z$$

is involved where z is the random normal deviate and k_t, k_{t+1} are correlated normal deviates except for t=1 (k_t, t<1 is undefined)

10. the inverse of the transform of step 5

$$y = \{[(\frac{g}{6})(k - \frac{g}{6}) + 1]^3-1\} \frac{2}{g}$$

is employed to produce a standardized gamma deviate;

11. the standardized gamma deviate is multiplied by the standard deviation and added to the sample mean (both computed in step 3)

$$X = yS + \bar{X}$$

12. the antilogarithm is taken;

13. the small increment is subtracted

Steps 1 thru 6 comprise the analysis part of the routine. Steps 7 thru 13 are the generation part of the routine and might, when the routine is used in a simulation mode, be repeated several hundred or several thousand times.

What concerns us here, though, is not the use of this routine in a simulation mode but the establishment of a discrete probability dependency matrix which is as nearly congruent as possible.

ALTERNATE SOLUTIONS

What is sought is a discrete dependency matrix between streamflow amounts, not a discrete dependency matrix between logarithms, gamma deviates, or normal deviates. Except in one respect, the use of transforms that is made does not present computational problems. The analyst sets up the limits of interest, say the class 400,000 to 500,000 acre feet in January and 500,000 to 600,000 acre feet in February. Then using the transforms specified, he determines the appropriate normal deviates. Those are: -0.379828 and -0.001516 for January and 0.043420 and -0.177227 for February. A problem can occur in this step only when considering an interval whose lower limit is zero flow. Even though the probability of a problem occuring when the lower limit is zero flow is very slight, it is, nonetheless, worth mentioning the possible outcome. If the normal deviate exceeds the expected lower limit due to the random generated variables, then a negative flow will be recorded when the inverse transformation is performed. Of course, the negative flow value is meaningless, thus it will be discarded. The probability distributions can either be bounded or unbounded at the lower end depending on whether the skew coefficient, g, is positive or negative. It is is unbounded at the lower end there is no problem, inasmuch as the probability distribution can be truncated. If it is bounded at some lower limit $\underline{X}$ and that lower limit $\underline{X}$ is a logarithm such that the flow which is the antilog of $\underline{X}$, $\underline{Q}$, is greater than zero, then either a portion of the lowest interval or the lowest n intervals and a portion of the n + 1 interval has an unconditional probability equal to zero. If a negative skew is observed a similar situation exists with respect to high flow intervals. Even if the analyst believes that the bounds inferred from the skew factors are not proper, there is little that can be done about this without either proposing an ad hoc method for changing the simulation routine or destroying the objective of the work, that is, making the discrete and continuous routines as nearly congruent as possible.

The serious problem that does occur is one that was not expected. Namely, given that we accept the transformations, how do we go about calculating the conditional dependency based on the bivariate normal distribution. All flow interval limits have been transformed to standard normal deviates and the correlation coefficient, an estimate of the covariance, has been computed. We wish, for instance, to compute the probability

$$P(\underline{Q}_F \leq Q_F \leq \overline{Q}_F \mid \underline{Q}_J \leq Q_J \leq \overline{Q}_J) \qquad (1)$$

where $\underline{Q}_F$ is the lower limit on the interval of February flows expressed in normal standard deviates, $\overline{Q}_F$ is the upper limit, and $\underline{Q}_J$ is the lower limit on the interval of January flows expressed in normal standard deviates, $\overline{Q}_J$ the upper limit. This appears to be a ridiculously simple problem in elementary probability theory. One need only employ the relationship

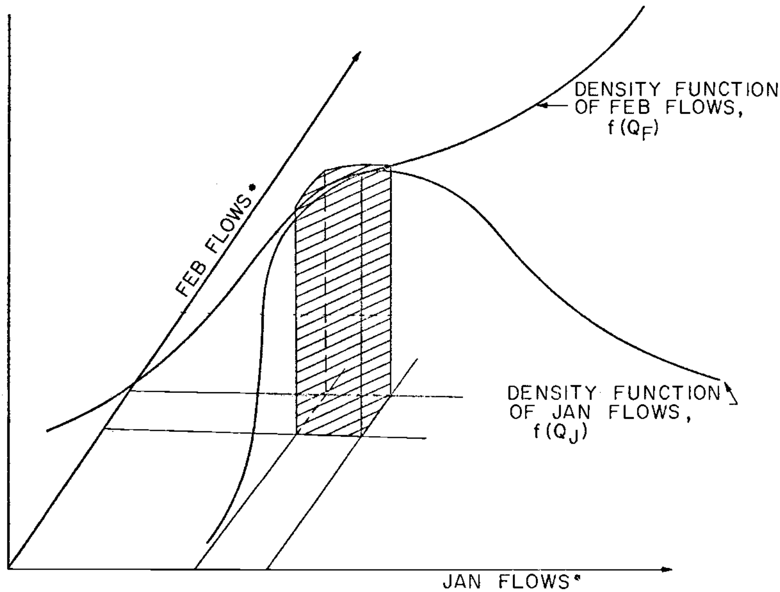
$$P(\underline{Q}_F \leq Q_F \leq \overline{Q}_F \mid \underline{Q}_J \leq Q_J \leq \overline{Q}_J) =$$

$$P(\underline{Q}_F \leq Q_F \leq \overline{Q}_F, \underline{Q}_J \leq Q_J \leq \overline{Q}_J) \ / \ P(\underline{Q}_J \leq Q_J \leq \overline{Q}_J) \qquad (2)$$

and compute the joint and unconditional probabilities. The unconditional probabilities are easy enough to calculate, using either a very exact table of normal distributions [*Tables of Probability Functions*, 1942] of by performing numerical integration. The joint probability is the volume represented by the shaded prism shown on Figure 1. One can get this joint probability from the National Bureau of Standards Mathematical Handbook [1964], but only if you are considering intervals much larger than the ones specified herein. The tables are simply not accurate to the degree required--intervals of 100,000 acre feet! No more accurate tables seem to be available. This leaves one with the alternative of performing the double integration shown at the bottom of Figure 1. Consider Figure 2. If no flow is taken as a minimum, the maximum as given in the table the size

Figure 1

JOINT PROBABILITY DENSITY FUNCTION, $P(Q_J, Q_F)$



VOLUME = JOINT PROBABILITY OF JAN AND FEB FLOWS

VOLUME = $P(Q_J, Q_F) = \iint f(Q_J)\, f(Q_F)\, dQ_J\, dQ_F$

* ALL FLOWS ARE EXPRESSED AS STANDARD NORMAL DEVIATES.

Figure 2

COMPUTED FLOWS USED FOR DEPENDENCY TABLES*

MONTH	FLOW P(Q < .001)**	FLOW (MAX)**
OCT	1173	1200
NOV	1259	1300
DEC	5432	5500
JAN	4342	4400
FEB	4149	4200
MAR	2260	2300
APR	2555	2600
MAY	1455	1500
JUNE	809	900
JULY	432	500
AUG	331	400
SEPT	322	400

* COMPUTED FOR FLOWS WITH UNCONDITIONAL PROBABILITY OF LESS THAN .001

** IN THOUSANDS OF ACRE FEET

of a cell is 100,000 acre feet by 100,000 acre feet, the conditional dependency matricies have the following size:

MONTHS	MATRIX		CELLS
Oct-Nov	13X14	=	182
Nov-Dec	14X56	=	784
Dec-Jan	56X45	=	2520
Jan-Feb	45X43	=	1935
Feb-Mar	43X24	=	1032
Mar-Apr	24X27	=	648
Apr-May	27X16	=	432
May-Jun	16X10	=	160
Jun-Jul	10X 6	=	60
Jul-Aug	6X 5	=	30
Aug-Sep	5X 5	=	25
Sep-Oct	5X13	=	65
Total Cells			7873

Even if the computer time could be restricted to 10 seconds per double integration (the double integrations would, of course, have to be done numerically) 78,730 seconds or something over 21 hours of computer time would be required.

This would have represented more expenditure than the entire budget of the research project for all purposes and was thus deemed infeasible. It might be feasible in a specific project planning or operation environment, but given the customs of water resource management agencies with regard to computer expenditures this need not necessarily be so. These facts require that some sort of numerical approximation be made. A possible approximation that could be made is to compute:

$$P(\underline{Q}_F \leq Q_F \leq \overline{Q}_F \mid \hat{Q}_J) \tag{3}$$

where $\hat{Q}_J$ is a flow representing the flow interval $(\underline{Q}_J, \overline{Q}_J)$. January and February flows are taken as an example here and hereafter but our statements are meant to apply to all pairs of months.

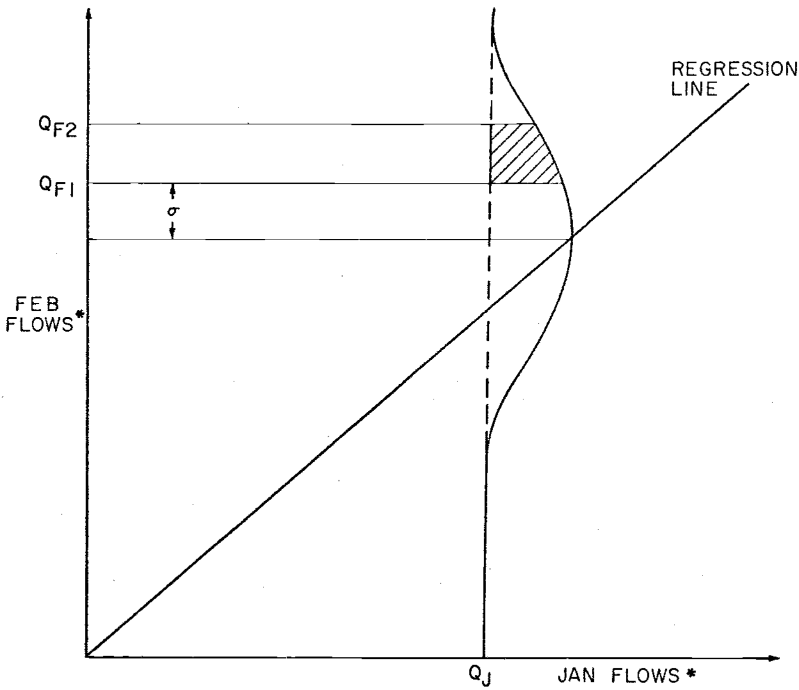
In essence what is being indicated by the approximation is that the conditional probability estimated at a point will be sufficiently close to the true interval conditional probability. One obvious place at which to make a one-dimensional estimate of conditional probability is at the midpoint,

$$\hat{Q}_J = (\underline{Q}_J + \overline{Q}_J)/2 \tag{4}$$

Although $\hat{Q}_J$ acre-foot is the midpoint of the interval of January flows $\underline{Q}_J$ to $\overline{Q}_J$ it may not be the best place at which to make the one-dimensional conditional probability estimate. There is another point, Q_J^*, such that

Figure 3

CONDITIONAL PROBABILITY, $P(Q_F|Q_J)$



$\sigma = (1-r^2)^{1/2}$

$r \triangleq$ SERIAL CORRELATION COEFFICIENT

* ALL FLOWS ARE EXPRESSED AS STANDARD NORMAL DEVIATES.

$$P(\underline{Q}_J \leq Q_J \leq Q_J^*) = P(Q_J^* \leq Q_J \leq \overline{Q}_J) \tag{5}$$

this point is called the centroid in figures 4,5, and 6. In order to compare these methods to each other, a computation of the conditional probabilities for each of the possible intervals for February flow was done for $\hat{Q}_J$ equal to the midpoint and $\hat{Q}_J = Q_J^*$. The results are shown in figure 4. The difference is never more than .001 and less than that for most of the range.

While the comparison measures the difference between the results of the two means of computing the conditional probabilities of February flow, it does not necessarily measure which one is closer to the truth. One way of looking at this question is to make ten point estimates rather than one. Consider the interval $\underline{Q}_J$, $\overline{Q}_J$. It can be divided into ten equal intervals $\underline{q}_{j1}, \overline{q}_{j1}, \underline{q}_{j2}, \overline{q}_{j2}; \ldots\ldots\ldots\ldots \underline{q}_{j10}, \overline{q}_{j10}$ where $\underline{q}_{j,n+1} = \overline{q}_{j,n}$, and $\hat{q}_{j,n}$ is the midpoint of the nth interval. The conditional probability

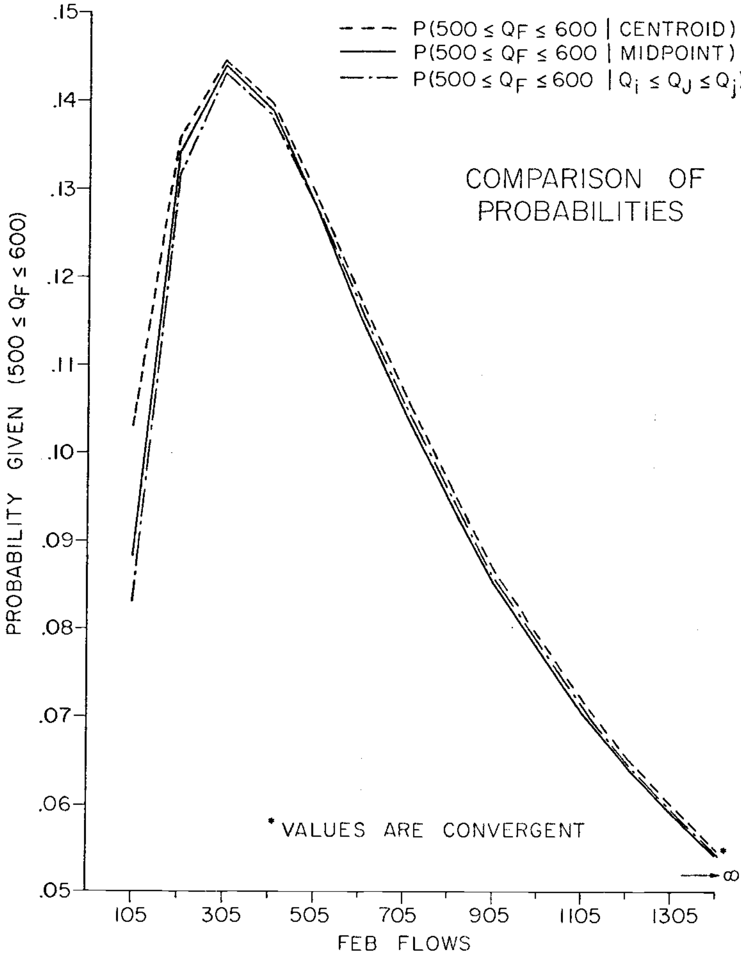
$$P(\underline{Q}_F \leq Q_F \leq \overline{Q}_F \mid \hat{q}_{jn}) \tag{6}$$

can be computed. Likewise each of the probabilities

$$P(\underline{q}_{jn} \leq Q_J \leq \overline{q}_{jn}) \tag{7}$$

can be computed. Presumably the result of

Figure 4



$P(500 \le Q_F \le 600 \mid CENTROID)$
$P(500 \le Q_F \le 600 \mid MIDPOINT)$
$P(500 \le Q_F \le 600 \mid Q_i \le Q_J \le Q_j)$
COMPARISON OF PROBABILITIES
PROBABILITY GIVEN $(500 \le Q_F \le 600)$
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
* VALUES ARE CONVERGENT
*
→ ∞
105
305
505
705
905
1105
1305
FEB FLOWS

Figure 5

SAMPLE COMPUTER OUTPUT

(JAN FLOW INTERVAL: 400-500 THOUSAND ACRE FEET. FEB FLOW INTERVAL: 500-600 THOUSAND ACRE FEET).

JAN FLOW	$P(Q_J)$	$P(Q_F \mid Q_J)$	$\frac{P(Q_J)}{\Sigma P(Q_J)} X P(Q_F \mid Q_J)$
405.0	.015413	.141475	.015797
415.0	.015019	.140821	.015322
425.0	.014640	.140099	.014859
435.0	.014275	.139316	.014407
445.0	.013924	.138478	.013968
455.0	.013585	.137593	.013541
465.0	.013258	.136664	.013126
475.0	.012943	.135698	.012723
485.0	.012638	.134699	.012332
495.0	.012344	.133671	.011954

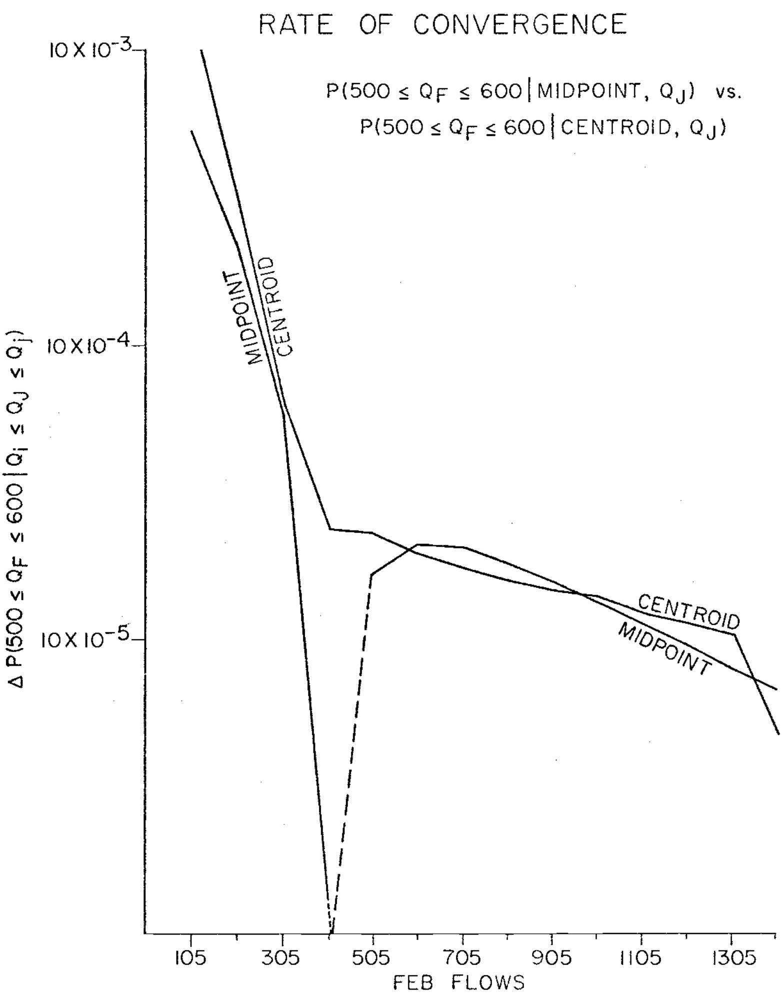
$$P_1 \ (500 \le Q_F \le 600 \mid 400 \le Q_J \le 500) = \sum\left(\frac{P(Q_J)}{\Sigma P(Q_J)} \ X \ P(Q_F)\right)$$

$P_1 \ (500 \le Q_F \le 600 \mid 400 \le Q_J \le 500) = 0.138028$

$P_2 \ (500 \le Q_F \le 600 \mid \text{MIDPOINT}, \ Q_J) = 0.138041$

$P_3 \ (500 \le Q_F \le 600 \mid \text{CENTROID}, \ Q_J) = 0.138263$

Figure 6


RATE OF CONVERGENCE
P(500 ≤ QF ≤ 600 | MIDPOINT, QJ) vs.
P(500 ≤ QF ≤ 600 | CENTROID, QJ)
10 X 10-3
10 X 10-4
10 X 10-5
Δ P(500 ≤ QF ≤ 600 | Qi ≤ QJ ≤ Qj)
MIDPOINT
CENTROID
CENTROID
MIDPOINT
105
305
505
705
905
1105
1305
FEB FLOWS

$$\sum_n \left[\frac{P(\underline{Q}_F \leq Q_F \leq \overline{Q}_F | q_{jn}) \cdot P(\underline{q}_{jn} \leq Q_J \leq \overline{q}_{jn})}{P(\underline{Q}_j \leq Q_J \leq \overline{Q}_J)} \right]$$

will give a closer approximation to the truth than either of the wider interval methods discussed. A sample computation is shown in Figure 5. The results of this computation are shown by the graph in Figure 6.

TENTATIVE CONCLUSIONS

Calculating theoretically exact conditional dependencies is too expensive. For the problem addressed, the use of one-dimensional conditional probabilities based on the midpoint is an adequate, and effective, procedure.

REFERENCES

Baran, N. A., Kisiel C. C., Duckstein L. A Stochastic Analysis of Flows on Rillito Creek, joint meeting of Arizona Section American Water Resources Association and Hydrology. Section Arizona Academy of Science, Tempe, Arizona, April 1971

Butcher, W. S., "Stochastic Dynamic Programming and the Assessment of Risk," American Water Resources Society, Procedings. pp. 315-320, Denver, Col., July, 1968.

Hall, W. A., and T. G. Roefs, "Hydropower Project Output Optimization," Journal of the Power Division, American Society of Civil Engineers Vol. 92, No. PO1, pp. 67-79, January, 1966.

Handbook of Mathematical Functions, Edited by M. Abramowitz and I. A. Stegun, National Bureau of Standards, AMS 55, Government Printing Office, Washington, D. C., 1964, pp. 936-939.

Hufschmidt, M. M., and M. B. Fiering, Simulation Techniques for Design of Water-Resource Systems, Harvard University Press, Cambridge, Massachusetts, pp. 212, 1966.

Loucks, D. P. "Stochastic Methods for Analyzing River Basin Systems," Research Project Technical Completion Report, OWRR Project No. C-1034, Department of Water Resources Engineering and the Water Resources and Marine Sciences Center, Cornell University, Ithaca, New York. August, 1969.

McLaughlin, R. T., "Experience with Preliminary System Analysis for River Basins," P/408, International Conference on Water for Peace, Washington, D. C., May, 1967.

Meier, W. L., Jr., and C. S. Beightler, "An Optimization Method for Branching Multistage Water Resource Systems," Water Resource Research, Vol. 3, No. 3, pp. 645-652, 1967.

Monthly Streamflow Simulation, Computer Program 723-X6-L2340, Hydrologic Engineering Center, Corps of Engineers, U. S. Army, February 1971.

Reservoir System Analysis, Computer Program 723-X6-L2030, Hydrologic Engineering Center, Corps of Engineers, U. S. Army, February 1971.

Roefs, T. G., "Reservoir Management: The State of the Art," IBM Washington Scientific Center, Wheaton, Maryland, Report No. 320-350, 85p., July 15, 1968.

Tables of Probability Functions, Vol II, Federal Works Agency, Works Projects Administration for the City of New York, New York, 1942.

Young, G. K., Jr., "Techniques for Finding Reservoir Operating Rules," Ph.D. Thesis, Harvard Water Program, Harvard University, Cambridge, Massachusetts, November, 1966.

Acknowledgement. The work upon which this paper is based was supported in part by funds provided by the United States Department of the Interior, Office of Water Resources Research as authorized under the Water Resources Research Act of 1964.

A STOCHASTIC ANALYSIS OF FLOWS ON RILLITO CREEK

N. E. BARAN

Hydrology & Water Resources, University of Arizona

C. C. KISIEL

Hydrology & Water Resources, University of Arizona

L. DUCKSTEIN

Systems Engineering, University of Arizona

INTRODUCTION

Measurements of the ephemeral streamflow of Rillito Creek, Tucson, Arizona, were analyzed for the period 1933 through 1965. The purpose of the analysis was twofold: (1) to construct a simulation model for ephemeral streamflow, and (2) to examine in depth the problem of the worth of data for that model.

The simulation model was based on the following hypotheses:

1. The durations of flows and their preceding or succeeding dry periods (periods of time when no flow is present) are independent.
2. The distribution of the lengths of the dry periods and flows is stationary over a certain period of the year (say, July 1 to Sept. 15).
3. A stationary probability distribution for the duration of the flows and a stationary distribution for the length of the dry periods can be derived.
4. In this manner one can simulate a series of flows and dry periods corresponding to the one in nature.

A corresponding problem was how to derive a simulation model for the total amount of flow (in acre-feet) within one flow period. For this purpose three variables were considered:

(1) the duration of the flow,

(2) the peak intensity of the flow, and

(3) the length of the dry period preceding the flow (the antecedent dry period).

It was hypothesized that the relationship between the total flow and these three variables is of the following form:

$$F = aD^{b_1}P^{b_2}A^{b_3}\tilde{z}$$

or

$$\ln(F) = \ln(a) + b_1\ln(D) + b_2\ln(P) + b_3\ln(A) + \tilde{z}$$

where

F = total flow (in acre-feet x 100) during a wet period

$\tilde{z}$ = a random variable

a, b_1, b_2, b_3 = constants ≃ 4.12, .62, .78, -.01

D = duration of flow (in minutes)

P = peak intensity of flow (in cubic feet/sec)

A = antecedent dry period (in minutes)

$\tilde{z}$ = a random variable $N(0,\sigma^2)$

The reason that a multiplicative regression model was used, rather than a regular linear regression model, is that, in the linear regression model, the assumption of constancy of variance does not hold since the variance increases as the three regression variables increase. From the data, the multiple correlations R for both summer and winter flows were on the order of 0.95, the correlation between "independent" variables ranged from 0.04 to 0.49 which implies a form of independence, and the residuals $\underset{\sim}{z}$ were distributed normally about the regression hyperplane.

The regression model can be used for the two purposes mentioned above: to predict the total amount of flow during a flow period, and to examine the worth of data as applied to the regression analysis.

For the purpose of simulating streamflow the following algorithm can be used:

1. Monte-Carlo a dry period and record the length of the dry period.
2. Monte-Carlo a flow duration and record the flow duration.
3. Monte-Carlo a peak flow intensity.
4. Predict an expected total flow from 1, 2, and 3.
5. Monte-Carlo a deviation from the mean total flow.
    a. Add the predicted total mean flow and the deviation.
    b. Record the resulting predicted total flow.
6. Go to step 1.

This algorithm is repeated for as many times as is necessary to predict a sequence of flows.

The following sections will examine problems related to the above-mentioned goals.

AN ANALYSIS OF THE WORTH OF DATA BY ANALYSIS OF VARIANCE RELATIONS BETWEEN CUMULATIVE MULTIPLE LINEAR REGRESSIONS

The technique of the analysis of variance was used to examine the worth of the data in the following manner: examine the data to see which variables are important or valuable, and examine how many years of data are required to become confident of any result. The worth of three kinds of data -- peak flow, flow duration, and antecedent dry periods -- was examined in relation to total flow.

Analyses of Variance (Tables 1-I through 6-V). The analysis of variance relations were derived as follows:

1. $SST = \Sigma(Y_i - \bar{Y})^2$ = Total sum of squares [*Control Data Corporation,* 1966]

2. $R_{yx} = \dfrac{\Sigma(Y_i - \bar{Y})(X_i - \bar{X})}{\sqrt{SST}\ \sqrt{\Sigma(X_i - \bar{X})^2}}$ [*Control Data Corporation,* 1966]

3. $SSR = \dfrac{[\Sigma(Y_i - \bar{Y})(X_i - \bar{X})]^2}{\Sigma(X_i - \bar{X})^2}$

4. $SSE = [1 - (R_{yx})^2]\ SST = SST - SSR$ = Error sum of squares.

This leads to the following relations

Source	df	SS	MS	F
Regression	1	SSR	SSR	$\dfrac{SSR}{SSE/(n-2)}$
Error	n-2	SSE	SSE/(n-2)	

If the Fisher ratio $F_{1,n-2}$ is greater than the critical value [see *Johnson and Leone,* 1964], then the hypothesis that the regression coefficients are zero cannot be rejected. Subtable I of Tables 1 through 6 presents analyses of this type for Flow-Peak, Flow-Duration, and Flow-Antecedent Dry Period (ADP) relations.

The analysis of variance tables are numbered 1-I through 6-V. The first number is the table number and stands for the time period of the analysis; the second number (the Roman numeral) stands for the type of analysis. Therefore, for example, Table 4-IV presents the fourth time period (1933 through 1942) and the fourth type of analysis (the significance of adding two variables to a regression already containing one variable).

General Analysis of Variance. Assume that a model of the following form is desired:

$$Y = B_0 + B_1 X_1 + B_2 X_2 + B_3 X_3 + \varepsilon(p, \sigma^2)$$

where in this case

$Y = \ln(\text{flow})$ in $\ln(\text{acre-feet})$

$X_1 = \ln(\text{peak})$ in $\ln(\text{cubic feet per second})$

$X_2 = \ln(\text{duration})$ in $\ln(\text{minutes})$

$X_3 = \ln(\text{antecedent dry period})$ in $\ln(\text{minutes})$

The problem is to choose B_0, B_1, B_2, B_3 in order to minimize

$$(Y_i - B_0 - B_1 X_{1i} - B_2 X_{2i} - B_3 X_{3i})^2.$$

To do so, use the following relations:

For error sum of squares:

$$SSE = \Sigma(Y_i - \bar{Y})^2$$

For matrix $\underline{p}$, the elements are:

$$p_i = \sum_j (Y_i - \bar{Y})(X_{ij} - \bar{X}_j)$$

For matrix t, the elements are:

$$t_{ii} = \sum_j (X_{ij} - \overline{X}_j)$$

$$t_{hi} = \sum_j (X_{jh} - \overline{X}_h)(X_{ji} - \overline{X}_i),$$

where

Y_i, i = 1, 2, ..., n is the ith observation of the dependent variable;

n is the number of observations of the variables, the sample size;

X_{ij}, i = 1, 2, ..., n, j = 1, 2, 3 is the ith observation of the jth variable

and

$$\overline{X}_j = (\sum_{i=1}^{n} X_{ij})/n$$

If b_i's are the estimates for B_i, if C_{ij}, an element in matrix C, is the inverse of t_{ij}, and if we let b_i, i = 1, ..., 3, be the matrix of estimators for the regression coefficient, then $\underline{tb} = \underline{p}$ is the matrix relation that solves the problem of regression estimation. The solution to this is $\underline{b} = \underline{t}^{-1}\underline{p} = \underline{Cp}$ [*Williams*, 1959; *Johnson and Leone*, 1964].

The analysis of variance relations can be derived as follows:

$$SSR = b_i p_i;\ SST = \text{(as given above)};\ SSE = SST - SSR$$

This can be displayed as the following ANOVA table [*Smillie*, 1966]:

Source	df	SS	MS	F
Regression	3	SSR	SSR/3	$\frac{SSR/3}{SSE/(n-4)}$
Error	n-4	SST-SSR	SSE/(n-4)	

The significance of this can be tested by an F value with (3, n-4) degrees of freedom [*Johnson and Leone*, 1964]. To determine the contribution to the regression made by adding any variable to the other two variables (say, the difference between a regression containing duration and antecedent dry period and a regression containing all three variables), one can use the following formula:

$$SSX_i/X_j\ X_k = (b_i)^2/C_{ii}$$

where $SSX_i/X_j\ X_k$ is the contribution added to the regression sum of squares by adding X_i to a regression already containing X_j and X_k; b_i is the regression coefficient for the ith variable; C_{ii} is the iith component of the inverse matrix as defined above [*Williams*, 1959].

It is also evident that

$$SSX_j\ X_k = SSR - SSX_i/X_j\ X_k$$

where $SSX_j\ X_k$ is the regression sum of squares for a regression containing X_j and X_k, and SSR is the total regression sum of squares for a regression containing all three variables (X_1, X_2, X_3).

To derive the contribution or increase in the regression sum of squares added by the addition of two variables to a regression containing only one variable, one can use the results of the previous section (Analysis of Variance).

Let SSX_j be the sum of squares for a regression with flow and X_j derived from the correlation coefficients and the total sum of squares. Then:

$$SSX_iX_k/X_j = SSR - SSX_j,$$

which can be interpreted as the contribution to the total explained variance made by X_i and X_k after the contribution of X_j has been already taken into account.

We can now derive any of the regression relations from the correlation matrix, the total sum of squares, the total regression sum of squares, the estimated regression coefficients and the inverse matrix. Tests for the significance of the contribution of sets of variables to a regression are as follows: let SSR be the regression sum of squares for p variables, and let SSR' be the regression sum of squares for k variables with $k < p$. If n sets of observations were taken, then

$$F = \frac{(SSR - SSR')/(p-k)}{SSE/(n-p-1)}$$

tests the significance of the variables not included in the regression for the first k variables but included in the total regression [*Smillie*, 1966]. An analysis of variance table can be made for this as follows:

Source	df	SS	MS	F
All p variables	p	SSR		
First k variables	k	SSR'		
Difference due to the added variables	p - k	SSR - SSR'	$MSR' = \frac{(SSR-SSR')}{p-k}$	$\frac{MSR'}{MSE}$
Error	n-p-1	SSE	$MSE = \frac{SSE}{n-p-1}$	

In our problem we wish to evaluate:

1. the significance of each pair of variables (Tables 1 through 6, subtable II in each Table),
2. the significance of adding each variable to a regression containing the other two variables (Tables 1 through 6, subtable III in each Table),

3. the significance of adding the other two variables to a regression already containing one variable (Tables 1 through 6, subtable IV in each Table),

4. the significance of each variable in a regression containing two variables (Tables 1 through 6, subtable V in each Table), and

5. the significance of the overall regression (Tables 1 through 6, first lines of subtables III and IV in each Table).

The significance of the pairs of variables (Tables 1 through 6, subtable II in each Table) is derived from three analyses of variance as follows:

Source	df	SS	MS	F
X_iX_j	2	SSX_iX_j	$MS_{ij} = \frac{SSX_iX_j}{2}$	$\frac{MS_{ij}}{MSE_{ij}}$
Error	n-3	$SSEX_iX_j$	$MSE_{ij} = \frac{SSEX_iX_j}{n-3}$	

where SSX_iX_j is derived, as previously described, as follows: let SSR = total regression sum of squares and SX_k/X_iX_j = addition to the total regression sum of squares added by X_k. Then

$$SSX_iX_k = SSR - SX_k/X_iX_j$$

and

$$SSEX_iX_j = SST - SSX_iX_k$$

where SSR = total regression sum of squares,

SST = total sum of squares,

SSX_iX_j = sum of squares for regression containing X_i, X_j, and

$SSEX_iX_j$ = error sum of squares for a regression containing X_i, X_j.

The significance of these regressions containing two variables can be summarized as follows:

1. A regression containing peak and duration is very highly significant even with the smallest sample.
2. A regression containing peak and ADP is significant but not as good as the above.
3. A regression containing ADP and duration becomes very highly significant at the .999 level after 10 years, but this relationship cannot be properly evaluated without 10 years of data.

Subtable III of Tables 1 through 6 evaluates the contribution of each variable to the total regression in the following manner:

$$SX_k/X_iX_j = (B_i)^2/C_{ii}$$

$$SX_iX_j = SSR - SX_k/X_iX_j$$

where

SX_k/X_iX_j = added contribution of X_k to a regression containing X_iX_j and can be interpreted as the effect of X_k given the contribution of X_i and X_j has already been evaluated,

SX_iX_j = sum of squares for a regression containing X_i and X_j,

SST = total sum of squares for the whole regression (containing X_1, X_2, X_3),

SSR = total regression sum of squares, and

SSE = SST - SSR = error sum of squares for the total regression.

Then an analysis of variance can be made as follows:

Source	df	SS	MS	F
X_1, X_2, X_3	e	SSR	MSR = SSR/3	MSR/MSE
Total error	n-4	SSE	MSE = SSE/(n-4)	
X_i, X_j	2	SX_iX_j		
Difference due due to X_k	1	SX_k/X_iX_j	$MS_k/_{ij} = SX_k/X_iX_j$	$\frac{MS_k/_{ij}}{MSE}$

The third line, X_iX_j, is redundant and is put in only for illustration. Lines 3 and 4 are repeated to evaluate the contribution of each variable.

Here it rapidly becomes evident that the contribution due to adding ADP into the regression is negligible. The difference due to ADP is not significant at 3 years and indeed at 33 years of data the contribution of ADP to the total regression is .4 out of 1588.8 or .025 percent of the total regression variance. It can be concluded from this that ADP is useless as far as the total regression is concerned as virtually all the variance accounted for by ADP is accounted for by a combination of duration and peak. The conclusion to be drawn from this is that the expense of processing data containing antecedent dry periods should be foregone. The contribution of the peak, however, is very highly significant after 3 years and the contribution of duration is also very highly significant after 3 years, indicating that the contribution of these variables can be discovered with very little data.

Subtable IV of Tables 1 through 6 further illustrates the negligible contribution made by adding ADP into the regression.

Subtable V of Tables 1 through 6 is meant to evaluate the contribution of each variable in regressions containing two variables. Since ADP has been rejected, it is necessary to determine if each of the other two variables, peak and duration, contributes significantly to the regression containing both. An analysis of variance can be constructed as follows:

SSPD = sum of squares for regression containing peak and duration,

SSP/D = SSPD - SSD = contribution of peak to regression,

SSD/P = SSPD - SSP = contribution of duration to the regression, and

Error = SSEPD = SST - SSPD

= error sum of squares for regression containing peak and duration.

The analysis of variance table is as follows:

Source	df	SS	MS	F
Peak, duration	2	SSPD		
Difference due to peak	1	SSP/D	MSP/D	$\frac{MSP/D}{MSEPD}$
Difference due to duration	1	SSD/P	MSP/D	$\frac{MSP/D}{MSEPD}$
Error	n-3	SSEDP	MSEPD = $\frac{SSEDP}{n-3}$	

Examining the significance of duration and peak to overall regression, one finds that the contribution of each is very highly significant at only two years, indicating that both variables contribute to the overall regression and that their significance becomes evident with very small amounts of data.

EVALUATION OF THE ABOVE RESULTS

The following conclusions can then be drawn from the extensive analysis of variance:

1. ADP should not be used.

2. A regression containing peak and duration is significant and this significance becomes evident from a very small amount of data.
3. Both peak and duration make a significant contribution to the overall regression. This also becomes evident with a very small amount of data.
4. The significance of peak alone is evident with minimal amounts of data.
5. The significance of duration alone becomes evident if one uses about 10 years of data.
6. All of the above conclusions could have been drawn with 10 years of data. Therefore, as far as the significance of the variables in the regression is concerned, more than 10 years of data is wasted expense.
7. These results will not be too surprising to a hydrologist acquainted with the hydrograph shape in semi-arid lands, which is of the form of a curvilinear triangle. If we use untransformed variables, the area F of the curvilinear triangle is a function of (Base D) x (Height P) as shown in Figure 1(a). The merit of the above development is that it points out the mathematical transformation which gives an almost perfect triangular hydrograph (as seen in Figure 1(b). We have $F = a(D^{b_1})(P^{b_2})$ where D^{b_1} and P^{b_2} are, respectively, the base and the height of an idealized hydrograph.

ANALYSIS OF SEASONAL VARIATIONS IN THE NUMBER FLOWS PER TIME PERIOD

In order to synthesize streamflow phenomena, consideration should be given to the meteorological phenomena occurring within a year. One way to analyze these within-year fluctuations is to consider the changes in the flow arrival rate (the number of flows per time period). A FORTRAN program was written in order to analyze streamflows for any arbitrary time periods within the year. Data from the Rillito Creek from 1930 through 1965 were used for this analysis. One output from the program was the number of flows in each time period (say, the month of July, for example) for each of the 36 years. These flow arrivals proved most amenable to analysis in determining "seasonal" fluctuations in streamflow.

The flows were tabulated for each "two week" period throughout the year. A "two week" period consists of days 1 through 15 of a month or days 16 through the end of the month. The simplest statistic that one can use to analyze seasonal variations is the flow arrival rate for each two week period. These appear in Figure 2, which shows, for example, that the last half of July and the month of August seem to have significantly higher arrival rates than the rest of the year; this hypothesis can be tested statistically.

The distribution of arrivals was tabulated for each two-week period (see Figure 2 for August 1-15 as an example). In order to evaluate whether or not the flow arrivals were the same in consecutive two-week periods a Kolmogorov-Smirnov test was used. The test statistic for a Kolmogorov-Smirnov test for the comparison of two distributions is,

$$D = \max |F_1(x) - F_2(x)|$$

where $F_i(x)$ is the cumulative observed probability for the ith variable.

If there are n_1 observations of variable 1 and n_2 observations of variable 2, then in order to test the hypothesis, H_0: $F_1(x) = F_2(x)$ at the .05 significance level, compute,

$$d = 1.36 \sqrt{\frac{n_1 + n_2}{n_1 n_2}}$$

Thus, d = 0.321 for n_1 = 36, n_2 = 36 and a significance level of .05. If D < d, do not reject H_0; but if D > d, reject H_0.

Each two-week arrival distribution was then tested against the next to see if they were different. For example, the respective flow arrival distributions for November 16-30 and December 1-15 are:

Flows	November	December
0	25	31
1	9	4
2	0	0
3	2	1

The respective cumulative distribution functions and the $[F_1(x) - F_2(x)]$ values:

Flows	November	December	$F_1(x) - F_2(x)$
0	.694	.861	-.167
1	.944	.972	-.028
2	.944	.972	-.028
3	1.000	1.000	0.000

Since max $F_1(x) - F_2(x)$ = .167, and the critical value d for a significance level of .05 is 0.321, one cannot reject H_0. Hence, the distributions are the same at this significance level. These results are shown in Table 2. This value shows that, by analyzing two-week time periods only, one can say with some confidence that there is a definite change in flow arrival rate at June 30 and on August 31.

An examination of the arrival rates indicates that grouping the observations would be useful. Five time periods were considered as follows:

Time Period	Number of Two-week Periods
1 (October 1 - April 15)	468
2 (April 16 - June 30)	180
3 (July 1 - July 15)	36
4 (July 16 - August 31)	108
5 (September 1 - September 30)	72

The cumulative distributions for these five time periods were compared by the Kolmogorov-Smirnov test with the preceding time periods to determine if the flow arrivals were the same. The results were computed for a comparison of Time Period 1 with Time Period 2 by using the following relation:

$$\Delta_{max} = \max |F_1(n) - F_2(n)| = .174$$

The critical level for $n_1 = 468$, $n_2 = 180$, and $\alpha = .05$ is 0.119. Hence, reject the hypothesis that the flow arrivals are the same. The full results are as follows for $\alpha = .05$:

Time Periods	Δ_{max}	Critical value	Result
1 and 2	.174	.119	Reject H_0
2 and 3	.273	.248	Reject H_0
3 and 4	.565	.261	Reject H_0
4 and 5	.426	.207	Reject H_0
5 and 1	.224	.172	Reject H_0

These results indicate that there are five different periods per year when the flow arrival distributions are statistically different.

The usual hypothesis concerning the arrival distribution of flows is that the arrivals are Poisson. In order to test this, a Kolmogorov-Smirnov test was made on the arrival distributions for the above five time periods. The results are as below for α = .05 and H_0: the flow arrivals are Poisson:

Time Period	max	Critical value	Result
1	.076	.062	Reject H_0
2	.018	.101	Accept H_0
3	.087	.230	Accept H_0
4	.093	.131	Accept H_0
5	.120	.160	Accept H_0

This result concurs with the result reached by *Kisiel et al.* [1971].

The conclusion to be drawn from the above analysis is that there are at least five distinct time periods during the year when the flow arrivals differ significantly. Any model to predict runoff should take these deviations into account. Also, a Poisson flow arrival rate in summer explains why ADP is not important in the determination of flow volume. Events occur in an independent manner (at random) and are not clustered as in winter. This indicates that channel moisture is not very different before one flow event or another.

Acknowledgments. The research results were in part supported by an allotment grant A-010 from the Water Resources Research Center of the University of Arizona and by a matching grant B-007-ARIZ from the Office of Water Resources Research, U.S. Department of the Interior, to study the Efficiency of Hydrologic Data Collection Systems.

TABLE 1

Rillito Creek: Analysis of Variance - Regression Analysis

1933-1934

I

Variable(s)	df#	SS	MS	F
Peak	1	23.87	23.87	14.21**
Error	15	25.15	1.68	
Duration	1	3.32	3.32	1.09
Error	15	45.70	3.05	
ADP	1	18.65	18.65	9.21**
Error	15	30.37	2.02	

II

Variables	df	SS	MS	F
Peak, Dur	2	43.38	21.69	53.84***
Error	14	5.64	.403	
Peak, ADP	2	33.42	16.71	15.00***
Error	14	15.60	1.11	
Dur, ADP	2	27.36	13.68	8.84**
Error	2	21.66	1.55	

- For explanation of symbols, see list of definitions following Table 7.
* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

1933-1934 -- continued

III

Variables	df	SS	MS	F
Peak, Dur, ADP	3	45.12	15.04	50.13***
Total error	13	3.90	.300	
Peak, Dur	2	43.38	1.74	5.80*
Difference due to ADP	1	1.74	1.74	
Peak, ADP	2	33.42		39.00***
Difference due to Dur	1	11.70		
Dur, ADP	2	27.36		59.20***
Difference due to Peak	1	17.76	17.76	

IV

Variables	df	SS	MS	F
Peak, Dur, ADP	3	45.12	15.04	50.13***
Total error	13	3.90	.300	
Peak	1	23.87		35.42***
Difference due to Dur, ADP	2	21.25	10.63	
Dur	1	3.32		69.67***
Difference due to Peak, ADP	2	41.80	20.90	
ADP	1	18.65		44.12***
Difference due to Peak, Dur	2	26.47	13.24	

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

1933-1934 -- continued

V

Variables	df	SS	MS	F
Peak, Dur	2	43.38		
Difference due to Peak	1	40.06	40.06	99.40***
Difference due to Dur	1	19.51	19.51	48.41***
Error for Peak, Dur	14	5.64	.403	
Peak, ADP	2	33.42		
Difference due to Peak	1	14.77	14.77	13.31**
Difference due to ADP	1	9.55	9.55	8.60*
Error for Peak, ADP	14	15.60	1.11	
Dur, ADP	2	27.36		
Difference due to Dur	1	8.71	8.71	5.62*
Difference due to ADP	1	24.04	24.04	15.51**
Error for Dur, ADP	14	21.66	1.55	

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

TABLE 2

Rillito Creek: Analysis of Variance - Regression Analysis

1933-1935

I

Variable(s)	df	SS	MS	F
Peak	1	86.74	86.74	61.34***
Error	29	41.01	1.414	
Duration	1	18.92	18.92	5.04*
Error	29	108.83	3.75	
ADP	1	10.10	10.10	2.49
Error	29	117.65	4.057	

II

Variables	df	SS	MS	F
Peak, Dur	2	117.84	58.72	159.47***
Error	28	10.31	.368	
Peak, ADP	2	90.03	45.02	33.42***
Error	28	37.72	1.347	
Dur, ADP	2	75.23	12.61	3.45*
Error	28	102.52	3.661	

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

1933-1935 -- continued

III

Variables	df	SS	MS	F
Peak, Dur, ADP	3	118.11	39.37	114.39***
Total error	27	9.64	.357	
Difference due to ADP	1	.68	.68	1.96
Peak, ADP	2	90.03		78.66***
Difference due to Dur	1	28.08	28.08	
Dur, ADP	2	25.23		260.17***
Difference due to Peak	1	92.88	92.88	

IV

Variables	df	SS	MS	F
Peak, Dur, ADP	3	118.11	39.37	114.39***
Error-Total	27	9.64	.357	
Peak	1	86.74		43.93***
Difference due to Dur, ADP	2	31.37	15.68	
Dur	1	18.92		139.92***
Difference due to Peak, ADP	2	99.19	45.60	
ADP	1	10.0		151.27***
Difference due to Peak, Dur	2	108.01	54.01	

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

1933-1935 -- continued

V

Variables	df	SS	MS	F
Peak, Dur	2	117.44		
Difference due to Peak	1	98.52	98.52	267.72***
Difference due to Dur	1	30.70	30.70	83.42***
Error for Peak, Dur	28	10.31	.368	
Peak, ADP	2	90.03		
Difference due to Peak	1	79.93	79.93	59.34***
Difference due to ADP	1	3.29	3.29	2.44
Error for Peak, Dur	28	37.72	1.347	
Dur, ADP	2	25.23		
Difference due to Dur	1	15.13	15.13	4.13
Difference due to ADP	1	6.31	6.31	1.72
Error for Dur, ADP	28	102.52	3.661	

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

TABLE 3

Rillito Creek: Analysis of Variance - Regression Analysis

1933-1937

I

Variable(s)	df	SS	MS	F
Peak	1	148.23	148.23	139.77***
Error	46	48.786		
Duration	1	25.336	25.336	6.7883*
Error	46	171.68	3.7323	
ADP	1	7.7787	7.7787	1.8908
Error	46	189.24	4.1139	

II

Variables	df	SS	MS	F
Peak, Dur	2	180.87	90.434	252.03***
Error	45	16.147	.35882	
Peak, ADP	2	149.76	74.88	71.29***
Error	45	47.26	1.0503	
Dur, ADP	2	28.97	14.485	4.293*
Error	45	168.05	3.734	

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

1933-1935 -- continued

III

Variables	df	SS	MS	F
Peak, Dur, ADP	3	180.89	60.297	164.55***
Error-Total	44	16.123	.36643	
Peak, Dur	2	180.87		
Difference due to ADP	1	.024	.024	.0655
Peak, ADP	2	149.76		
Difference due to Dur	1	31.14	31.14	84.98***
Dur, ADP	2	28.97		
Difference due to Peak	1	151.92	151.92	414.59***

IV

Variables	df	SS	MS	F
Peak, Dur, ADP	3	180.89	60.297	164.55***
Error-Total	44	16.123	.36643	
Peak	1	148.23		
Difference due to Dur, ADP	2	32.66	16.33	44.56***
Dur	1	25.34		
Difference due to Peak, ADP	2	155.55	77.78	212.25***
ADP	1	7.78		
Difference due to Peak, Dur	2	173.11	86.55	236.21***

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

TABLE 4

Rillito Creek: Analysis of Variance - Regression Analysis
1933-1942

I

Variable(s)	df	SS	MS	F
Peak	1	376.43	376.43	386.88***
Error	92	89.54	.973	
Duration	1	103.85	103.85	26.39***
Error	92	362.12	3.93	
ADP	1	21.84	21.84	4.52*
Error	92	444.13	4.83	

II

Variables	df	SS	MS	F
Peak, Dur	2	419.91		414.81***
Error	91	46.06	.506	
Peak, ADP	2	376.91		192.56***
Error	91	89.06	.979	
Dur, ADP	2	117.36		15.32***
Error	91	348.61	3.831	

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

1933-1942 -- continued

III

Variables	df	SS	MS	F
Peak, Dur, ADP	3	417.98	139.32	261.29***
Total error	90	47.99	.533	
Peak, Dur	2	419.91		
Difference due to ADP	1	.07	.07	.131
Peak, ADP	2	376.91		
Difference due to Dur	1	41.07	41.07	77.05***
Dur, ADP	2	117.36		
Difference due to Peak	1	300.62	300.62	564.02***

IV

Variables	df	SS	MS	F
Peak, Dur, ADP	3	417.98	139.32	261.29***
Total error	90	47.99	.533	
Peak	1	376.43		
Difference due to Dur, ADP	2	41.55	20.78	38.98***
Dur	1	103.85		
Difference due to Peak, ADP	2	314.13	157.07	294.68***
ADP	1	21.84		
Difference due to Peak, Dur	2	396.14	198.07	371.61***

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

1933-1942 -- continued

V

Variables	df	SS	MS	F
Peak, Dur	2	419.91		
Difference due to Peak	1	316.06	316.06	624.62***
Difference due to Dur	1	43.48	43.48	85.93***
Error for Peak, Dur	91	46.06		
Peak, ADP	2	376.91		
Difference due to Peak	1	355.07	355.07	362.69***
Difference due to ADP	1	.48	.48	.49
Error for Peak, ADP	91	89.06	.979	
Dur, ADP	2	117.36		
Difference due to Dur	1	95.52	95.52	24.93
Difference due to ADP	1	13.51	13.51	3.53
Error for Dur, ADP	91	348.61	3.831	

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

TABLE 5

Rillito Creek: Analysis of Variance - Regression Analysis

1933-1951

I

Variable(s)	df	SS	MS	F
Peak	1	818.00	818.00	1058.21***
Error	197	152.24	.773	
Duration	1	241.01	241.01	65.11***
Error	197	729.23	3.702	
ADP	1	9.05		
Error	197	961.19	4.879	1.86

II

Variables	df	SS	MS	F
Peak, Dur	2	888.56	444.28	1066.20***
Error	196	81.68	.4167	
Peak, ADP	2	818.09	409.05	526.93***
Error	196	152.15	.7763	
Dur, ADP	2	245.01	122.51	33.11***
Error	196	725.23	3.700	

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

1933-1951 -- continued

III

Variables	df	SS	MS	F
Peak, Dur, ADP	3	888.57	296.19	707.20***
Total error	195	81.67	.4188	
Peak, Dur	2	888.56		
Difference due to ADP	1	.01	.01	.0239
Peak, ADP	2	818.09		
Difference due to Dur	1	70.48	70.48	168.29***
Dur, ADP	2	245.01		
Difference due to Peak	1	643.56	643.56	1536.68***

IV

Variables	df	SS	MS	F
Peak, Dur, ADP	3	888.56	296.19	707.20***
Total error	195	81.67	.4188	
Peak	1	818.00		
Difference due to Dur, ADP	2	70.57	35.29	84.25***
Dur	1	241.01		
Difference due to Peak, ADP	2	647.56	323.78	773.11***
ADP	1	9.05		
Difference due to Peak, Dur	2	879.52	439.76	1050.05***

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

1933-1951 -- continued

V

Variables	df	SS	MS	F
Peak, Dur	2	888.56		
Difference due to Peak	1	647.55	647.55	1554.00***
Difference due to Dur	1	70.56	70.56	169.33***
Error for Peak, Dur	196	81.68	.4167	
Peak, ADP	2	818.09		
Difference due to Peak	1	809.04	809.04	1042.17***
Difference due to ADP	1	.09	.09	.12
Error for Peak, ADP	196	152.15	.7763	
Dur, ADP	2	245.01		
Difference due to Dur	1	235.96	235.96	63.77***
Difference due to ADP	1	4.000	4.000	1.08
Error for Dur, ADP	196	725.23	3.700	

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

TABLE 6

Rillito Creek: Analysis of Variance - Regression Variance

1933-1965

I

Variable(s)	df	SS	MS	F
Peak	1	1471.5		
Error	341	230.6	.6762	2176.13***
Duration	1	551.46		163.43***
Error	341	1150.6	3.374	
ADP	1	22.39		4.55*
Error	341	1679.71	4.926	

II

Variables	df	SS	MS	F
Peak, Dur	2	1588.4	794.2	2386.67***
Error	340	113.33	.3333	
Peak, ADP	2	1473.54	736.77	1096.00***
Error	340	228.56	.6722	
Dur, ADP	2	568.37	284.19	85.23***
Error	340	1133.73	3.3345	

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

1933-1951 -- continued

III

Variables	df	SS	MS	F
Peak, Dur, ADP	3	1588.8	529.6	1584.73***
Total error	339	113.29	.33419	
Peak, Dur	2	1588.8		
Difference due to ADP	1	.4	.4	1.20
Peak, ADP	2	1473.54		
Difference due to Dur	1	115.26	115.26	344.89***
Dur, ADP	2	568.37		
Difference due to Peak	1	1020.43	1020.43	3053.44***

IV

Variables	df	SS	MS	F
Peak, Dur, ADP	3	1588.8	529.6	1584.73***
Total error	339	113.29	.33419	
Peak	1	1471.5		
Difference due to Dur, ADP	2	117.3	58.65	175.50***
Dur	1	551.46		
Difference due to Peak, ADP	2	1037.34	518.67	1552.02***
ADP	1	22.39		
Difference due to Peak, Dur	2	1566.41	783.21	2343.59

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

1933-1951 -- continued

V

Variables	df	SS	MS	F
Peak, Dur	2	-1588.4		
Difference due Peak	1	1036.94		3111.13***
Difference due to Dur	1	116.9	116.9	350.74***
Error for Peak, Dur	340	113.33	.3333	
Peak, ADP	2	1473.54		
Difference due to Peak	1	1451.15	1451.15	2158.81***
Difference due to ADP	1	2.04	2.04	3.03
Error for Peak, ADP	340	228.56	.6722	
Dur, ADP	2	568.37		
Difference due to Dur	1	545.98	545.98	163.74***
Difference due to ADP	1	16.91	16.91	5.07
Error for Dur, ADP	340	1133.73	3.3345	

* - significance at .95 level
** - significance at .99 level
*** - significance at .999 level

TABLE 7

Kolmogorov-Smirnov Test

Test to Test Differences Between Successive 2-week Periods

$\alpha = .05$ Critical level = .321 n = 36

Time Period		Max Δ	Result
Dec 15-31	Jan 1-15	.028	Accept
Jan 1-15	Jan 16-31	.056	Accept
Jan 16-31	Feb 1-15	.111	Accept
Feb 1-15	Feb 15-28	.139	Accept
Feb 15-28	Mar 1-15	.056	Accept
Mar 1-15	Mar 16-31	.139	Accept
Mar 16-31	Apr 1-15	.083	Accept
Apr 16-30	May 1-15	.056	Accept
May 1-15	May 16-31	0	Accept
May 16-31	June 1-15	.028	Accept
June 1-15	June 16-30	.056	Accept
June 16-30	July 1-15	.250	Accept
July 1-15	July 16-31	.528	Reject***
July 16-31	Aug 1-15	.139	Accept
Aug 1-15	Aug 16-31	.167	Accept
Aug 16-31	Sept 1-15	.444	Reject***
Sept 1-15	Sept 16-31	.111	Accept
Sept 16-31	Oct 1-15	.194	Accept
Oct 1-15	Oct 16-31	.111	Accept
Oct 16-31	Nov 1-15	.083	Accept
Nov 1-15	Nov 16-31	.250	Accept
Nov 16-31	Dec 1-15	.167	Accept
Dec 1-15	Dec 16-31	.167	Accept

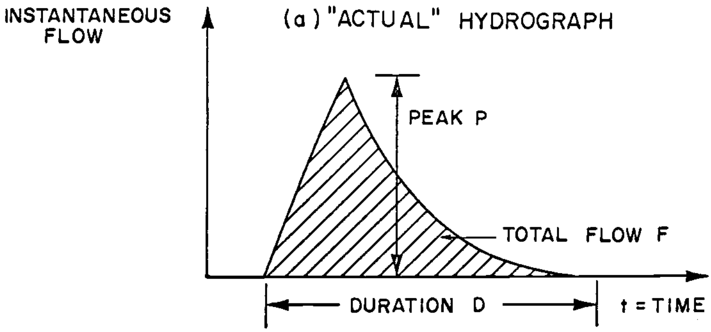


Figure 1(a). Hydrograph shape as a curvilinear triangle.

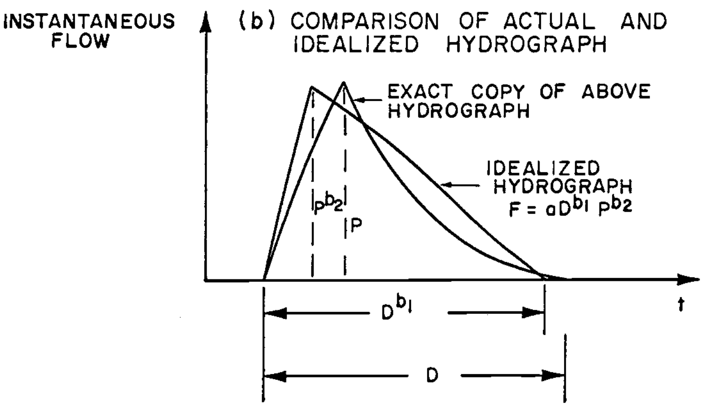


Figure 1(b). Comparison of hydrographs as "pure" and curvilinear triangles.

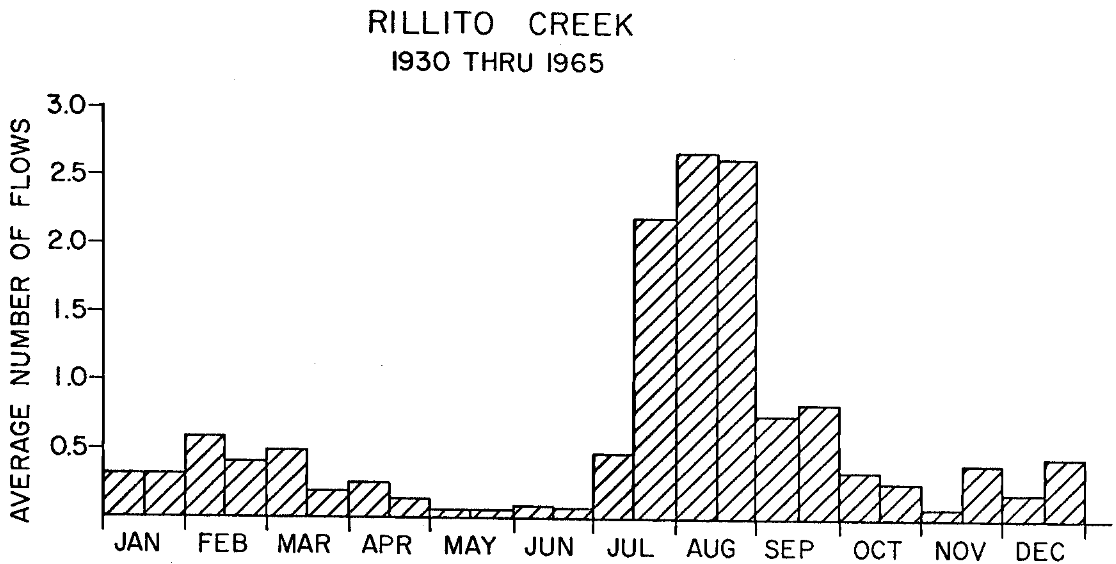


Figure 2. Average flow arrival rates for two week periods over the time period 1930-1965 on Rillito Creek.

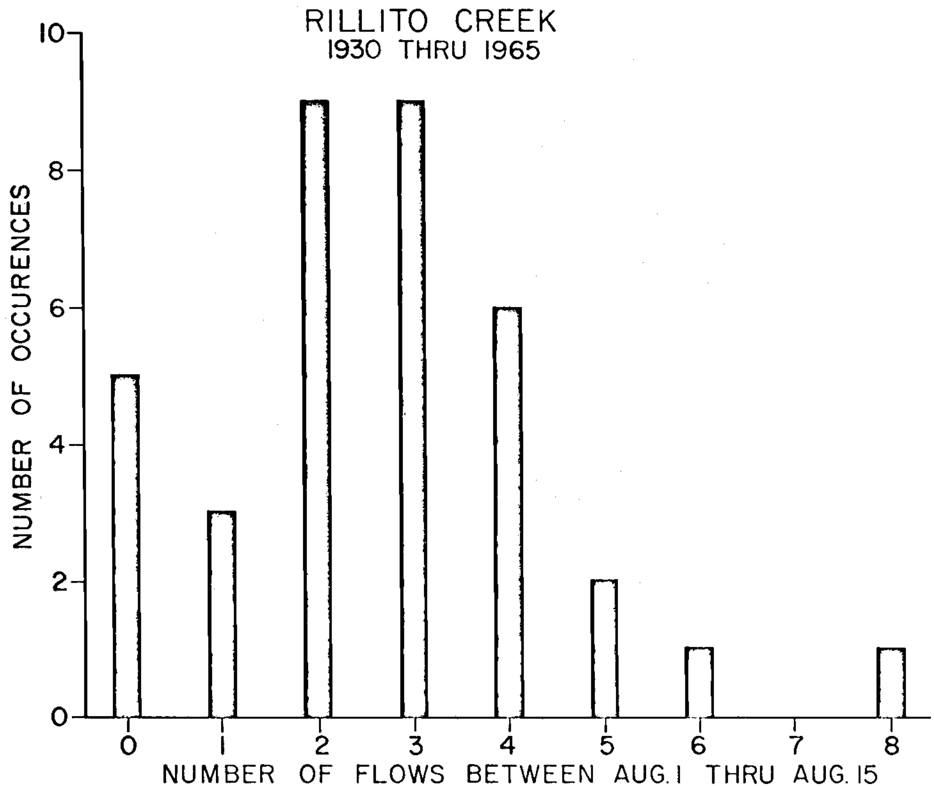


Figure 3. Distribution of 0, 1, 2, ... flow arrivals between Aug. 1 and Aug. 15 for the period 1930-1965 on Rillito Creek.

NOTATION

(Tables 1-6)

df,	degrees of freedom;
SS,	sum of squares;
SSE,	error sum of squares;
SSR,	regression sum of squares;
MS,	mean square;
F,	Fisher's ratio of variances;
Peak,	peak flows (in cfs), ln(peak) was used;
Dur,	duration of flows (in minutes), ln(duration);
ADP,	antecedent dry period, the length of time the channel was dry preceding a flow (in minutes), ln(ADP);
ln,	natural or naperian logarithm

In the regression analyses ln(peak), ln(dur) and ln(ADP) were used in Tables 1 through 6. This corresponds to the model hypothesized.

REFERENCES

Control Data Corporation, *Statistical Subroutines Reference Manual, Control Data 6000 Series Computer Systems*, Documentation Department, 1966.

Johnson, N. L., and F. C. Leone, *Statistics and Experimental Design*, vol. 1, John Wiley & Sons, New York, 1964.

Kisiel, C. C., L. Duckstein, and M. Fogel, Stochastic Analysis of Ephemeral Flow in Aridlands, *Journal of Hydraulics Division, Proc. Am. Soc. Civil Engrs.*, 1971 (in press).

Smillie, K. W., *An Introduction to Regression and Correlation*, Academic Press, Inc., 1966.

Williams, E. J., *Regression Analysis*, John Wiley & Sons, New York, 1959.

Acknowledgements. The work upon which this paper is based was supported in part by funds provided by the United States Department of the Interior, Office of Water Resources Research, as authorized under the Water Resources Research Act of 1964. The computations were done at the University of Arizona Computer Center on the CDC-6400 installed there.

THE USE OF CHEMICAL HYDROGRAPHS IN GROUNDWATER QUALITY STUDIES

Kenneth D. Schmidt

Harshbarger and Associates
Tucson, Arizona

INTRODUCTION

A graph showing changes with respect to time of some property of water in a stream, or underground, is gênerally termed a hydrograph. Hem (1959) illustrated the significance of both long and short-term fluctuations in the quality of groundwaters. The purpose of this paper is to illustrate how chemical hydrographs were used in a study of nitrate in groundwater of the Fresno-Clovis Metropolitan Area (F.C.M.A.) of central California.

High nitrates in drinking water are significant in relation to an infant disease, methemoglobinemia. Concentrations exceeding the 1962 U.S. Public Health Service limit of 45 parts per million (ppm) were noted in the F.C.M.A. by the California Department of Water Resources (1965). The primary sources of nitrate were identified as sewage percolation ponds and septic tank disposal systems. Schmidt (1971) noted several other sources, such as winery wastewaters, meat-packing plant wastes, and agricultural fertilizers. Hydrogeologic factors were shown to be intricately related to the distribution of nitrate in groundwater of the F.C.M.A.

The Fresno-Clovis Metropolitan Area comprises about 145 square miles which lie between the Kings and San Joaquin Rivers in the east-central portion of the San Joaquin Valley. Population of the metropolitan area in 1969 was 310,000. Urban water use is derived entirely from wells, whereas the surrounding agricultural area relies on surface water and groundwater. Climate is Mediterranean in type and annual precipitation averages eleven inches at Fresno. Groundwater recharge comes from streamflow infiltration and canal seepage.

Alluvial-fan deposits comprise the unconfined aquifer of the Fresno area. Sand, gravel, cobbles, silt, and clay strata dip gently to the southwest and occur to depths of several thousand feet near Fresno. Depth to water averages about seventy feet and well depths range from less than 100 to more than 500 feet. The average specific capacity is about 130 gallons per minute per foot and the average transmissibility exceeds 220,000 gallons per day per foot. Cobble zones are related to deposits of the ancestral San Joaquin River and comprise the most favorable water-bearing materials. An impermeable hardpan locally limits the percolation of surface water in some parts of the area.

Chemical hydrographs were prepared for all wells in the F.C.M.A. with more than four separate chemical analyses. The following paragraphs summarize some of the more pertinent uses of chemical hydrographs in relation to the distribution of nitrate in the groundwater of the F.C.M.A.

DETERMINATION OF ERRONEOUS OR ATYPICAL ANALYSES

There are a number of sources of errors in chemical analyses.

One method of checking analyses involves comparing the summation of cations to the summation of anions (American Public Health Association, Inc., 1965). A close balance should be obtained for most groundwater. This method of checking the correctness of analyses has inherent limitations, because of the occurrence of calculated values for some constituents.

Other factors besides errors can lead to atypical analyses for certain constituents. Several methods of analysis are in common use for the determination of most ionic species, and results for the same water sample may not be equivalent. Concentration of nitrate can change with time since pumping began. The period of time between sample collection and determination can be crucial for some constituents, such as nitrate. Contamination of the sample bottles and variation in the method of sampling can cause variations in analytical results.

Plotting of chemical hydrographs commonly indicates these erroneous or atypical values. Erroneous or atypical values can lead to invalid conclusions regarding changes occurring in water quality. Judgment as to the determination of erroneous or atypical concentrations for a specific well must necessarily be based on a knowledge of the hydrologic framework and seasonal variation of constituent concentrations. Once these erroneous or atypical values are deleted from consideration, meaningful trends are usually apparent, and generally illustrate that changes in chemical quality are gradual in groundwater.

DOCUMENTATION OF MAJOR CHANGES IN GROUNDWATER QUALITY

Natural concentrations of the ionic species in groundwater are very low in the F.C.M.A. As a result, man-induced changes in quality are reflected by locally high concentrations. The development of septic tank disposal systems, sewage percolation ponds, industrial waste disposal ponds, and nitrogen fertilization in agricultural areas have resulted in substantial increases in the nitrate content of groundwater.

Chemical hydrographs usually display increases in nitrate content since about 1950 (Figure 1). Well PS 27 was in a sewered area and the primary source of nitrate was groundwater inflow from the vicinity of the Fresno Sewage Treatment Plant. The nitrate content exceeded 45 parts per million in 1963 and the well was abandoned in 1966. The increasing nitrate was primarily due to a decline in water level near the well. Groundwater inflow of sewage effluent was hastened by the lower head near the well.

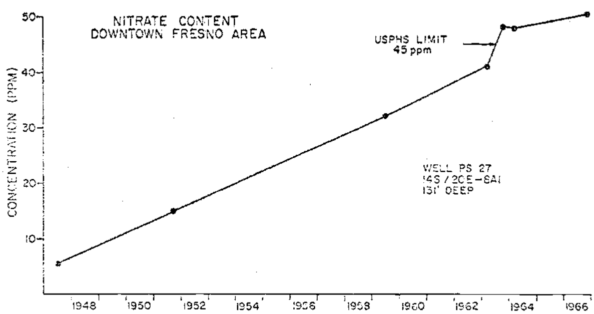


Figure 1

Long term increases in nitrate content can also be attributed to the lowering of the water level near shallow wells in septic tank areas. Nitrate in these areas is stratified in the aquifer of the F.C.M.A., with shallow groundwater having higher concentrations. As water levels have declined in these areas at an average rate of about three feet per year, wells have tended to draw on shallower portions of the aquifer. This factor alone tends to increase the nitrate concentration in a well over a period of years or decades. Hydrographs for wells penetrating deeper portions of the aquifer generally show little long-term variation in nitrate concentration. These wells are seemingly sampling background concentrations of nitrate.

ILLUSTRATION OF SEASONAL VARIATIONS IN QUALITY

Comparisons of chemical quality from one year to the next have sometimes been made without regard to the seasonal variation. Engineering-Science, Inc. (1970) noted that in the Fresno area, samples for nitrate should be collected at approximately the same time each year in order to make valid comparisons. Chemical hydrographs can indicate both the range of concentration exhibited on a seasonal basis and significant trends.

Nitrate hydrographs for wells in septic tank areas of the F.C.M.A. indicate declining concentrations as the summer progresses, with lowest contents in the fall. This trend occurs where the impermeable hardpan is absent and is related to canal recharge during the irrigation season. Abundant unlined canals traverse most of the area. Exceptions to this trend are found in areas where the impermeable hardpan is present. In this case recharge from canal seepage is minimal, and nitrate contents increase during the summer to a peak in the fall. This trend is apparently related to the temperature effect on nitrification, i.e., more nitrification during the warmer months; and to downward flow of shallow water during summer pumping. Vertical flow into the deeper producing zones of many wells results in higher nitrate as the summer progresses.

ILLUSTRATION OF EFFECTS OF HYDROLOGIC FACTORS ON QUALITY

Long term trends shown by chemical hydrographs for wells can illustrate significant changes in the hydrologic regimen. Chloride and nitrate hydrographs are presented for a well in a septic-tank area (Figure 2). Increases in concentration prior to 1966 were due to the development of unsewered suburban areas. Canal recharge was a significant factor in the greatly decreased concentrations of nitrate and chloride in 1967. Annual streamflow for the Kings River, which supplies water to canals of the area, was the largest recorded to that time. Dilution by low nitrate and chloride surface water also occurred in substantial amounts in 1969, which was also a year of very high streamflow.

Several investigators have focused on nitrate changes alone and hypothesized concepts such as denitrification to explain these

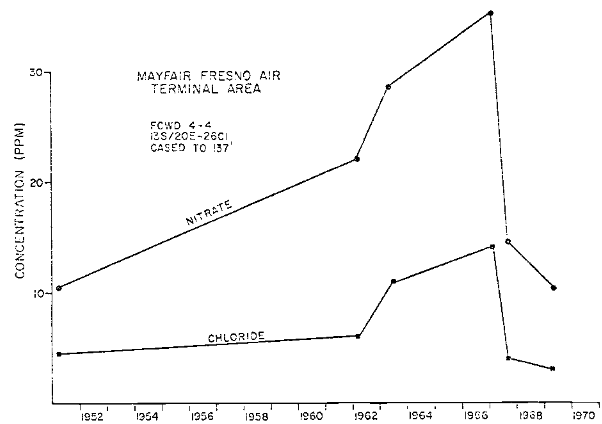


Figure 2

changes. However, plots of other constituents, particularly chloride, can indicate if a change is peculiar to nitrate alone. In the case illustrated by Figure 2, chloride trend is similar to that of nitrate. Thus hydrogeologic factors have likely produced the significant changes in trend. Chloride is perhaps an ideal tracer in this area due to its mobility and low abundance in natural groundwater. A discussion of long-term trends displayed by chemical hydrographs must include reference to the historical streamflow records of the area.

ILLUSTRATION OF EFFECTS OF CHANGES IN WELL CONSTRUCTION

Changes in well depth can produce substantial changes in trend for nitrate content (Figure 3). The nitrate hydrograph

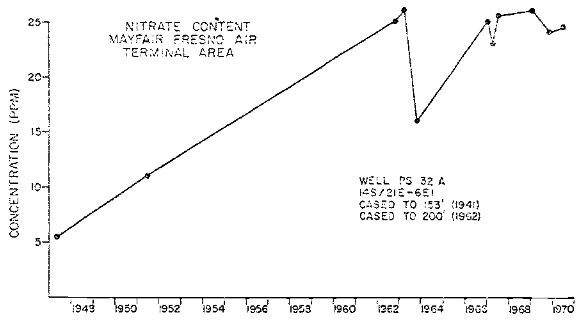


Figure 3

indicates a linear increase to about 1962, with relatively constant concentrations thereafter. Prior to 1962 well PS 32A was open-bottomed and cased to 153 feet. However, in 1962 the well was deepened and cased to 200 feet. This well sampled shallower water in the aquifer prior to 1962 and the increasing trend was related to septic tank development. Once the well was cased to a greater depth, nitrate concentration did not significantly change with time. Deeper portions of the aquifer tend to have less fluctuation in nitrate content due to the damping of near-surface effects.

DETERMINATION OF NITRATE SOURCE

Several potential sources of nitrate occur in some parts of the F.C.M.A. Nitrate and chloride hydrographs were prepared for many wells in septic tank areas (Figure 2). Chloride short-term trends were similar to those for nitrate in virtually all cases. Both chloride and nitrate are contributed by septic-tank effluent and the two ions are both mobile in groundwater of the Fresno area.

Hydrographs were also plotted for wells in the vicinity of sewage treatment plants. The chemical hydrographs in this case indicated an abundance of opposite nitrate and chloride short-term trends. Thus when chloride concentration increased for a specific well, nitrate concentration often decreased. The exact reason for this pattern is unknown, but it may be related to the interference effect of high chloride concentrations on the phenoldisulfonic method for nitrate determination (Malhotra and Zononi, 1970).

Nitrate and chloride hydrographs were plotted for wells in areas where both septic tanks and sewage effluent ponds were potential sources of nitrate. These hydrographs were used in conjunction with trilinear diagrams, distribution of major chemical constituents, and hydrologic data to effectively delineate sources of nitrate in water pumped by specific wells. Conflicting evidence in some cases suggested more than one nitrate source for a specific well, whereas in other areas one source was clearly predominent.

INTERPRETATION OF NITROGEN TRANSFORMATIONS NEAR SEWAGE TREATMENT PLANTS

A typical hydrograph for nitrate in groundwater near the Fresno Sewage Treatment Plant (Figure 4) shows a seasonal variation ranging from 20 to almost 45 parts per million. The highest nitrate contents in groundwater occur during the winery season of

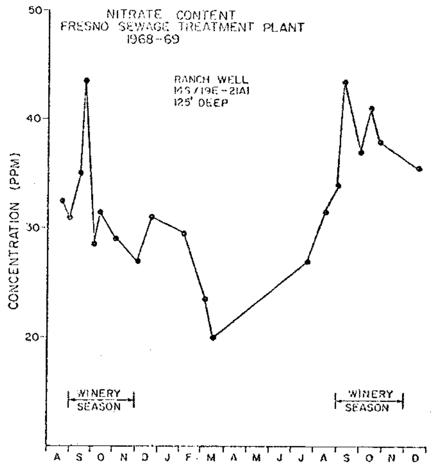


Figure 4

September 1 to December 1. High-nitrogen winery wastewaters during this period produce ammonia and nitrate-nitrogen contents of pond waters about four times greater than during the remainder of the year. However, wastewaters at this time have the highest biochemical oxygen demand for the entire year. As these waters rapidly utilize the available oxygen in the percolation ponds, little nitrification occurs. The nitrogen is retained in the soil in the organic and ammonia forms under these circumstances. Therefore, leached water is low in nitrate and concentrations in the groundwater decrease during this period.

Water lower in biochemical oxygen demand enters the percolation ponds following the winery season. More ponds are periodically dried out as wastewater diminishes in flow, and aerobic conditions develop beneath many ponds. However, nitrification does not proceed rapidly during the winter months, and nitrate contents in groundwater continue to decline. Nitrification proceeds rapidly with the warming temperature of spring and summer. Nitrate is formed and readily leached to the groundwater; thus nitrate contents increase during the summer to a peak in the fall. The peak nitrate contents in the groundwater for a specific year may be derived from nitrogen supplied during the previous winery season. Denitrification occurring under anaerobic conditions could also explain portions of the seasonal variation.

SUMMARY

One of the most troublesome problems in water quality studies concerns erroneous or atypical analyses. A measure of the accuracy of the sample can be determined by plotting chemical hydrographs for individual wells. If hydrographs are prepared and kept up to date, then analyses taken at any particular time can be rechecked when results deviate significantly from previous analyses.

Major changes in groundwater quality over a period of years and decades were documented by chemical hydrographs. Seasonal fluctuations in nitrate were consistent for many parts of the Fresno-Clovis Metropolitan Area and were related to hydrogeologic factors and parameters directly affecting nitrification. Chloride hydrographs were extremely valuable in a study of nitrate in groundwater. However, interpretation of the significance of chemical hydrographs can be difficult. Well deepening commonly results in lower nitrate contents of water pumped by wells. Similarly, changes in water level and pumping patterns, as well as recharge, produce changes in concentration of constituents over a period of years.

Nitrate and chloride hydrographs were used to help determine the source of nitrate in several areas where several possible sources were present. Nitrogen transformations in the vicinity of the Fresno Sewage Treatment Plant were clarified by interpretation of nitrate hydrographs for nearby wells. Seasonal fluctuations in nitrate were related to the nitrogen content of percolation pond water, the waste strength of these wastewaters, temperature effects, and pond operation.

REFERENCES

American Public Health Association, Inc., "Standard Methods for the Examination of Water and Wastewater," Twelfth Edition, 36-38, 1965.

California Department of Water Resources, "Fresno-Clovis Metropolitan Area Water Quality Investigation," Bulletin 143-3, 1965.

Engineering-Science, Inc., "Central Fresno County Water and Liquid Waste Program," Report for Fresno County, Contract No. Calif. P-308(G), 1970.

Hem, J. D., "Study and Interpretation of the Chemical Characteristics of Natural Water," U. S. Geological Survey Water-Supply Paper 1473, 186-188, 1959.

Malhotra, S. K., and Zanoni, A. E., "Chloride Interference in Nitrate Nitrogen Determinations," Journal AWWA, Sept., 1970, 568-571.

Schmidt, K. D., "The Distribution of Nitrate in Groundwater of the Fresno-Clovis Metropolitan Area," Unpublished Ph.D. dissertation, Hydrology Department, University of Arizona, 1971.

RENOVATING SEWAGE EFFLUENT BY GROUND-WATER RECHARGE

Herman Bouwer, J. C. Lance, and R. C. Rice

U. S. Water Conservation Laboratory, Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture, Phoenix, Arizona 85040

INTRODUCTION

Sewage effluent is commonly used for irrigation [Wilson and Beckett, 1968]. It contains enough nutrients (Table 1) to meet the fertilizer requirements of a number of crops if the sewage supplies all or most of the water for the crop. The most critical use of sewage effluent from a public health standpoint would be sprinkler irrigation of lettuce and other crops that are consumed raw. This requires a well treated effluent, usually consistent with the quality obtainable by secondary treatment and disinfection, to yield total coliform densities of less than 5000 per 100 ml and fecal coliform densities of less than 1000 per 100 ml [Water Quality Criteria, 1968; Wilson and Beckett, 1968]. In some cases, however, the requirements are much stricter. The State of California, for example, requires filtration of coagulated waste water through natural soil or filter media and disinfection to obtain total coliform concentration not exceeding 2.2 per 100 ml before the effluent can be used for sprinkler irrigation of produce. Less stringent requirements are generally used for effluent that is used for irrigation of nonedible crops or crops that are processed before they are consumed [Calif. Standards, 1968].

If more sewage water is applied than needed for crop growth, the excess water will move deeper into the ground to become "renovated" water, which can be allowed to move naturally to streams or lakes, or can be collected with wells or drains for rather unrestricted reuse. Sometimes, waste water renovation is the major objective of land disposal, and agricultural use of the disposal fields is of secondary importance, particularly if permeable soils are available so that large land areas are not required. Another objective of land disposal systems could be to keep the waste water out of streams or lakes, to reduce pollution of surface water.

Because of the increasing need for using sewage effluent for purposes with a higher economic return than irrigation of nonedible crops, interest in land application as a form of tertiary treatment is rapidly increasing. The waste water would then be used for ground-water recharge, employing basins, furrows, or sprinklers to infiltrate the water into the soil, and drains or wells to collect the renovated water for unrestricted irrigation, recreation, and industrial and municipal uses.

The performance of a system for renovating waste water by ground-water recharge depends on the local conditions of climate, soil, and ground water. An experimental project is, therefore, frequently desirable to obtain design information for the operational system so that renovated water with the desired quality can be obtained at minimum cost. An example of such a pilot facility is the Flushing Meadows Project near Phoenix, Arizona, which will be discussed in the following sections.

REUSE OF SEWAGE EFFLUENT IN THE SALT RIVER VALLEY

Most of the sewage effluent of the cities in the Salt River Valley is treated by the 91st Avenue Plant, which is an activated sludge plant handling sewage from Phoenix, Tempe, Scottsdale, Mesa, and Glendale. The plant discharges some 50 mgd of secondary effluent which may increase to about 250 mgd (about 300,000 acre-feet per year) by the year 2000. At 4.5 feet average annual water use, this could irrigate about 70,000 acres, which may be more than the agricultural land remaining in the Salt River Project at that time. The urban waste water would thus be sufficient to meet all agricultural demands in the not too distant future while leaving some for recreation and other purposes.

Because of the varied agriculture and the use of canal water for irrigation of parks, playgrounds, private yards, and for recreational lakes, large scale return of sewage effluent to the canal system requires that the effluent be given tertiary treatment. Since the hydrogeological conditions in the Salt River bed are favorable for ground-water recharge, the most economical way for renovating the sewage effluent could be by ground-water recharge with infiltration basins in the river bed. This bed is normally dry below Granite Reef dam (a diversion structure 25 miles east of Phoenix) and it attains a width of about one-half mile in the western part of the valley. The movement of the effluent water through the sands and gravels of the river bed could be expected to remove essentially all biodegradable materials and microorganisms, and to reduce the concentration of other substances in the effluent. This would yield a renovated water suitable for unrestricted irrigation, primary-contact recreation, and other purposes.

To study the feasibility of renovating sewage effluent by ground-water recharge, an experimental project, called the Flushing Meadows Project, was installed in 1967. The project is located in the Salt River bed about 1 1/2 miles west of 91st Avenue. It is a cooperative effort between the U. S. Water Conservation Laboratory of the U. S. Department of Agriculture and the Salt

River Project, and it was partially supported by a grant from the Federal Water Quality Administration.

FLUSHING MEADOWS PROJECT

Description of System.

The project contains six parallel recharge basins, 20 x 700 ft each and spaced 20 ft apart (Fig. 1). Secondary effluent is pumped from the discharge channel of the 91st Avenue treatment plant into the basins at one end where the flow is controlled by an alfalfa valve and measured with a triangular, critical depth flume [Replogle, 1969]. The water depth in each basin is controlled by an overflow structure at the other end, where the outflow is measured with another flume. Water depths of 0.5 and 1 ft have been used. The infiltration rate for each basin is calculated from the difference between the inflow and the outflow rates.

The soil beneath the basins consists of about 3 ft of fine, loamy sand underlain by a succession of coarse sand and gravel layers to a depth of 240 ft where a clay deposit begins. The original saturated hydraulic conductivity of the fine, loamy sand top layer was about 4 ft/day. The underlying sand and gravel layers, which have been described in detail [Bouwer, 1970], can be considered as one anisotropic medium. The hydraulic conductivity of this medium is 282 ft/day horizontally and 17.6 ft/day vertically. These values were obtained by electrical analog analysis and confirmed by permeability tests on the observation wells in the project area [Bouwer, 1970]. The static ground-water table is at a depth of about 10 ft. Observation wells consisting of 6-inch diameter cased holes open at the bottom were installed at various locations in the project area (Fig. 1). These wells, which range from 20 to 100 ft deep, are used to obtain samples of the reclaimed water for chemical and bacteriological analyses and to measure the response of the ground-water level to ground-water recharge.

In conformance with the theory of ground-water-mound formation below infiltration basins [Bouwer, 1962], the ground-water level rises rapidly after the start of a new inundation period, but reaches a pseudo-equilibrium level in a few days. When a dry-up period is started, the ground-water levels recede and reach their original levels in a few days. Because of the high hydraulic conductivity in horizontal direction of the aquifer, the height of the ground-water mound during recharge is relatively low, i.e., 1.09 ft per 1 ft/day infiltration rate.

Infiltration Rates.

To evaluate the effect of surface condition of the basins on infiltration rate, one basin was covered with a gravel layer, another was left in bare soil, and the four remaining basins were planted with bermudagrass in 1968. Inundation schedules ranged from 2 days wet and 3 days dry to 3 weeks wet and 3 weeks dry (periodic drying of the basins is necessary to restore infiltration rates and to allow oxygen to enter the soil). The infiltration rates were generally between 1 and 4 ft/day, depending on the water depth, the suspended solids content of the effluent, and the length of the inundation and dry-up periods. During inundation, the infiltration rate usually decreased almost linearly with time. Tensiometer measurements in the soil beneath the basins and measurements of the effect of water depth in the basins on the infiltration rate indicated that the decrease in infiltration during inundation was mostly caused by clogging at the soil surface.

After accounting for the soil variability between the basins, the infiltration in the grass basins was about 20% higher, and in the gravel-covered basin

50% lower, than in the bare soil basin [Bouwer, 1970]. The higher infiltration rates in the grass basins were attributed mainly to the prevention of algal growth on the bottom of the basins. The low infiltration rate in the gravel basin was probably caused by poor drying of the soil beneath the gravel with consequent slow recovery of the infiltration rate.

Maximum hydraulic loading or long-term infiltration was obtained with inundation periods of about 2 weeks and dry-up periods of about 10 days in the summer and 20 days in the winter. With this schedule, the average accumulated infiltration for the year 1970 was 400 ft. Thus, one acre of recharge basin can renovate 400 acre-feet per year, or 0.36 mgd.

Quality Improvement of Water.

The East Center Well (ECW, Fig. 1) is 30 ft deep. Water pumped from this well has traveled vertically about 8 ft from the basin bottom to the ground water table, and 22 ft from the water table to the bottom of the well. Since the well is located midway between basins 3 and 4, the water has also traveled about 10 ft horizontally. The time required for this travel ranged from 1 to 2 weeks, depending on the infiltration rate. Quality parameters of the water from this well, which receives reclaimed sewage water that has infiltrated in basins 3 and 4, and of the reclaimed water from the 20-ft-deep wells 1 and 7 outside the basin area (Fig. 1) are shown in Table 2 in relation to the quality of the sewage effluent (see also [Bouwer, 1970]).

Oxygen Demand. The data in Table 2 show that the 5-day BOD of the reclaimed water is essentially zero. The chemical oxygen demand (COD) is reduced from 50 to 17 ppm, which is about the same as the COD of the native ground water.

Nitrogen. The nitrogen in the effluent is almost all in the ammonium form. This is mostly converted to nitrate in the reclaimed water if sequences of short inundation periods (2 days wet - 3 days dry) are used. With longer inundation periods (2 weeks wet - 2 weeks dry), nitrate nitrogen concentrations in the reclaimed water are much lower (Table 2), with those below the grass basins being lower than those below the nonvegetated basins. In 1968, for example, the NO_3-N concentration in ECW-water during sequences of long inundation periods dropped from about 10 ppm to about 0.2 ppm after the bermudagrass had reached maturity in basins 3 and 4, but the NO_3-N concentrations in the water from well 1-2, which had infiltrated in the nonvegetated basins 1 and 2, remained in the 5- to 10-ppm range.

The dependence of the NO_3-N concentration in the reclaimed water on the length of the inundation period is illustrated in Fig. 2, which shows that for the short inundation periods in July and August 1968 the NO_3-N concentration was about 21 ppm. For the long inundation periods for the rest of the year and with full grass cover in basins 3 and 4, NO_3-N concentrations were close to zero after the passage of a NO_3-peak. This peak, which always occurred a few days after the start of a new inundation period when sequences of long inundations were held, is due to the arrival of nitrified sewage water that was held as capillary water in the soil during the preceding dry-up period. Also, nitrate may have been formed by nitrification of ammonium held by the exchange complex in the soil. The NO_3-peak arrived in ECW from 5 to 11 days after the start of an inundation period, depending on the infiltration rate in the basins. Thus, the underground detention time of the water pumped from ECW is in the

5- to 11-day range. At greater distances from the recharge basins, the peaks become less distinct.

The NH_4-N content of the reclaimed water usually ranges from 5 to 15 ppm and apparently is not much affected by the length of the inundation periods used at the Flushing Meadows Project. Thus, before and after the passage of the NO_3-peak, the total nitrogen in the reclaimed water during long inundation periods in the vegetated basins is about 40 to 80% less than that in effluent.

The nitrogen behavior in the renovated water is probably due to adsorption of ammonium by the clay and organic matter in the soil, which could begin after the start of an inundation period when oxygen for nitrification is no longer available. Before the adsorption capacity for ammonium is reached, the basins should be dried. The presence of oxygen in the soil will then cause nitrification of the adsorbed ammonium. Part of the nitrates formed in this process can subsequently be denitrified, either during dry-up or during the next inundation, with the nitrogen gas escaping to the atmosphere or moving out as dissolved nitrogen with the downward moving water. Storage of nitrogen in the soil was small and could not account for the amounts of nitrogen removed from the sewage water.

Phosphates. Phosphorus, which occurs mainly in the form of orthophosphates in the effluent, is reduced from about 13 ppm P in the effluent to about 5 ppm P in the reclaimed water from ECW (Table 2). Further reductions in P-content occur with additional lateral movement of the reclaimed water below the water table (see P-contents for wells 1 and 7 in Table 2). Extrapolation of the P-removal in relation to distance of underground travel shows that at a distance of about 100 to 200 ft from the recharge basins, very small P concentrations can be expected.

In the sandy and gravelly materials of the Flushing Meadows Project, P probably is removed by precipitation of calcium-phosphate complexes such as apatite. Assuming that all P is precipitated as apatite in a soil volume 30 ft deep and 4 times as wide as the width of the recharge area, the apatite would occupy 0.5% of the total volume after a period of 200 years. Assuming a porosity of 20%, the apatite would thus take up about 2.5% of the pore space. This is small and will likely not have a significant effect on the hydraulic conductivity of the aquifer. If the soil is rich in iron and aluminum oxides, high rates of P-removal can be expected over shallow depths of soil [Kardos, 1967; Taylor, 1967].

Fluorides. The removal of fluorides also continues as the water moves laterally below the water table, as indicated by the lower F-concentrations in wells 1 and 7 than in ECW, which in turn contains about half as much fluorides as the effluent (Table 2). Fluorides may be adsorbed on clay minerals [Bower and Hatcher, 1967] or be precipitated as fluor-apatites or calcium fluoride.

Boron. The boron concentration is about 0.7 ppm and remains unchanged as the water moves downward through the soil and laterally below the water table (Table 2). Thus the sands and gravels appear to contain few aluminum and iron oxides, which are effective in removing boron [Sims and Bingham, 1968]. Boron concentrations above 0.5 ppm in irrigation water can be damaging to some of the more sensitive crops such as citrus, stone and pome fruits.

Salts and pH. The average salt concentration of the reclaimed water is 1060 ppm, which is about 4% higher than that of the sewage effluent (Table 2). This can be attributed to evaporation from the water in the recharge basins (average annual evaporation from a free water surface in the Phoenix area is about 6 ft). The pH of the reclaimed water is somewhat lower than that of the sewage effluent (Table 1), probably because of CO_2 production by the soil bacteria.

Coliform Density. The total coliform density in the reclaimed water from ECW, determined weekly with the multiple-tube fermentation technique, was higher during sequences of inundation periods of 2-3 weeks than during inundation periods of 2-3 days, i.e., median MPN-values were about 200 per 100 ml for the long periods and 5 per 100 ml for the short periods.

The fecal coliform density in the reclaimed water was very low and often zero (Table 2). The number of fecal coliforms tended to increase somewhat after the start of a new inundation period when newly infiltrated water had arrived at the bottom of the well. The same trend was true for the presumptive MPN of coliforms, which sometimes reached a value of several hundred per 100 ml. After the end of an inundation period, the presumptive MPN of coliforms in the ECW water generally decreased and reached a value of close to zero in about 3 weeks. Therefore, it is concluded that an additional underground detention time of about 1 month should be sufficient for essentially complete removal of all coliform organisms. Regrowth of nonfecal coliforms, such as Aerobacter aerogenes in sewage water as it moves through the ground has sometimes been observed [McMichael and McKee, 1965].

Economic Aspects and Large-Scale System.

The cost of reclaiming water from sewage effluent or other liquid waste by soil percolation and ground-water recharge depends on the climate and on the topographic and hydrogeologic conditions. On flat land, the effluent may be applied by basins or furrows. On sloping land, contour furrows or sprinkler systems may be used. Where the infiltration rates are low, large land areas may be required and it may be more economical to combine the recharge system with agricultural utilization of the land [Bouwer, 1968; Kardos, 1967; and references therein].

The design of ground-water recharge systems for waste-water reclamation should be based on three criteria: (a) avoiding a rise of the ground-water table below the recharge basins above a certain maximum elevation, (b) locating the facilities for collecting the reclaimed water (wells, drains, or trenches) a certain distance from the recharge areas to allow sufficient time and distance of underground travel for the reclaimed water, and (c) minimizing the spread of reclaimed water into the aquifer outside the recharge system. For a more detailed discussion of the design of recharge systems for renovating waste water and of techniques for evaluating hydraulic properties of aquifers and predicting water table positions and underground detention times, reference is made to [Bouwer, 1970].

For the Salt River bed, recharge basins could be located on both sides of the river bed (Fig. 3). The distance between the two recharge strips would be about 1000 ft. Wells for pumping the reclaimed water could be placed in the center of the river bed, thus insuring a minimum underground travel distance of about 500 ft for the renovated water. With an annual infiltration of about 330 ft in the basins, about 900 acres of recharge basins would be required to renovate the annual volume of 300,000 acre-feet of sewage water expected by the year 2000. The cost of reclaiming the sewage water in this manner is expected to be about $5 per acre-foot, including amortization of capital investment and operating and pumping costs. The cost of in-plant tertiary treatment to obtain reclaimed water of similar quality would be at least ten times as much [Bouwer, 1968, and references therein].

SUMMARY

Due to continued population growth in the Salt River Valley, Arizona, reuse of municipal waste water becomes essential. A pilot project was installed in 1967 to determine if the tertiary treatment necessary to permit large-scale reuse of sewage water for irrigation and recreation could be obtained effectively and economically by ground-water recharge with infiltration basins in the normally dry Salt River bed. The hydrogeological conditions of the Salt River bed, i.e., about 3 ft of fine, loamy sand underlain by sand and gravel layers to great depth and a ground-water table at about 10 ft depth, are favorable for high-rate waste water reclamation by ground-water recharge. Results so far indicate that the infiltration rate in grass-covered basins is 25% higher, and in a gravel-covered basin 50% lower, than in a bare soil basin. Alternating 2-week inundation periods with 10-day dry-up periods (17 days in winter) yields an annual infiltration rate of about 400 ft.

Reclaimed water, pumped from 30 ft depth in the center of the recharge area, has a biochemical oxygen demand of about 0.5 mg/liter (BOD of the sewage effluent is about 15 mg/liter) and a median fecal coliform density of 10 per 100 ml. Nitrogen, which is almost all in the ammonium form at a concentration of 25 ppm N in the sewage effluent, is essentially all converted to the nitrate form in the reclaimed water if sequences of short inundation periods (3 days or less) are held. With inundation periods of 2 to 3 weeks, the reclaimed water has about 40 to 80 percent less nitrogen than the sewage effluent, except for a short period occurring 1 to 2 weeks after the start of a new inundation, when

a nitrate peak occurs in the reclaimed water. This peak is due to the arrival of nitrified effluent water held as capillary water in the soil during the preceding dry-up period. The nitrogen removal is probably mostly due to denitrification and adsorption of ammonium in the soil. More nitrogen was removed under vegetated infiltration basins than under nonvegetated basins.

Phosphate concentrations in the reclaimed water pumped from 30-ft depth in the center of the recharge area are around 5 ppm P, as compared to 13 ppm in the effluent. Further horizontal movement of the reclaimed water below the water table gives additional reduction in the phosphate content, as indicated by the concentration of 1.5 ppm P in the water pumped at 100 ft distance from the infiltration basins. Fluorides are reduced from 4.5 ppm in the effluent to 2.5 ppm at 3-ft depth in the center of the area and to 1.9 ppm at 100 ft from the basins. Boron removal does not take place because the sands and gravels contain little or no iron or aluminum oxides. The boron concentration is around 0.7 ppm, however, which is slightly above the level where the yield of the more sensitive crops will be affected when the water is used for irrigation.

To reclaim the sewage flow of about 300,000 acre-feet per year that is expected in the Phoenix area by the year 2000, about 900 acres of infiltration basins would be required. These basins could be located on both sides of the Salt River bed. The reclaimed water would be pumped up by wells in the center of the river bed. The minimum underground travel distance and detention time would be about 500 ft and 1 month, respectively. Cost of reclaiming water in this manner would be about $5 per acre-foot, which is less than one-tenth the cost of equivalent, in-plant tertiary treatment.

REFERENCES

Bouwer, Herman, "Analyzing Ground-Water Mounds by Resistance Network," Journal, Irrigation and Drainage Division, American Society of Civil Engineers, 88(IR 3), 1962, pp. 15-36.

Bouwer, Herman, "Returning Wastes to the Land -- A New Role for Agriculture," Journal, Soil and Water Conservation, 23, 1968, pp. 164-168.

Bouwer, Herman, "Ground-Water Recharge Design for Renovating Waste Water," Journal, Sanitary Engineering Division, Proceedings, American Society of Civil Engineers, 96(SA 1), 1970, pp. 59-74.

Bouwer, Herman, "Water Quality Aspects of Intermittent Systems Using Secondary Sewage Effluent," Paper No. 8, Artificial Ground-Water Recharge Conference, University of Reading, England, sponsored by Water Research Association, 21-24 September 1970.

Bower, C. A., and Hatcher, J. R., "Adsorption of Fluoride by Soil and Minerals," Soil Science, 103, 1967, pp. 151-154.

California Department of Water Resources, "Feasibility of Reclamation of Water from Wastes in the Los Angeles Metropolitan Area," Bul. 80, California Department of Water Resources, Sacramento, 1961.

California Statewide Standards for Safe Direct Use of Reclaimed Waste Water for Irrigation and Recreational Impoundments. Calif. Adm. Code, Title 17, Chapter 5, 1968.

Kardos, L. T., "Waste Water Renovation by the Land - A Living Filter," In Agriculture and the Quality of our Environment, N. C. Brady, editor, Publication 85, American Association for the Advancement of Science, Washington, D. C., 1967.

McMichael, F. C., and McKee, J. E., "Research on Waste Water Reclamation at Whittier Narrows," W. M. Keck Laboratory of Environmental Health Engineering, California Institute of Technology, Pasadena, 1965.

Replogle, J. A., "Flow Measurement with Critical Depth Flumes," International Commission on Irrigation and Drainage, Proceedings, 7th Congress, Mexico City, Question 24, R15, 1969, pp. 215-235.

Sims, J. R., and Bingham, F. T., "Retention of Boron by Layer Silicates, Sesquioxides, and Soil Materials: II. Sesquioxides," Proceedings, Soil Science Society of America, 32, 1968, pp. 364-369.

Taylor, A. W., "Phosphorus and Water Pollution," Journal, Soil and Water Conservation, 22, 1967, pp. 228-242.

Water Quality Criteria. Report of Nat. Techn. Adv. Comm. to Secretary of Interior. Federal Water Quality Administration, April 1, 1968, Washington, D. C.

Wilson, C. W., and Beckett, F. E., Edtrs., Municipal Sewage Effluent for Irrigation. Louisiana Polytechnic Institute, Ruston, July, 1968.

Table 1. Normal range of mineral increase in water by one cycle of domestic use [Calif. Dept. of Water Resources, 1961].

	Parts per Million	Pounds per Acre-foot
Total salts	100-300	270-820
Boron (B)	0.1-0.4	0.3-1.1
Sodium (Na)	40-70	110-190
Potassium (K)	7-15	19-41
Magnesium (Mg)	3-6	8-16
Calcium (Ca)	6-16	16-44
Total nitrogen (N)	20-40	55-110
Phosphate (PO_4)	20-40	55-110
Sulphate (SO_4)	15-30	41-82
Chloride (Cl)	20-50	55-140
Alkalinity (as $CaCO_3$)	100-150	270-410

Table 2. Chemical and bacteriological parameters (average values) of secondary effluent and reclaimed sewage water from observation wells (in milligrams/liter, except for pH and coliform density).

(1)	Effluent (2)	ECW (3)	Well No. 1 (4)	Well No. 7 (5)
BOD_5	15	0.3		
COD	50	17	14	14
Organic N	1	trace		
NH_4-N	25	10	3	1
NO_3-N	0.1			
short inundations		15		
long inundations (bare)[a]		9		
long inundations (grass)[b]		0.2		
PO_4-P	13	5	1.5	1.5
F	4.5	2.5	1.7	2.1
B	0.7	0.7	0.7	0.7
Dissolved salts	1020	1060		
pH	7.9	7.2	7.7	7.4
Fecal coliforms (MPN/100 milliliters)	10^6	20[c]		10[c]

a - reclaimed water below bare-soil basins

b - reclaimed water below grass-covered basins

c - median value (range 0-100)

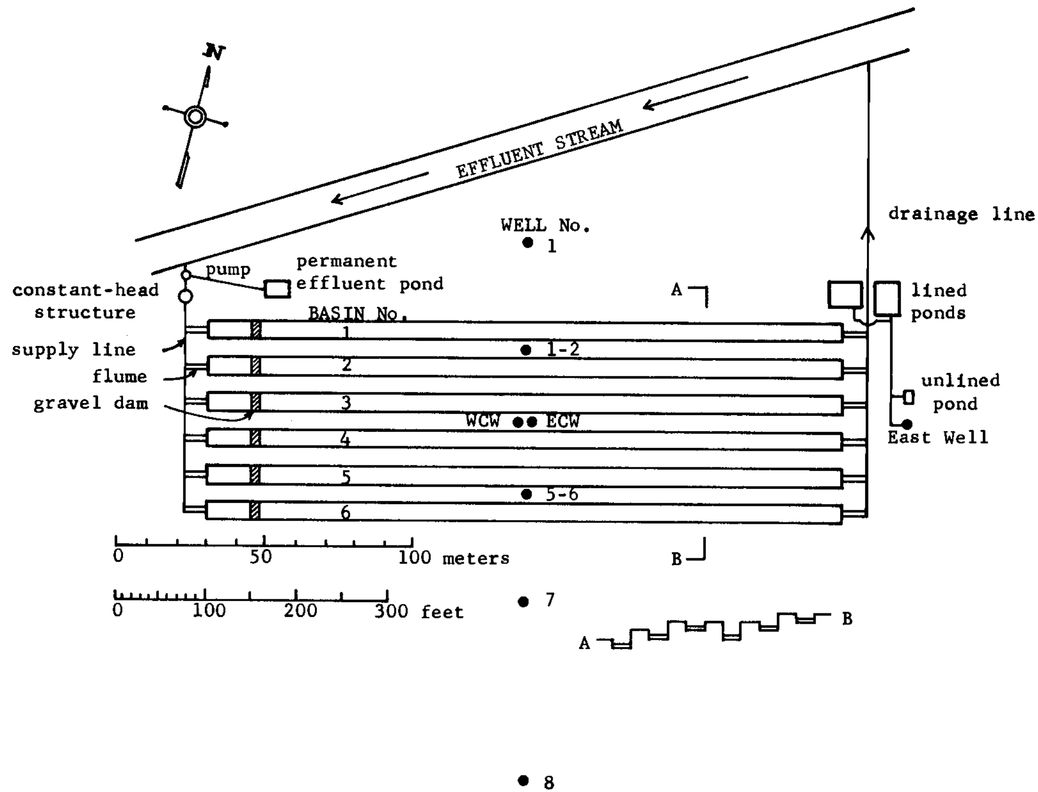


Fig. 1. Plan of Flushing Meadows Project.

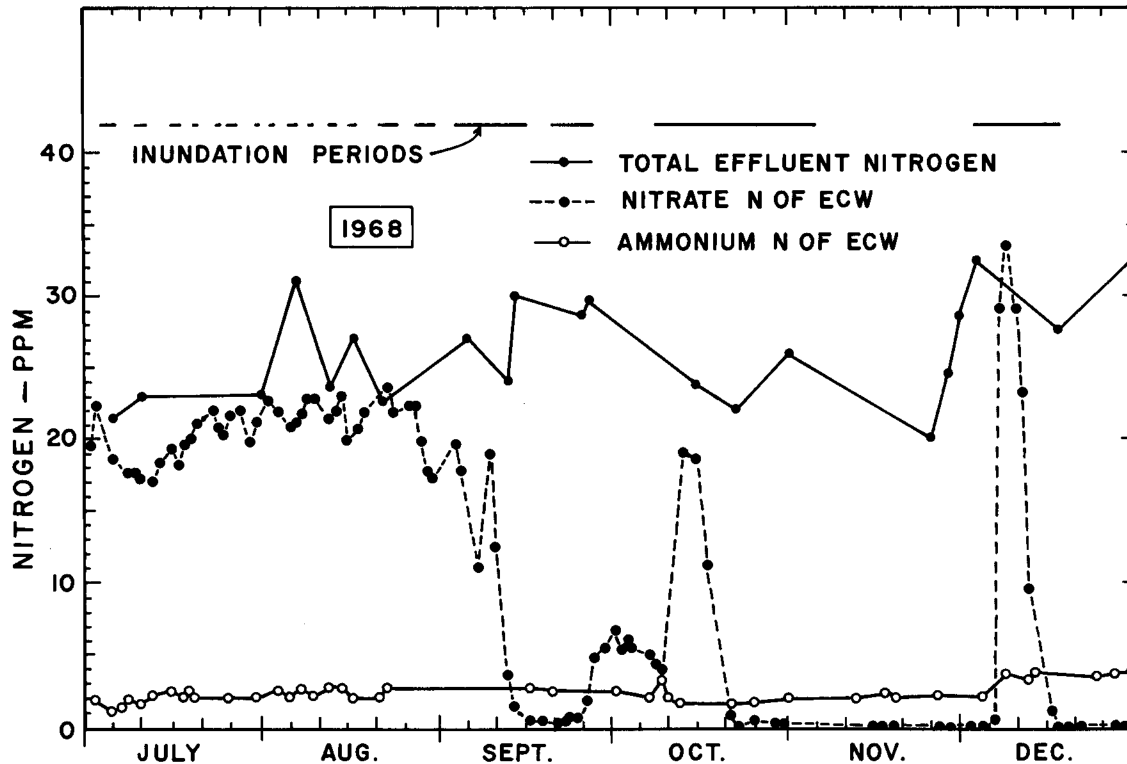


Fig. 2. Total nitrogen in sewage effluent and nitrate and ammonium nitrogen in reclaimed water from East Center Well in relation to inundation schedule (July-December 1968).

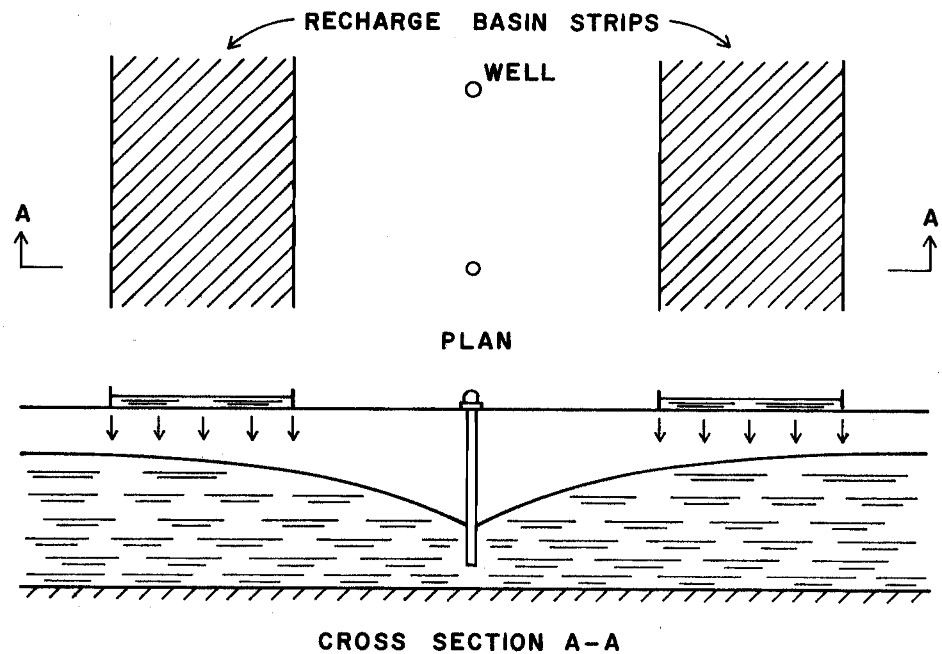


Fig. 3. Plan and cross section of two parallel recharge strips with wells midway between strips.

RECHARGING THE OGALLALA FORMATION USING SHALLOW HOLES

M. J. DVORACEK

Hydrology & Water Resources, University of Arizona

S. H. PETERSON

Agricultural Engineering Department, Texas Tech University

INTRODUCTION

The Ogallala aquifer, an immense unconfined aquifer underlying parts of Texas, New Mexico, Oklahoma, Colorado, and Kansas, has been the scene for many artificial recharge studies. The extent of the Ogallala can best be visualized from Figure 1. The primary reason for the multitude of efforts, particularily in the High Plains of Texas, is the existing evidence that natural recharge will not sustain the aquifer in this geographical area. Virtually all the water used in this region is derived from the Ogallala and this can best be illustrated by the statistic, irrigation wells within the High Plains of Texas. In 1970, there were 65,214 wells supplying water for the irrigation of 5.5 million acres [*New*, 1970].

The southern bed of the Ogallala is hydrologically isolated from all outside areas of recharge requiring all natural recharge in this area to originate from precipitation falling on the lands immediately above the aquifer. Figure 2 illustrates this isolation showing the Pecos and Canadian river canyons and the eastern escarpment. Since the Southern High Plains is considered a simi-arid region with limited and highly erratic rainfall, poorly

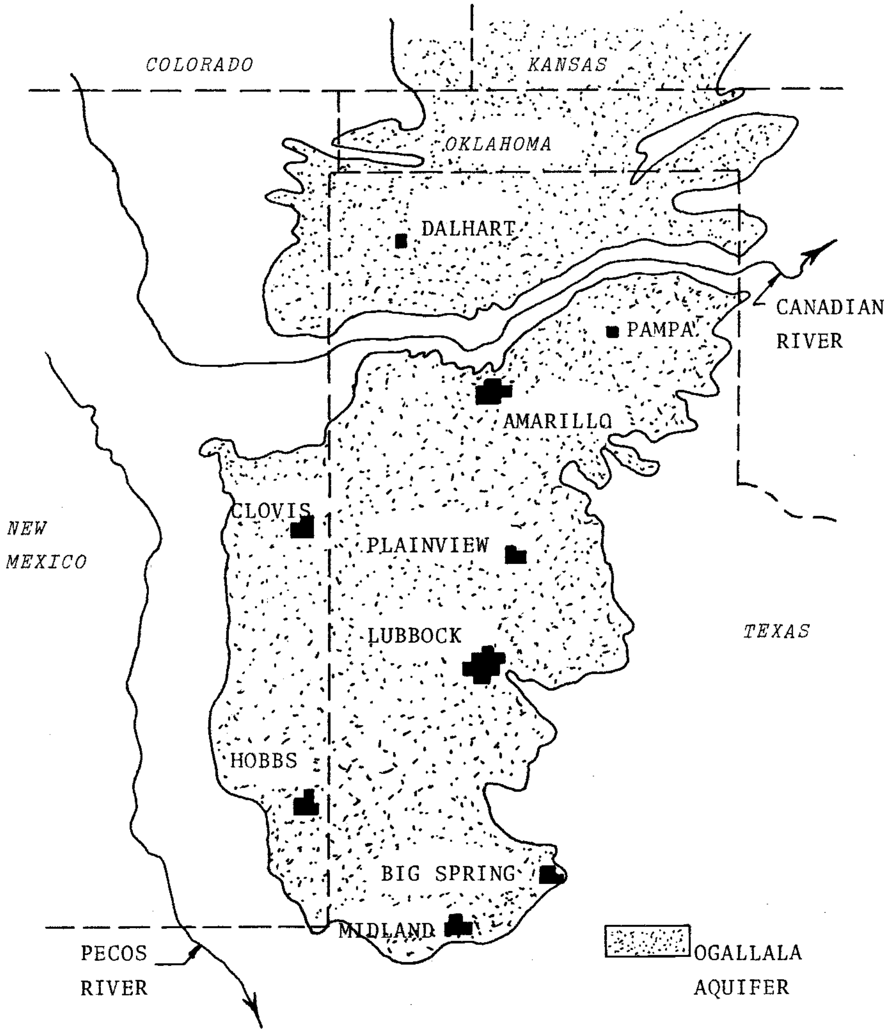


Figure 1. Location map of the Ogallala aquifer in the Texas High Plains.

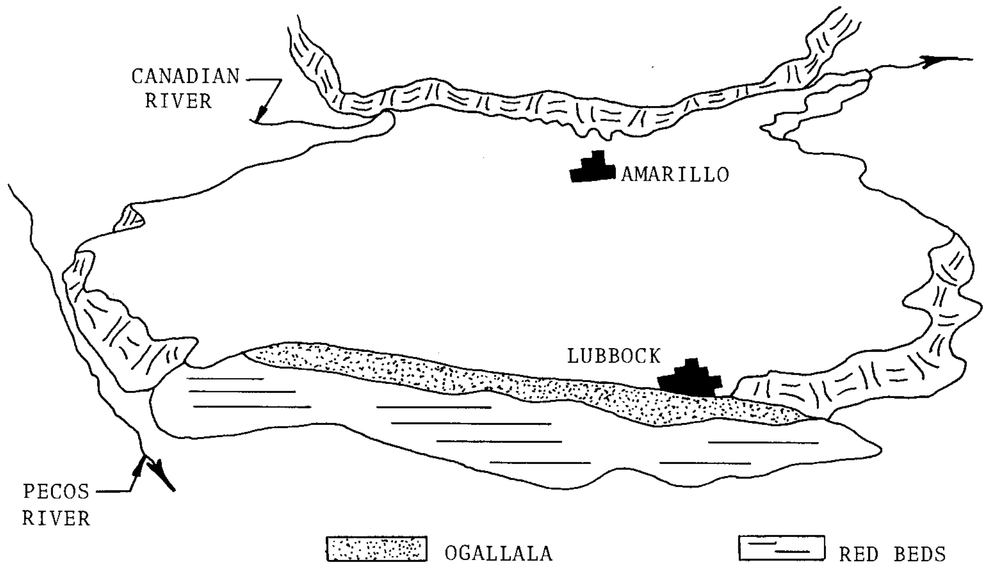


Figure 2. Three-dimensional sketch of the Southern High Plains showing the aquifers hydrologic isolation.

established drainage nets, and limited lakes and reservoirs, there exists only a limited opportunity for natural recharge.

The actual volume of natural recharge has been estimated by several reports and investigations [*Cronin*, 1969; *Havens*, 1966] as less than a 1-inch increase in water level elevation per year. Contrasting this with the volume of water withdrawn manifast in water level declines of 2-3 feet, it can be seen that withdrawal is many times greater than estimated natural recharge [*Signor*, 1968; *The Texas Water Plan*, 1968]. In order to preserve the economic utility of the aquifer, it appears that artificial recharge affords the only means of establishing at least a pseudo-balance between withdrawals and the natural recharge into the Ogallala.

DEVELOPMENT

Artificial groundwater recharge efforts utilize various methods which include multiple-purpose wells, shafts, pits, trenches, spreading, and modifications of these methods. All of these methods have been subject to research and investigations by various federal, state, and private research organizations [*Clyma*, 1966; *Dvoracek*, 1964-65; *Dvoracek and Peterson*, 1970; *Dvoracek and Wheaton*, 1968; *Dvoracek and Wheaton*, 1969; *Hauser*, 1967; *Signor*, 1968 (Sep); *Signor*, 1968 (Dec), *Valliant*, 1962]. All of the efforts have experienced success in at least an isolated area, however, not one method has been deemed regionally successful. The prime reason for this failure is the extreme heterogenity or variability which exists within the aquifer itself.

During the course of one recent investigation, a rather unique way of recharging the Ogallala was found. In January, 1969, a network of ten 5-inch observation wells were being installed in the Groundwater Recharge area on the Texas Tech University farm. At one of the proposed well sites, the well driller, using the hydraulic-rotary method, lost circulation at a depth of approximately 30 feet. Being unable to reestablish circulation at this site, the site was abandoned and a new site 5 feet south was selected. At approximately the 40 foot depth, loss of circulation was again experienced. Moving to a new location 50 feet south of the second site, an observation well was drilled to a depth of 150 feet. Figure 3 shows the location of the holes and the entire recharge area.

Due to a lack of water for recharge at this time, the holes were capped to maintain their initial condition. In early May, 1969, surface runoff water became available and an initial attempt to recharge through the holes used a 2-inch plastic tube inserted to the bottom of the first hole. The size of the pipe was inadequate to permit filling the hole with water. To permit increases in the recharge rates and also to prevent collapse of the hole, a 30 foot joint of 4-inch aluminum irrigation pipe was placed in the hole as shown in Figure 4. Water was pumped into the hole and permitted to freefall into the hole. During this period of recharge, the second hole experienced a cave-in at a point below the surface.

RESULTS

The initial recharge for a period of 12 days in early May, 1969 was 2.5 acre-feet of water at rates ranging from 120 gpm at the start of recharge to 60 gpm at the termination of the period. The 120 gpm rate was relatively short, approximately 1 day, after which the 60 gpm rate was relatively constant. The recharge period was broken for short periods due to maintenance of equipment.

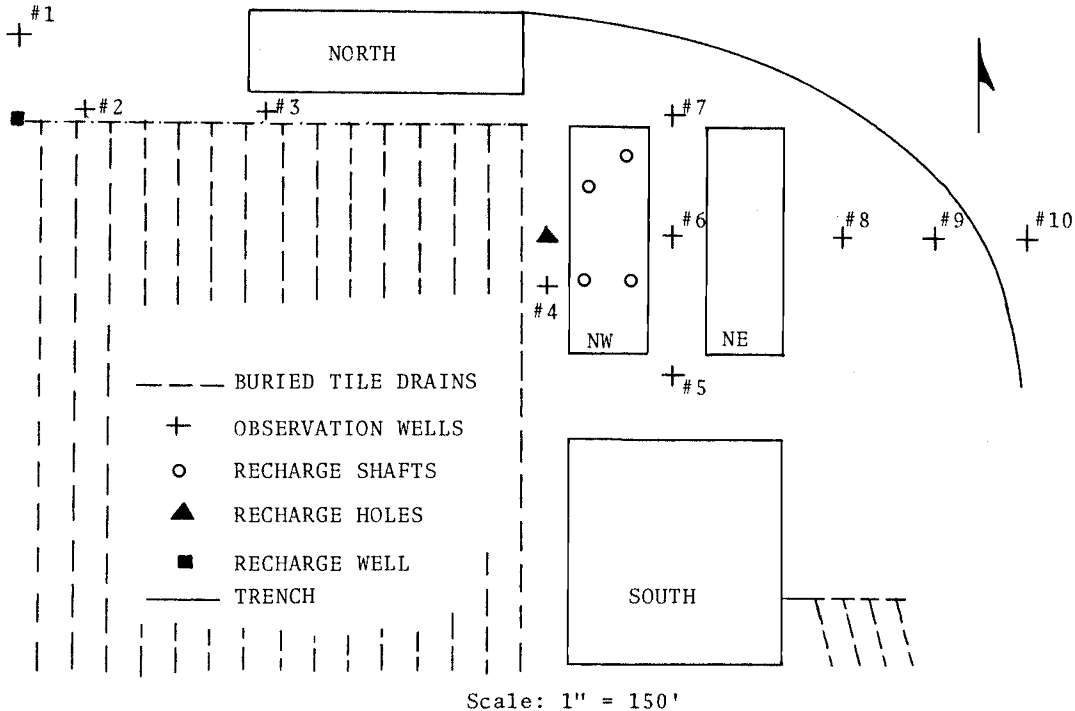


Figure 3. Topographic map of the Agricultural Engineering Department, Texas Tech University recharge area.

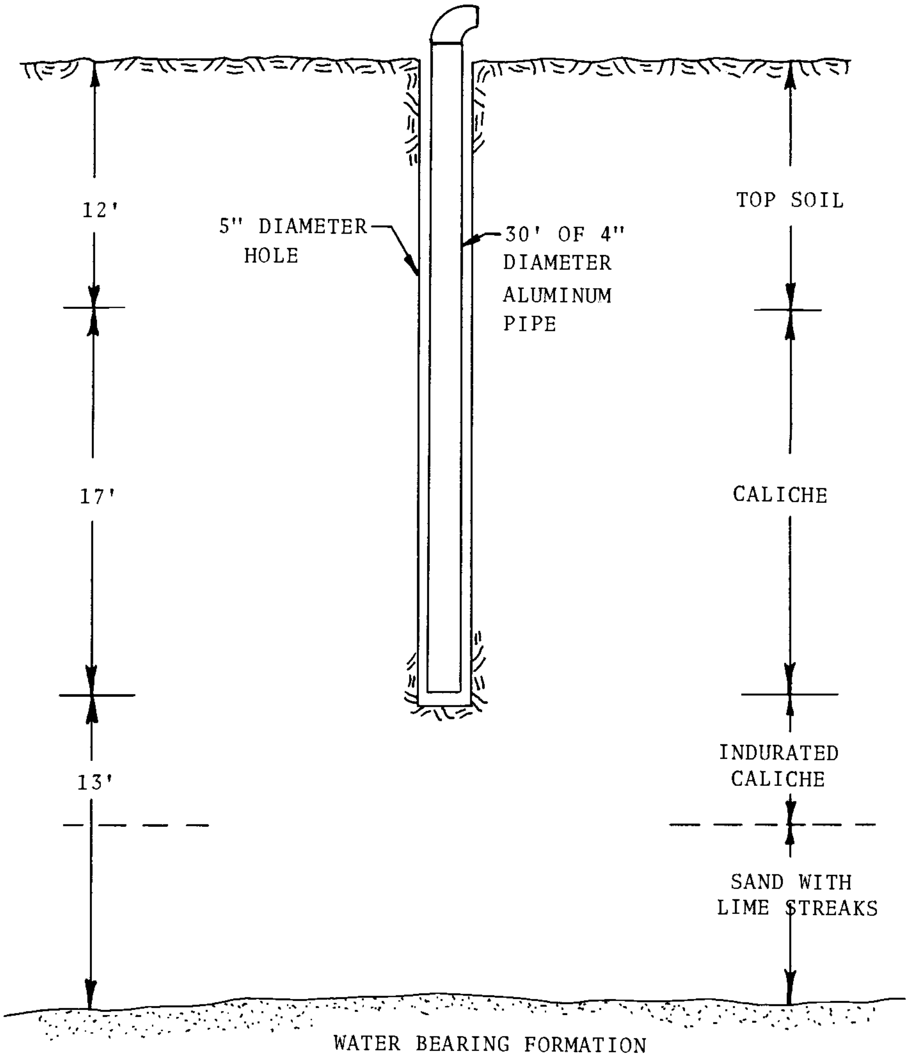


Figure 4. Schematic of the initial hole recharge facility.

Approximately 1 month later, a second test was conducted covering a period of 3 days and a total recharge of 1.2 acre-feet. A decline in rate from 140 gpm to 90 gpm was observed and a water level increase of 3.9 feet was observed in observation well no. 4. It became evident during this attempt that a cavity was present at the bottom of the hole being recharged. The cavity size was estimated to have a volume of approximately 60 cubic feet. A cavity of sufficient size to include both holes was found to exist at the relatively shallow depth of 4 feet.

Ten days after the second test, recharge was again practiced. A slight increase in rate of recharge was observed with rates ranging from 140 gpm to 100 gpm. During a 4 day period, 2.1 acre-feet were recharged to the formation resulting in a 4.7 foot rise in water level elevation in observation well no. 4. Two months passed before the water level returned to its original position.

Approximately 2 months of extremely dry conditions preceded the next recharge in late August, 1969. This period permitted the most extensive recharge period as 4.4 acre-feet were recharged with the rate ranging from 160 to 120 gpm. After 12 days, the water level in observation well no. 4 had risen 11.1 feet. All other wells in the observation well network exhibited water level increases approximately proportional to their distance from point of recharge. All of the increase could not be attributed to hole recharge as pits and a multiple-purpose well were also recharging during this period. Therefore the decay of groundwater could not be monitored as desired. An 8 day recharge period was possible in mid-September, 1969 permitting recharge of 2.7 acre-feet through the hole with a corresponding net increase in water level of 11.2 feet in well no. 4. The rates were consistent with those of the previous period. During the period between August 26 - September 26, the water level rise in well no. 4 amounted to over 22 feet.

In late October, 1969, 1.1 acre-feet were recharged with the rate increasing to a high of 170 gpm reducing to 120 gpm. Evidence supported the contention that an increase in the size of the bottom cavity had occurred. The upper cavity also reached proportions making a structural failure of the surface imminent. Excavation of a 1 foot thick surface layer exposed an irregular cavity approximately 8 X 4 X 5 feet in dimension. To prevent further cavitation at the surface, a 1-foot diameter pipe was inserted around the hole and anchored into the hard caliche layer.

An instrument was developed to permit photographing the cavity. After many attempts, a sufficient number of photos were obtained to allow for the preparation of a representative mosaic. Analysis of the mosaic indicated a southeast direction and an upward dip of 40 degrees existed. The depth of the cavity at the terminus of the hole is approximately 3 feet with a total length of 12 feet. Figure 5 represents a schematic of the cavity and location of both holes.

In February, 1970, the second hole was re-excavated with a hand auger and cased similar to the first hole. This hole did not appear to pass through the cavity of the first but did appear to possess a cavity 5 feet below the first. This however remains unconfirmed as the hole was to small to permit passage of the photographic equipment.

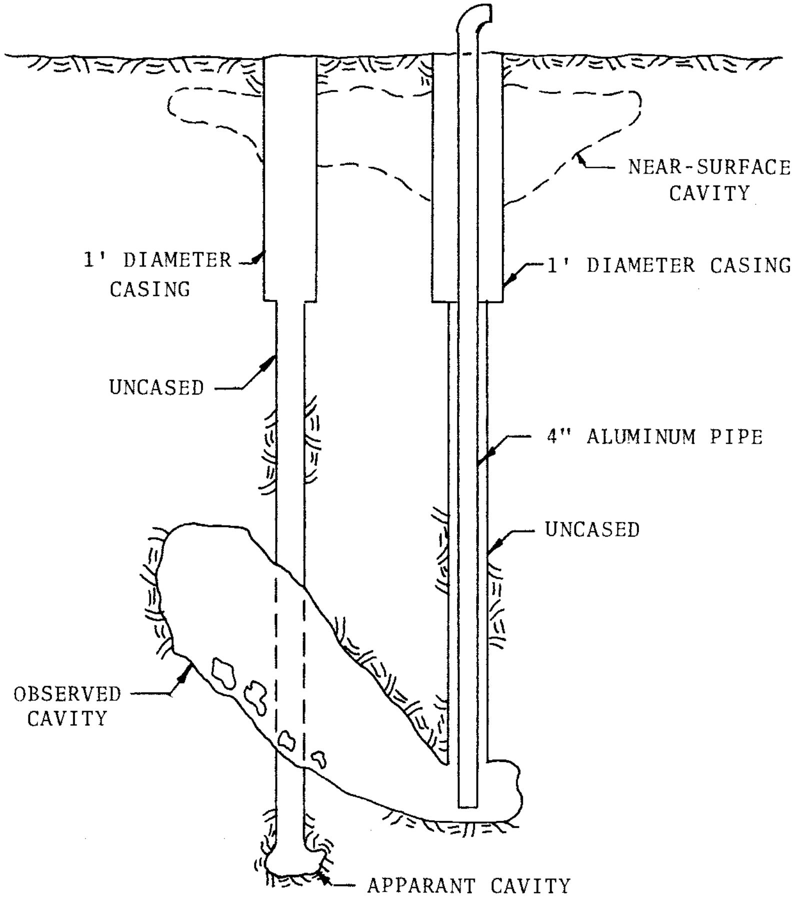


Figure 5. Schematic of cavity at base of hole, March, 1970.

The initial recharge period in 1970 and after re-excavation of the second hole was of relatively short duration. One observation significant to note was the reduction in recharge rates to 140 gpm maximum with a sustained rate of 100 gpm. The reason for the decline is attributed to the clay material which fell into the cavities during redrilling. A recharge period in early April, 1970 presented a tremendous increase in the initial rate, 220 gpm, with a sustaining rate of 120 gpm. Apparently a shift in materials occurred during the previous period and this was supported by photographs of the cavity after this recharge period.

Another significant period of recharge occurred during mid May, 1970. The initial rate of recharge was 260 gpm with a sustained rate of 155 pgm. During this 26 day period of recharge (May 13 - June 9), a total of 12.7 acre-feet were recharged into the formation. Water levels were significantly raised due to this extended recharge period. Photographs of the cavity revealed further enlargement and displacements within the cavity.

Table I summarizes the recharge efforts within the small diameter hole. As can be noted, rates varied as well as water levels however both are quite significant for the various recharge periods. It should also be noted that all recharge was accomplished using surface runoff waters characteristically high in sediment content.

SUMMARY AND CONCLUSIONS

During the past two years more than 28 acre-feet of surface runoff water have been recharged through the shallow hole with increases in recharge

TABLE I - HOLE RECHARGE - TEXAS TECH UNIVERSITY

Period of Recharge	Rate of Recharge (gpm)	Volume of Recharge (acre-feet)	Water Level in Observation Well #4 (feet)
5-5 to 5-17-69	120[a] / 60[b]	2.5	3182.99[c] / 3189.99[d]
6-3 to 6-6-69	140 / 90	1.2	3187.49 / 3191.69
6-16 to 6-20-69	140 / 100	2.1	3187.89 / 3192.59
8-26 to 9-6-69	160 / 120	4.4	3182.39 / 3193.49
9-18 to 9-26-69	160 / 120	2.7	3196.09 / 3207.29
10-25 to 10-27-69	170 / 120	1.1	3199.69 / 3205.09
3-9 to 3-10-70	140 / 100	0.5	3189.25 / 3190.83
4-6 to 4-9-70	220 / 120	0.8	3188.48 / 3190.03
5-13 to 6-9-70	260 / 155	12.7	3189.62 / 3204.86

[a] Upper number represents maximum

[b] Lower number represents sustained

[c] Upper number represents beginning

[d] Lower number represents end of recharge

rates for each subsequent recharge period. There remain several unanswered questions. One, where did the volume of earthen material which constituted the upper and lower cavities go? It is possible that a cavity of some form existed prior to recharge however the upper cavity had to be developed during recharge. Perhaps of greater significance is why the material did not plug the formation surrounding the hole? Another source of earthen material was the sediment carried in the recharge waters which carried concentrations to 200 ppm.

As previously stated, the rate of recharge has shown a steady increase rather than an expected decline. The prime factor which seems to influence the rate is the degree of saturation of the formation surrounding the hole. It is felt that a condition of soil piping [*Cedergren*, 1967] may be responsible for the increasing rates and disposition of the cavity material. Soil piping, however, may be hard to support as channel sizes increase, sediments from the channel must also be displaced.

A phenomena more unexpected than the surprisingly high rates occurred after the re-excavation of the second hole. When recharge commences, the water within both holes rises simultaneously however the level in the second hole stabilizes at a level lower than in the first. This difference in level seems to correspond with the rate of recharge as the difference is 2.5 feet at 200 gpm but only 1.5 feet at 150 gpm. An explanation for this phenomena has not been attained to date.

In conclusion, hole recharge has proven to be a very effective and economical method of recharge in the area of the test. The big question remaining is "Can this success be duplicated in other areas?" Efforts to obtain at least a partial answer were made as eight additional holes in two areas were drilled. However, an exceptionally dry fall and winter has precluded even one recharge effort in the new locations.

If a positive answer could be attained to the above question, an efficient and economical method of artificial recharge will have been discovered. Indications are that this may be possible but must be the subject of increased research efforts.

REFERENCES

Cedergren, H. R., Seepage, Drainage, and Flow Nets, John Wiley and Sons, Inc.: New York, 1967.

Clyma, W., "Artificial Groundwater Recharge by a Multiple-Purpose Well," Texas Agr. Exp. Sta. Bulletin MP-712, 1966.

Cronin, James G., "Ground Water in Ogallala Formation in the Southern High Plains of Texas and New Mexico," U.S. Geological Survey Atlas-Map HA-330 1969.

Dvoracek, M. J., "Feasibility of a Constructed Pit for Ground Water Recharge," Progress Reports on Research, School of Agriculture, Texas Technological College, 1964-65.

Dvoracek, M. J. "Use of Wells and Pits to Recharge Underground Formations in Semi-Arid Areas," paper presented at Internatioanl Conference on Arid Lands in a Changing World, Tucson, Arizona, June, 1969.

Dvoracek, M. J. and S. H. Peterson, "Artificial Recharge in Water Resources Management," A.S.C.E. Preprint No. 1111, 1970.

Dvoracek, M. J., and R. Z. Wheaton, "Development of Systems for Ground Water Recharge into the Ogallala Formation," In Water Resources Institute 1968 Annual Report, Texas A & M University, College Station, Texas.

Dvoracek, M. J. and R. Z. Wheaton, "Development of Systems for Ground Water Recharge into the Ogallala Formation," Water Resources Center, Texas Tech University, Report #69-5, May, 1969.

Hauser, V. L. and F. B. Lotspeich, "Artificial Ground Water Recharge Through Wells," Journal of Soil & Water Conservation, Vol. 22, No. 1, January-February, 1967.

Havens, J. S. "Recharge Studies on the High Plains in Northern Lea County, New Mexico," U.S. Geol. Survey Water Supply Paper No. 1819-F, 1966.

New, Leon, "1970 High Plains Irrigation Survey," Agricultural Extension Service, Texas A & M University, 1970.

Signor, D. C. and V. L. Hauser, "Artificial Ground Water Recharge Through Basins," Texas Agr. Exp. Sta. Misc. Publ. 895, September, 1968.

Signor, D. C., V. L. Hauser, and O. R. Jones, "Ground Water Recharge Through Modified Shafts," paper presented at Winter Meeting, American Society of Agricultural Engineers, Chicago, Illinois, December, 1968.

The Texas Water Plan, Texas Water Development Board, Austin, Texas, November, 1968.

Valliant, J. C., "Artificial Recharge of Surface Water to the Ogallala Formation in the High Plains of Texas," High Plains Research Foundation, Halfway, Texas, Report No. 1, 1962.

MANAGEMENT OF ARTIFICIAL RECHARGE WELLS FOR GROUNDWATER QUALITY CONTROL[1]

L. G. WILSON

Water Resources Research Center
University of Arizona, Tucson

INTRODUCTION

An important application of artificial groundwater recharge techniques is for water quality control. Water spreading methods, for example, have been used for the tertiary treatment of sewage effluent [*McMichael and McKee*, 1966]. Although recharge wells are not generally used for sewage effluent management, such wells have been employed in various problems relating to chemical water quality. In Israel, where groundwater quality is a matter of national concern [*Aberbach and Sellinger*, 1967], recharge well techniques are used for the in-aquifer mixing of surface and groundwater supplies of dissimilar chemical quality.

As a result of theoretical, laboratory and field studies on underground mixing, the Israeli workers developed techniques to "predict and control the movement of water of various qualities...within the aquifers and in the water pumped for use" [*Harpaz et al.*, 1968]. The mixing theories and management techniques developed in Israel may have applicability to the solution of groundwater quality problems in Arizona. For example, high nitrate ion concentrations (>45 mg/l) have been reported in wells downstream of the outfall from the City of

[1]The research reported in this paper was supported by the Office of Saline Water, U. S. Department of the Interior, Research Grant No. 14-01-0001-1805.

Tucson Treatment Plant. By importing low-level nitrate water to these high nitrate groundwater areas, coupled with in-aquifer mixing techniques it is possible that nitrate concentrations could be reduced to acceptable levels.

This paper briefly reviews specific recharge well-mixing techniques of possible utility in underground mixing operations for nitrate control. Illustrative data from field studies at a recharge site near Tucson, Arizona are presented.

EXPERIMENTAL

In-aquifer mixing may be effected by two possible well recharge regimes: the so-called single- and two-well types. A single-well operation comprises recharging effluent through and subsequently pumping the mixture of effluent and native groundwater from a single well. In a two-well operation, recharge is initiated in one well and pumping in a second well. Mixing is a reflection of several possible mechanisms: hydrodynamic dispersion, natural flow in the aquifer and stratified flow.

Single-well tests were conducted on a 20-inch diameter, 150 ft recharge well at the Water Resources Research Center (WRRC) field laboratory. Two-well tests utilized the 20-inch well in conjunction with a 260 ft distant 16-inch pumping well. Recharge effluent consisted of cooling-tower blowdown effluent from the nearby Tucson Gas & Electric Company, Grant Road Plant.

Differences in chloride ion levels were used to distinguish between (or label) recharge effluent and native groundwater.

Of several possible single-well techniques three were examined during field studies: the no-pause, pause and pulse types. The no-pause regime entailed recharging a volume of tagged, or labeled, recharge water followed immediately by pumping. During the pause regime a seven-day delay was interposed between recharging and pumping. For the pulse type regime separate volumes of tagged and untagged effluent were recharged sequentially, followed immediately by pumping.

A two-well test at the WRRC field laboratory comprised 14 days of continuous recharge-discharge in the two-well combination with matched recharge and discharge rates.

RESULTS AND DISCUSSION

Single-Well Tests

A representative chloride ion breakthrough curve for a no-pause, single-well test is shown on Figure 1. This curve was constructed by plotting the relative concentration of effluent in pumped water versus the corresponding pumped volume ratios, V_p/V_i; where V_p and V_i are the pumped and recharged volumes, respectively. The total volumes recharged and pumped during the specific test shown were 50,000 gallons and 181,000 gallons, respectively.

The breakthrough curve on Figure 1 illustrates the mixing trends during pumping. Undiluted effluent was discharged (i.e., relative concentration values remained near 100 percent) until a pumped volume ratio of about 0.4. With increased pumping more and more native groundwater moved to the well, mixing with and diluting the effluent and producing a decrease in relative concentration values. After extracting about 2.8 times the volume recharged the displacement of effluent was virtually complete and the relative concentration values approached zero.

Hydrodynamic dispersion was the principal mixing mechanism producing the curve of Figure 1. That is, the curve is S-shaped and relative concentration values approached the value predicted by dispersion theory: 50 percent for a pumped volume ratio of unity [*Harpaz et al.*, 1968]. For aquifers with high in-

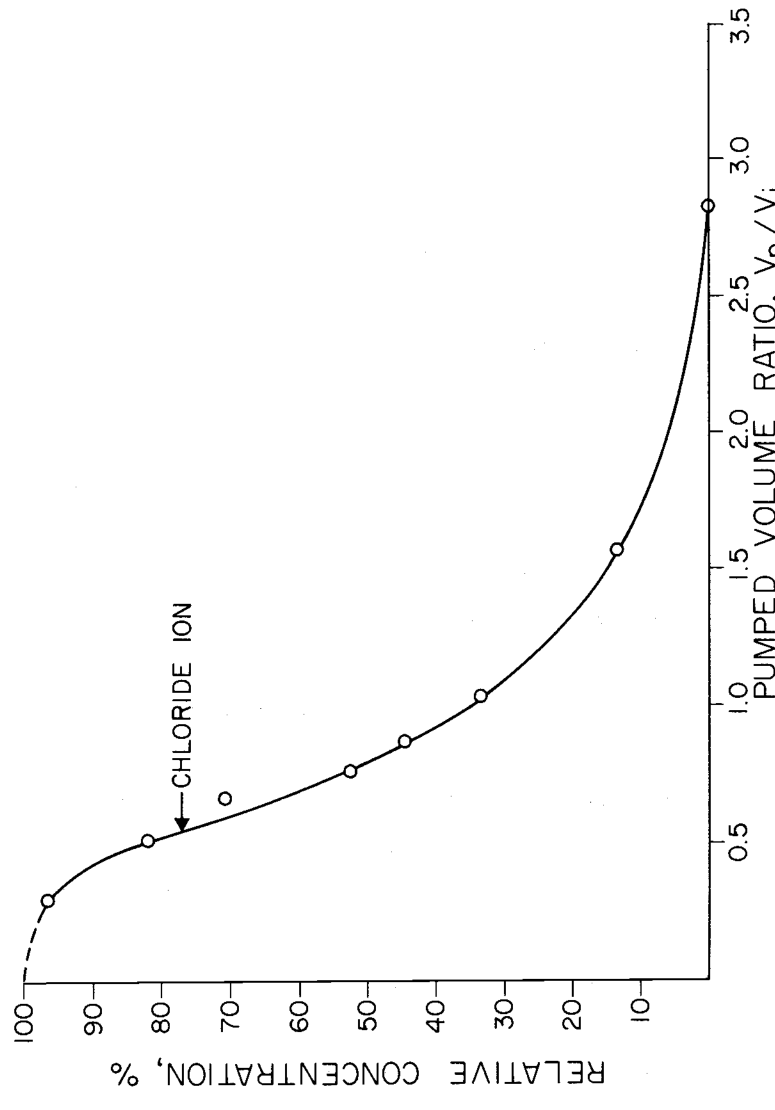


FIGURE I. BREAKTHROUGH CURVE SINGLE-WELL, NO PAUSE TEST digenous flow rates, such as the limestone aquifers in Israel, breakthrough curves are exponential in shape and relative concentration values are far less than 50 percent for pumped volume ratios of unity [*ibid.*]. Consequently, mixing is more effective when high groundwater velocities obtain.

Detailed results of a seven-day pause test were presented by *Wilson* [1971]. In general, by pausing between recharging and pumping more effective mixing was produced than by pumping without delay. After the seven-day pause the initial relative concentration values were about 20 percent [*ibid.*], c.f., 100 percent for the no-pause tests. Thereafter, relative concentration values for the pause case gradually approached zero.

The principal factor promoting dilution during the pause is probably indigenous groundwater movement which sweeps recharged water beyond the influence of the pumping unit. Other factors, listed by *Harpaz et al.* [ibid.], include percolation from above, density migration and molecular diffusion.

The results of pulse tests were also reported by *Wilson* [1971]. Relative concentration values on breakthrough curves for these tests were initially nearly zero, increasing to maximum values of about 25 percent for pumped volume ratios near 0.5, then decreasing thereafter. The initially low relative concentration values reflect the mixing of tagged and untagged effluent within aquifer materials. With continued pumping more and more tagged effluent was extracted but the low relative concentration values indicate that effective mixing of tagged and untagged effluent and native groundwater was occurring. After the maximal relative concentration values indigenous groundwater began to predominate in the extracted mixture.

Two-Well Test

A 14 day two-well test was conducted at the WRRC field laboratory using the 20-inch diameter recharge well and the downstream 16-inch pumping well. The constant recharge and pumping rates were matched at 200 gpm.

The chloride ion breakthrough curve at the pumping well is shown on Figure 2. An increase in relative concentration values was first evident on the fifth day. Values subsequently increased to 20 percent on the 11th day. A jog is evident on the curve between the 11th and 12th days, (possibly reflecting the effect of stratified flow) with an increase in relative concentration to 26 percent. This value was sustained to the end of the test.

The favorable dilution obtained during the two-well regime approached that during the pause-type, single-well regime. The principal advantage of the two-well regime over the single-well regime would be for the treatment of effluent or groundwater on a prolonged or continuous basis. *DaCosta and Bennett* [1960] indicated that effectiveness of the two-well regime may be increased by the judicious selection of recharge-discharge rates, by increasing the distance between the recharge-discharge wells and by aligning the wells at certain angles to the direction of indigenous flow.

Applicability of Mixing Techniques to Nitrate Dilution

Chloride ion breakthrough curves such as those shown herein illustrate the possible mixing trends during single- or two-well operations for nitrate control. Thus if the nitrate ion concentrations of the recharge source and groundwater are known for a specific site and empirical chloride ion breakthrough curves are available for various recharge-discharge regimes, the dilution principle may be used to estimate changes in nitrate ion concentrations during underground mixing.

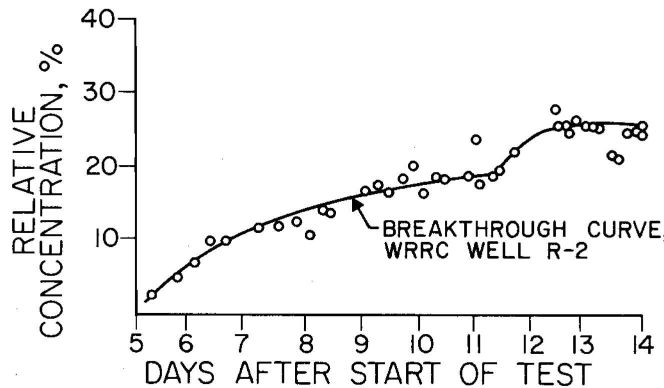


FIGURE 2. CHLORIDE ION BREAKTHROUGH CURVE, WELL DURING TWO-WELL, RECHARGE-DISCHARGE TEST

The most efficacious system for the quantity and quality of dilution water may then be selected for the site.

REFERENCES

Aberbach, S. H., and A. Sellinger, Review of artificial groundwater recharge in the Coastal Plain of Israel, in Artificial Recharge and Management of Aquifers, Int. Assoc. Sci. Hydrology, Symposium of Haifa, 1967.

DaCosta, J. A., and R. R. Bennett, The pattern of flow in the vicinity of a recharging and discharging pair of wells in an aquifer having areal parallel flow, Int. Assoc. Sci. Hydrol. Publ. 52, 524-536, Commission on Subterranean Waters, 1960.

Harpaz, Y., R. Sternau, A. Mercado, J. Schwarz and J. Bear, Underground Water Storage Experimental Project, Summary Report, P. N. 1019, TAHAL, Tel Aviv, 1968.

McMichael, F. C., and J. E. McKee, Wastewater reclamation at Whittier Narrows, State of California, State Water Quality Control Board, Publication No. 33, 1966.

Wilson, L. G., Investigations on the subsurface disposal of waste effluents at inland sites, Final Report on Grant No. 14-01-0001-1805, Office of Saline Water, (Multilith) Water Resources Research Center, The University of Arizona, 1971.

The Occurrence of Thermal Ground-water in the Basin and Range Province of Arizona

Jerome J. Wright

Geosciences
University of Arizona, Tucson

INTRODUCTION

Purpose

The principal object of this report is to examine on a regional basis the occurrence of ground-water having temperature considered to be higher than normal. Water emitted from natural springs and that produced by pumping for irrigation and industrial purposes is included in this study.

Location

The area included in this report is that portion of Arizona which lies within the Great Basin, (Basin and Range) Physiographic Province, (Fenneman, 1931, pp. 326-395) and comprises approximately 51,000 square miles of the state's surface area. The term "Desert Region" is also used in some reports for describing the subject area, (Halpenny, 1952).

Previous Investigations

Other than the brief compilation by Haigler (1969), no detailed work has been devoted entirely to a study of the occurrence of thermal ground-water in Arizona. Early workers such as Gilbert (1875) compiled a list of hot springs in the United States which included those springs whose water temperature exceeds the mean annual air temperature by 15° Fahrenheit. Peale (1883) further expanded the previous work in his report. Stearns et al (1937) and Waring (1965) compiled comprehensive sets of data on thermal springs in the United States. They reviewed the previous literature on the subject and their reports include extensive bibliographies. Included in their works were some springs whose water temperature may not exceed 10°F. above the mean annual air temperature of the locality but are appreciably warmer than normal for the area. White (1957) considers 10°F. above air temperature as significant and characteristic of thermal springs. For the purpose of this regional study, water must be 15°F. over the mean annual air temperature at their localities. (Waring, 1965, p.4)

Feth et al (1954) investigated the occurrence of springs in the Mogollon Rim area of Arizona; however, only a few of the many spring phenomena listed emit water with temperatures which can be classified as thermal. Several of the many studies made through the cooperative effort of the U.S. Geological Survey and the Arizona State Land Department which deal with the ground-water resources of particular areas in southern Arizona, contain statistical data on thermal springs and wells producing water of higher than normal temperature. Detailed work on most of the springs in the region is scanty to non-existant.

The general literature concerning hot springs and the occurrence of thermal water in other areas of the world is quite extensive (Waring, 1965). The scope of this study precludes a review of this material.

Acknowledgements and Method

The original investigation upon which this report is based was made possible through support granted by the Ground Water Branch, Water Resources Division, United States Geological Survey. Much of the work has been done by searching the literature and examining the records kept in the Tucson and Phoenix offices of the Ground Water Branch, U.S.G.S. The aid rendered by the personnel of these offices is gratefully acknowledged. Visits to the sites of some of the more important thermal springs have been made intermittently since 1961.

Land Forms

The Basin and Range portion of Arizona is a region of numerous, broad intermontane valleys or basins and sharply rising mountain ranges of variable height and areal extent. Within particular belts the basins and ranges trend parallel with one another. Although a northwest-north trend is commonly ascribed to them, many depart from this orientation and lie in a transverse direction (Wilson and Moore, 1959). In the southeastern part of the state the valleys and mountain areas are approximately equal whereas in the central and western areas the basins have a much greater areal extent than the mountains (Heindl and DeCook, 1952).

GEOLOGY

A detailed discussion of current theories pertaining to the geology and geologic history of the Basin and Range Province of Arizona is not considered necessary for the purpose of this study. Most of the thermal water produced in the area is obtained from wells penetrating the Tertiary, Quaternary, and Recent alluvial fill in the structural basins. Deposition of the fill in the basins was accomplished under varying conditions causing great discontinuity of the lenses of gravel, sand, and silt that constitute most of the section. A general exception to the irregular strata sequence of the older valley fill is the occurrence of variable thicknesses of lake-bed clay in the upper portion of the stratigraphic section in several basin areas. The presence of the clay and the lens-like character of the aquifers tend to create artesian conditions both within and below the sealing zones in some areas. Water table conditions generally prevail above the clay zones (Heindl and DeCook, 1952).

Igneous Activity

Igneous activity was extensive during the Tertiary-Quaternary time with a wide range of rock types having been intruded into existing sediments or emitted as lava flows. The Quaternary volcanic rocks consist almost entirely of basalt flows and are found over wide areas within the Basin and Range region (Heindl and DeCook, 1952).

Structure

Structural disturbances resulting in faulting, flexing, erosion, deposition of sediments, and volcanic activity have taken place intermittently and with variable intensity throughout the geologic history of southern Arizona (Wilson and Moore, 1959). The alternating mountains and valleys of the Basin and Range province are the result of large scale faulting. The depression of some blocks and subsequent deposition of detritus derived from the adjacent uplifted blocks gave rise to the land forms as we see them today. These structural events occurred over a long period of geologic time and were not necessarily uniform over the entire region. The upper parts of the alluvial fill in many basins exhibit some apparent continuity from basin to basin (Heindl and DeCook, 1952).

OCCURRENCE OF THERMAL WATER

Geographic Distribution

Arizona

Thermal ground-water occurs in many places in the subject area. By far the greatest number of these occurrences is the result of wells which have been drilled for irrigation and industrial purposes. In order to reduce the element of confusion only wells producing water over 90°F. are shown on the figures in this report. Although there are many natural springs within the region, only a small percentage of them can qualify as true thermal phenomena. The thermal springs listed by Stearns et al (1937) are widely scattered in southern Arizona with the only semblance of a concentration occurring in Graham and Greenlee counties. Although a part of this specific locality is located a short distance north of the Basin and Range boundary, as defined by the U.S.G.S., its importance precludes omission from this study.

Rates of flow from the springs in the Basin and Range region are generally small, some being little more than seeps. Temperatures range from 67°-184°F. Stearns et al (1937) associate most of the thermal springs with Late Tertiary and Quaternary lava flows and/or nearness to well recognized faults. None of the springs are of the eruptive type.

Sources of Heat and Water

Stearns et al (1937) state that the heat of thermal springs may be derived from:

1. The natural increase in temperature of the earth with depth.
2. An underlying body of hot or possibly molten rock.
3. Zones where there has been faulting of the rocks with the resultant development of heat.
4. Chemical reactions beneath the surface.
5. The energy derived by the disentegration of radioactive elements.

Plummer and Sargent (1931) contend that younger Tertiary beds might contain unaltered organic matter which would give rise to exothermic chemical activity, No.4 above. They also include the oxidation of sulphide minerals to limonites, hematites and other minerals as a possible heat source. Lovering (1948) discusses the oxidation of pyrite as a heat source in his study of geothermal gradients.

The association of the higher temperature ground-water in southern Arizona with Tertiary lava flows and intrusive rocks would suggest that there is a definite connection between them. This manifestation is apparent in the vicinity of Clifton and would include the area to the south and west in Graham county. The occurrence of thermal springs in Grant and Catron counties, New Mexico, east of Clifton, would also be included in this general area.

The literature on the occurrence of thermal water contains many theories as to the source of heat for particular areas. It was found that the categories as stated above will cover most of them satisfactorily.

The question of the source of water for the thermal phenomena has been the point of a great deal of speculation among investigators in the field. Meinzer (1924), in his discussion of certain thermal features in Nevada, states that the water may be of meteoric origin or it may be juvenile water given off by magmas. White (1957), in two studies, considers volcanic, magmatic, connate, and metamorphic waters and their association with thermal features. He has approached the problem by using the chemical analysis and isotope technique and presents a tentative criterion for recognizing the major types of ground-water of different origins.

In the Clifton area the thermal water emitted by springs is high in sodium and calcium chloride. Hem (Feth et al, 1954) states that this water may be of deep-seated origin and in part juvenile. Other springs and wells in the immediate area vary as to the degree of salinity. Gillard Hot Springs, Fig. 4, no. 11, located a few miles south of Clifton, emits high temperature water low in chlorides. This suggests that the two areas draw their water from different sources or that the water flows through different types of rock on its way to the surface.

Relation to Structure

Stearns et al (1937) summarize this aspect of thermal occurrences. They state that in regions where warm rocks lie near the surface it is not difficult to explain how meteoric water may reach the heat source and be recirculated back to the surface combined with some magmatic water. However, when the heat source lies at depth meteoric water may not reach it unless favorable conditions exist. The agent which heats this shallow water could be magmatic steam under high pressure. It has been found that thermal water is closely associated with major fault zones (Waring, 1915; Meinzer, 1924; White and Brannock, 1950; and many others). Stearns et al (1937) are of the opinion that thermal springs throughout the entire Basin and Range Province are closely associated with major fault lines. Plummer and Sargent (1931) summarize work which indicates that the temperature of fluids in the subsurface decreases outward, away from fault zones.

The close association of tectonic distrubance and the occurrence of thermal water in southern Arizona is illustrated in the figures in this report. The structural elements shown are taken from Mayo (1958), Wilson et al (1960), USGS and AAPG (1961), Feth (1954), Wertz (1968), some selected open file reports (USGS), and many theses and dissertations on file in the University of Arizona library. Most of the minor lines of faulting have been excluded from the map in order to keep the density to a minimum.

The coincidence of thermal water and fault zone is marked in several localities throughout the region. The highest temperature springs (120°-184°F.) in the state are found in the vicinity of Clifton, Fig.4, nos. 11 & 12. This area is the focal point for the intersection of several major lines of faulting. Southwest of Clifton, in the area around Safford, the Indian Hot Springs, Fig.4, no. 10, produce water at 119°F. Deep wells in this vicinity also produce considerable amounts of hot water ranging from 100°-120°F. One of the wells located a short distance north of Thatcher is artesian, flowing 500-600 gpm., temperature 118°F. The reported total depth of this well is 2162 feet. Several deep wells drilled for industrial purposes in this area have been reported as having water temperatures up to 138°F. but due to their being held confidential, little data is available on them. It will be noted that the Safford area lies directly in line with or adjacent to major structural trends. Hooker Hot Springs, Fig.4, no. 8, in northwestern Cochise county, follows the suggested pattern by being located upon a major structural trend. Other high temperature springs and wells located adjacent to the major trend are apparently being influenced by its proximity or possibly by minor parallel or branch faults. The coincidence of fault and thermal occurrence is not apparent in all cases. Irrigation wells which produce high temperature water in a number of areas were drilled in that part of the basin where the sediments are thickest, well away from the mountain front and at some distance from the line of faulting which generally outlines the uplift area. It is suggested that faults in the basin floor beneath the alluvium might act as conduits for circulating the high temperature water upward where it can be mixed with water of lower temperature (Meinzer, 1924; Armstrong and Yost, 1958). There is no positive way of proving this except the anomalous occurrence of unusually hot water in some of the older alluvium wells. The explanation for the occurrence of anamolous, high temperature water in alluvium-filled basins is usually explained by the presence of local, abnormally high geothermal gradients. This is obvious but the explanation for the actual cause of the increased gradient is in most cases unknown. Whether the high temperature water rises from sufficient depths to be affected by heating through release of pressure or porous plug expansion (Adams, 1924) is conjectural.

Geothermal Gradients

Wilson (1929) defines the geothermal gradient as being the number of degrees of temperature increase per unit of distance of depth through the earth's crust and the reciprocal geothermal gradient or reciprocal gradient as the depth per degree increase in temperature calculated between the 100 foot depth and the bottom of the hole.

In this study the increase in depth per one degree Fahrenheit is used as the geothermal gradient. The value is obtained by dividing the well depth by the difference between the mean annual air temperature for the locality and the observed water temperature at the well.

Darton (1920) states that the factors which may influence the rate of temperature increase include variation in rock conductivity, underground tension, mineralization, volcanic influences, movement of underground waters and variation in radioactivity. The geothermal gradient varies widely from place to place in the United States, Arizona being no exception. At Phoenix the gradient ranges from 13 to 64 feet per degree. At the Congress mine near Prescott the gradient ranges between 63 to 186 feet per degree.

In this study geothermal gradient computations were made on many wells throughout the region. Gradients for some representative areas are included in Table 1. It was assumed that the highest temperature water came from the greatest depth in a well. Certain errors are incorporated into the computations because of the difficulty in knowing how much cooler water is being pumped from shallower depths. Well perforations or open hole completions generally cover considerable intervals of water bearing section; consequently, the empirical value of the geothermal gradients obtained under such conditions is apparent. Kister and Hardt (1961) comment on the difficulties of making quality of water determinations under such conditions.

In some isolated cases it was found that the gradients in neighboring wells checked quite closely. The high gradients obtained in the Buckhorn area, Table 1, could possibly be associated with local areas of rock of low thermal conductivity close to the surface, by the confluence of faults as suggested in Figure 3, or by a combination of the two factors. Studies made by Plummer and Sargent (1931) indicate that local or abnormal gradients are due to structural features which interrupt the continuity of the strata. The features which they describe might be a volcanic plug, saltdome or sharply folded anticline, all of which would change the rate of conductivity and possibly introduce other factors such as opening up channels for upward migration of warm waters or retarding downward movement of fresh, cooler water. Local chemical activity might also be increased by such a feature.

There is a paucity of data concerning the nature of the rocks making up the basin floors. Irrigation or industrial wells are rarely drilled to the basement in the region. Maps drawn on "bedrock" are in many cases very difficult to reconcile and data for such maps are somewhat empirical.

Quality of Thermal Water

During the course of this study several attempts to compare the concentration of particular minerals in hot spring and well water were made with no tangible results. Plots using Fluoride, Sulphate (SO_4), Bicarbonate (HCO_3), and total dissolved solids content versus temperature produced graphs with widely scattered points and no reasonable correlations. Armstrong and Yost (1958) state that in the area they investigated there is no apparent relationship between the water temperature and the amount of dissolved solids in it.

Hem (1954) states that the Clifton spring water is essentially a solution of sodium and calcium chloride. He suggests that the dissolved minerals in this water might be derived by leaching of the igneous and metamorphic rocks occurring at or near the springs and at depth.

Some comparisons between the analyses of thermal spring water from nearby irrigation wells presented fairly close correlations, on an individual basis. The analysis of water from Agua Caliente Spring in western Maricopa county, Fig. 2, no. 4, agreed quite well with the analysis of high temperature water from an irrigation well located in the same section. This might indicate a common source of supply for them and further substantiate the reason for the gradual decline of flow from the spring. Wells located at a distance from the spring and producing cool water contain substantially higher amounts of dissolved minerals. In several cases it is not possible to make a comparison because of the lack of wells in the immediate vicinity of the spring.

The study of the mineral constituents in the ground-water of the many basins of southern Arizona is complex and requires a great deal of specialized effort. In order to arrive at well founded conclusions pertaining to the origin of thermal waters by the analysis method much more time and work than this study permitted would be required.

Utilization of Thermal Water

In this region where water is highly prized the natural flow of springs is used for all purposes, dependent of course upon its physical and chemical properties. It has long been believed that high temperature spring waters possess medicinal properties. Following up on that idea, hot bath facilities have been constructed at several locations. A brief discussion of this phase of water utilization follows.

Springs

Radium Hot Springs in Yuma county, Fig. 2, no. 3, was developed as a small bathing facility. A pump installed on a shallow well transferred the water to a storage tank from where it was piped to the private bathing cubicles. When this location was visited several years ago, there was no one in attendance and it appeared that the facility was seldom used.

Agua Caliente Springs, located a few miles north of Sentinel in western Maricopa county, Fig. 2, no. 4, could well be called a "ghost resort". For many years this site was a favorite of winter visitors despite the rather uninviting countryside. Extensive facilities were provided including a hotel, cabins, restaurant, school, garage, and numerous private bathing cubicles. During World War II a large swimming pool was constructed for the principal use of the troops from the nearby Desert Training Center. During the past several years the flow of water from the springs steadily declined, with the loss of water being blamed on the pumping of high capacity irrigation wells located a short distance to the north and east of the spring area.

To the writer's knowledge no other thermal springs, located in the western half of the region, are the subjects of commercial development.

Indian Hot Springs, Fig. 4, no. 10, near Pima in Graham county was, until a few years ago, a hot bath and resort establishment. All of the required facilities were provided, including a fully equipped hotel and restaurant. At the present time the property is privately owned and the hot springs are not being exploited.

The hot saline water of Clifton Hot Springs, Fig. 4, no. 12,which is located within the city, is presently used to supply partially a municipal swimming pool. The water no longer emits at the surface, therefore it is pumped through a spray system where it is cooled. Fresh, cool water is mixed with the spring water. Attempts to utilize the hot water for medicinal baths have not been successful.

Gillard Hot Springs, Fig. 4, no. 11, located near the confluence of the San Francisco and Gila Rivers, occupies a site which is too inaccessible for exploitation. Previous attempts to use the water for bathing purposes have been unsuccessful.

The remaining thermal springs in the region are used as sources of private water supplies.

Wells

At Buckhorn, east of Mesa, the high temperature water pumped from drilled wells is being used for hot baths on a rather large scale. The investment in housing and entertainment facilities for the clientele is apparently quite large. It is probably the largest establishment of its kind in the state. A few miles south of Safford, Fig. 4, deep wells producing water at 109°F. supply hot bath facilities.

At several locations deep wells drilled to provide water for power plants and other industrial purposes have encountered hot water. In some instances the expense of providing cooling equipment has caused the abandonment of the hot water producing aquifers. As previously stated, many irrigation wells produce high temperature water. Whether this water is detrimental to plant growth would depend upon its dissolved mineral content. It was found that in some cases hot water of fairly high salinity was mixed with fresher water for farming purposes.

Conclusions

1. The occurrence of thermal water in the Basin and Range Province of Arizona is closely allied to structural elements.

2. The amount of influence "bedrock" may have on thermal water occurrence is difficult to ascertain. Perhaps future geophysical studies will aid in answering this question.

3. In most of the areas of southern Arizona where thermal water occurs it seems reasonable to expect that we are dealing dominantly with meteoric water. Wherever possible, detailed studies of the local geology and quality of water should be made.

BIBLIOGRAPHY

Adams, L. H., 1924, Thermal effects accompanying release of pressure: Joun. of Geology, v. 32, p. 191.

Armstrong, C. A. and Yost, C. B. Jr., 1958, Geology and ground-water resources of the Palomas Plain-Dendora Valley Area, Maricopa & Yuma counties, Ariz: U.S. Geol. Sur. & Ariz. St. Land Dept., Water Res. Report No. 4.

Darton, N. H., 1920, Geothermal data of the U.S.: U.S. Geol. Sur. Bull. 70.

Fenneman, N. M., 1931, Physiography of western U.S.: New York, McGraw Hill Book Co., Inc.

Feth, J. H., 1954, The geology of northern Canclo Hills, Santa Cruz Co. Ariz: Uni. of Ariz., PhD. thesis, Unpub.

Gilbert, G. K., 1875, U.S. Geog. and Geol. survey, W. 100th Meridian Report, v. 3, pp. 17-155.

Haigler, L. B., 1969, Geothermal Resources in Mineral & Water Resources of Arizona: Ariz. Bur. Mines Bull. 180.

Halpenny, L. C., and others, 1952, Ground-water in the Gila R. Basin and adjacent areas, Ariz. -- a summary: U.S. Geol. Sur. & Ariz. St. Land Dept., open file report.

Heindl, L. A. and DeCook, K. J., 1952, See Halpenny and others.

Hem, J. D., 1954, See Feth and others.

Kister, L. R. and Hardt, W. F., 1961, Correlation of ground-water quality with different sediment types, Lower Santa Cruz Basin, Ariz.: Ariz. Geol. Soc. Digest, v. IV, pp. 79-85.

Lovering, T. S., 1948, Geothermal gradients, recent climatic changes, and rate of sulphide oxidation in the San Manuel Dist., Ariz.: Economic Geol. Bull., v. 43, No. 1, pp. 1-20.

Mayo, E. B., 1958, Lineament tectonics and some ore districts of the southwest: Mining Engineering, v. 10, No. 11, pp. 1169-1175.

Meinzer, O. E., 1924, Origin of thermal springs in Nev., Utah, So. Idaho.: Journ. of Geol., v. 32, p. 29.

Peale, A. C., 1883, U.S. Geol. & Geog. Survey Terr., 12th Ann. Report, for 1878, pt. 2, pp. 320-327.

Plummer, F. B., and Sargent, E. C., 1931, Underground waters and subsurface temperatures of the Woodbine sand in northeast Texas: Uni. of Texas Bull., No. 3138. (Biblio.)

Stearns, N. D., Stearns, H. T., Waring, G. A., 1937, Thermal springs in the United States: U.S. Geol. Surv. Water-Supply Paper 679-B.

U.S.G.S. & AAPG., 1961, Tectonic map of the U.S., 1:2,500,000.

Waring, G. A., 1915, Springs of California: U.S. Geol. Surv. Water-Supply Paper 338.

__________ 1965, Thermal Springs of the U.S. and other countries of the world-a summary: U.S.G.S. Prof. Paper 492.

Wertz, J. B., 1968, Structural elements of ore search in the Basin & Range Province, southeast Arizona: Domes and Fracture Intersections: Trans., Soc. Min. Eng. AIME, v. 241, pp. 276-291.

White, D. E., and Brannock, W. W., 1950, The sources of heat and water supply of thermal springs, with particular reference to Steamboat Springs, Nev.: Trans. Amer. Geophys. Union, v. 31, No. 4, pp. 566-574.

______ 1957, Magmatic, Connate, and metamorphic waters: GSA Bull., v. 68, No.12, pt. 1.

Wilson, E. D. and Moore, R. I., 1959, Structure of the Basin and Range Province in Ariz.: Ariz. Geol. Soc. Digest, Guidebook II, pp. 89-98.

__________________, O'Haire, R. T., 1960, Geologic map of Arizona: Ariz. Bur. of Mines, (U. of A.).

Wilson, J. H., 1929, Geophysical prospecting, Pt. 10: Geothermal methods: Colo. School of Mines Mag., v. 19, p. 13.

Well and Location		Depth (ft.)	Water Temp. °F.	Gradient ft./1°F.
4 wells near Ajo, Pima Co.	a/ (average)	1021	98.5	39
3 wells in Palomas Plain Yuma & Maricopa Co's.	a/	443	108	13
6 wells, Harquahala Plain Yuma & Maricopa Co's	a/	1150	93	49
Deep test for oil, South of Yuma	a/	6015±	125	120
3 wells, T3N:R1W, NW of Phoenix	a/	524-1468	87-92	44
2 wells, T1N:R2W	a/	925	90-95	12
3 wells in Buckhorn area east of Mesa.	a/	325	107	8
4 wells, Casa-Grande-Eloy	a/	708	89	39
Saguaro Power Plant Well #1 near Redrock		1950	108	49
" " " " #2		680	82	48
Tucson City well B-6 Randolph Park		1183	100	36
Tucson City Well SC-15		1715	104	43
Tucson City Well SC-19		832	88	40
Tucson G & E. well, SE of Tucson		2500	126+	42
" " " " well #8		975	93	37
5 wells in Safford area	a/	1095	99	30
Safford Golf Crse. well		2180-2420	99-100	30
5 wells, San Simon V. (Darton)	a/	920	103	26
Phelps Dodge well-Clifton		220-498	121-130	31
" " " "		140-500	132-143	33

Table 1. Geothermal Gradients for selected locations in So. Arizona

Map No.	Name & Location	Geology	Temp. °F.	Disch. gpm.	Use, Remarks.
	Mohave Co.				
1	Cofers Hot Springs. NW,Sec.36,T16:Ri3W	Faulting in lake beds?	95	20	Domestic, irrig., bath.
	Yavapai Co.				
2	Castle Hot Springs. Sec.3,T7N:R1W.	Tert. lavas.	115-122	280±	Resort, bath.
	Yuma Co.				
3	Radium Hot Springs. Sec.12,T8N:R18W.	Tert. volcanics.,Alluv.	122	Pump	Hot baths.
	Maricopa Co.				
4	Agua Caliente Sprgs. Sec.19,T5S:R10W.	Quat. lava, alluv.	100	Seep	Abandoned resort.
	Pima Co.				
5	Aguajito Sprg., at Quitoquibrito nr.Mex.	Schist hills alluv.	85	50±	Bathing & stock.
6	Agua Caliente Sprg. Sec.20,T13S:R16E.	Alluv. over faulting.	86	150±	Domestic & bathing.
	Santa Cruz Co.				
7	Agua Caliente Sprg. Sec.13,T20S:R13E.	K?,sh.,over Quat. granite.	82-90	10±	Not used.
	Cochise Co.				
8	Hookers Hot Sprig. Sec.6,T13S:R21E.	Alluv. over granitic rx.	122	20-30	Domestic,bathing
	Graham Co.				
9.	Hot Sprg.-Aravaipa Sec.35,T5S:R19E.	Tert. lava	90	6	Bathing
10	Indian Hot Springs 8 mi. NW.of Pima	Plio. lake beds, alluv.	119	300	Resort private.
	Greenlee Co.				
11	Gillard Hot Sprgs. Sec.27,T5N:R29E.	Alluv.,cglt. over Tert. volcs.	184	100±	Not used
12	Clifton Hot Sprgs. City of Clifton	Alluv., Tert volcs.	127-160	Pump	Bathing

Table 2. List of selected thermal springs in the Basin & Range of Arizona

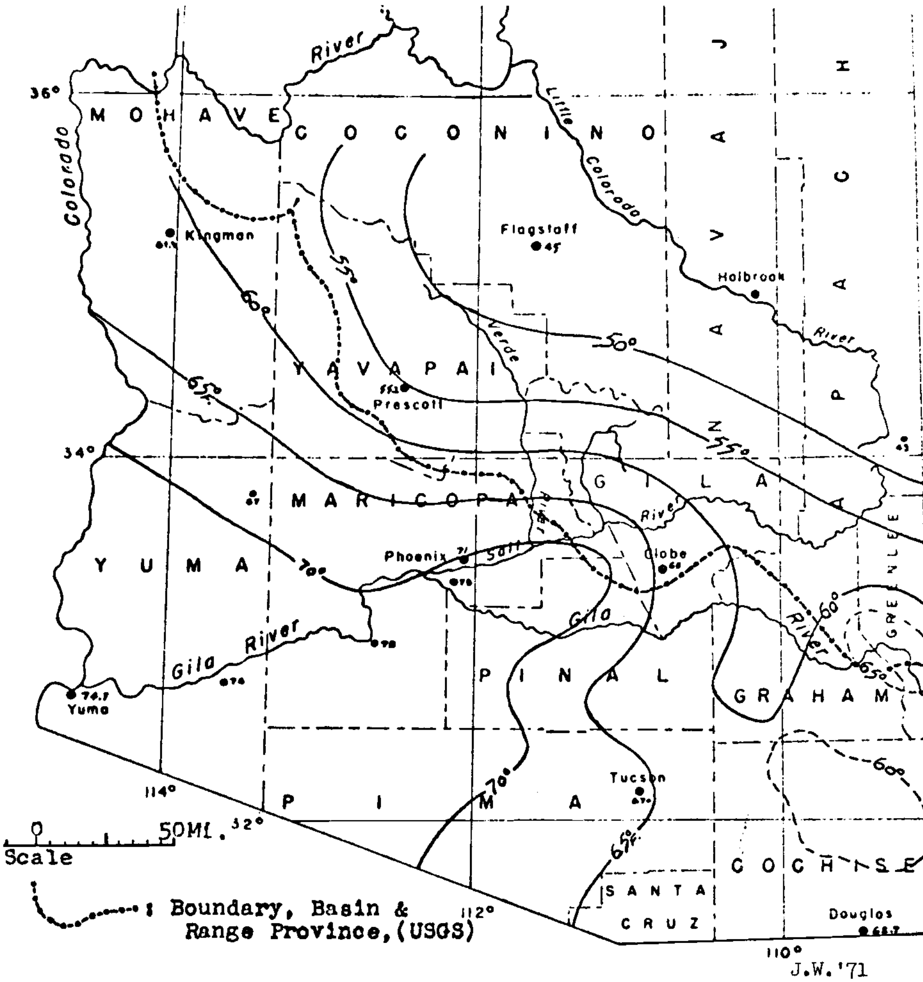


Figure 1 - Map of ARIZONA showing mean annual air temperature and area covered by this study.

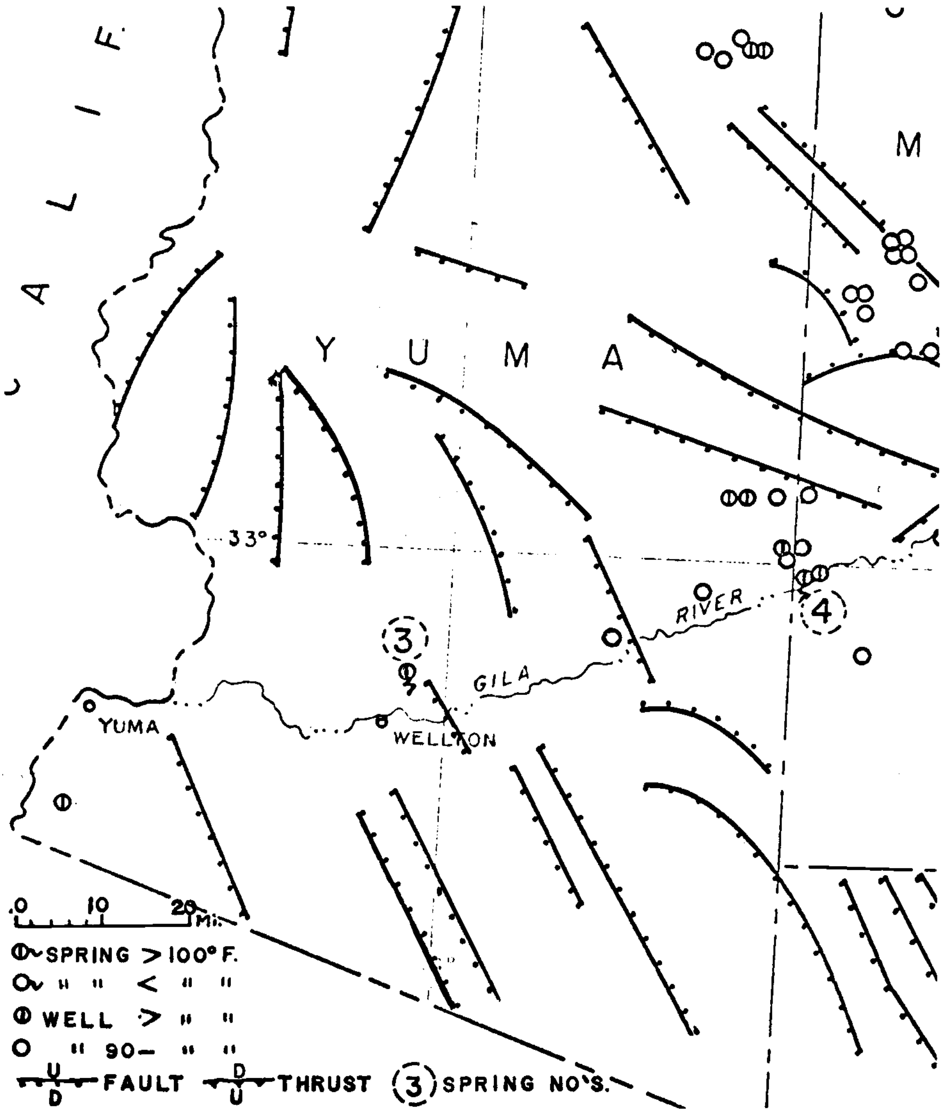


Figure 2 J.W.'71

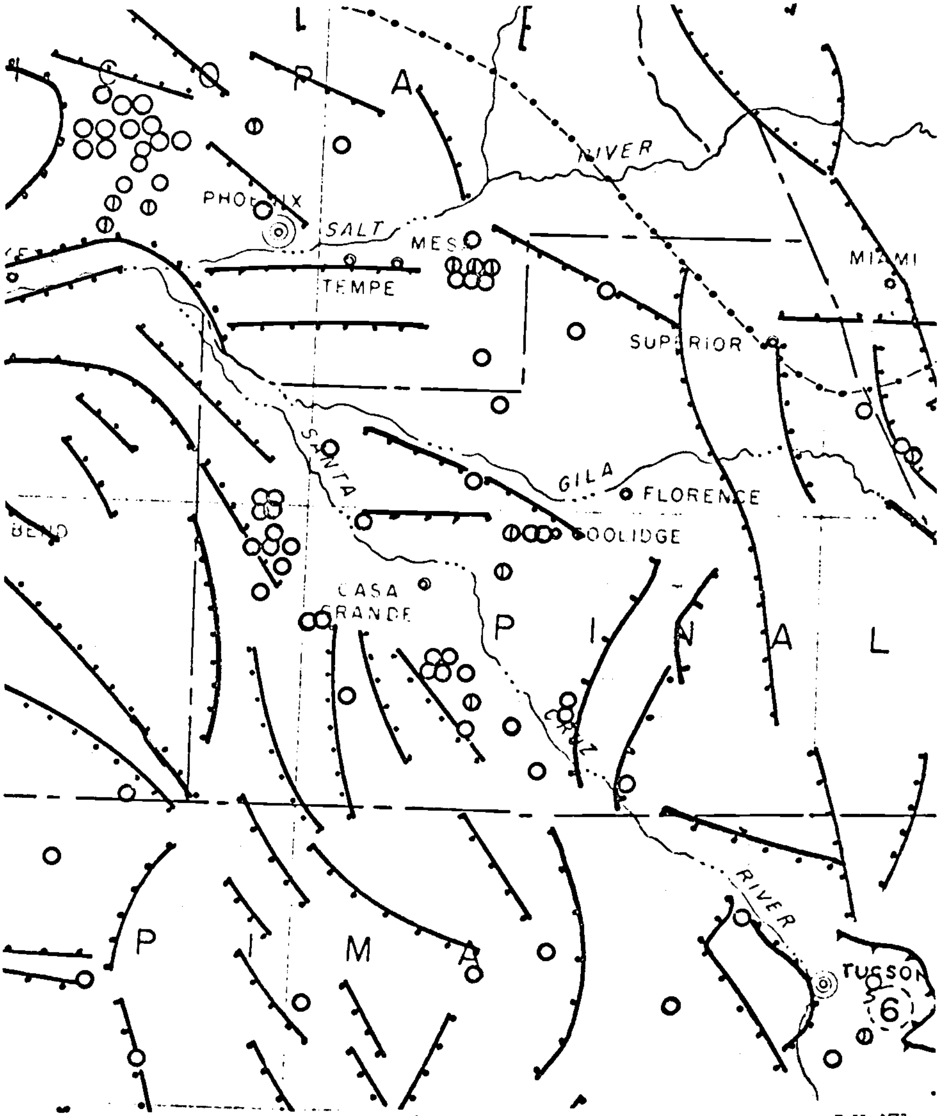


Figure 3 J.W.'71

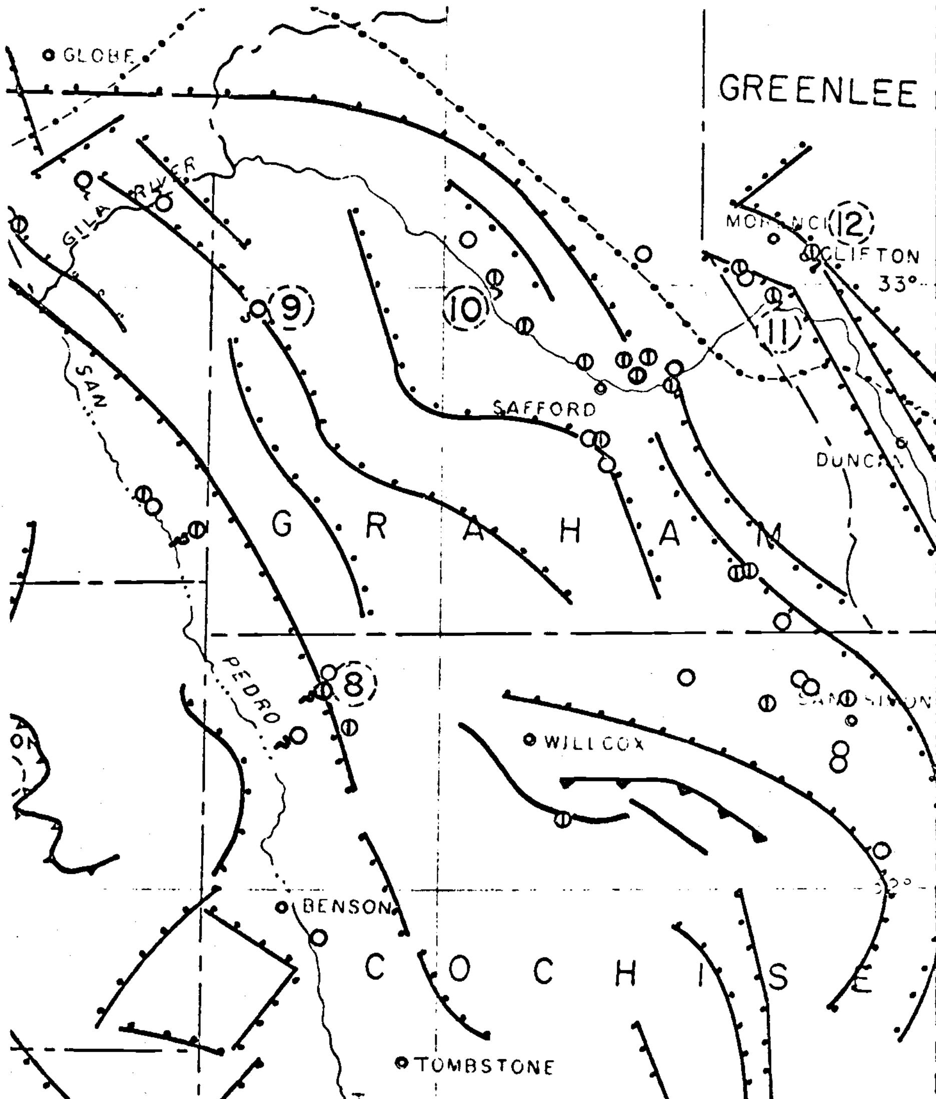


Figure 4

J.W. '71

PROGRESS IN DEVELOPING FOREST MANAGEMENT GUIDELINES
FOR INCREASING SNOWPACK WATER YIELDS

David B. Thorud and Peter F. Ffolliott

Department of Watershed Management
University of Arizona, Tucson

INTRODUCTION

Snowmelt is a major source of runoff and water yield for the reservoir systems in Arizona, and it also contributes to the recharge of groundwater aquifers. Much of the snowmelt runoff occurs in the ponderosa pine forest. This suggests the possibility of using forest management methods to enhance snowmelt water yield if trees and their spatial arrangements affect the snow regime. Basic research indicates that forest management does affect the snowpack (Anderson, 1963; Berndt, 1961; Goodell, 1965; Packer, 1962), and can cause increases in snowmelt runoff (Hoover and Leaf, 1967).

Another aspect of these encouraging water yield results supports the feasibility of their ultimate application in operational management programs. There is reason to believe that thinning and clearing of timber overstories can be made compatible with wood, forage, and wildlife production, and recreational use of forest lands.

The goal of the research project discussed in this progress report is the preparation of forest management guidelines for increasing water yields from snowpacks in the ponderosa pine type on the Salt-Verde River Basins. These Basins yield runoff for the municipal, agricultural, and industrial developments in the Phoenix and central Arizona area. Since this area is so important to the economy and welfare of the State, the project study areas have been centered on the Salt-Verde River Basins. However, the potential results should apply to comparable forest and physiographic conditions found elsewhere in Arizona, and may be applicable to forest regions outside Arizona where snowfall is an important component of the annual water yield.

BACKGROUND

Considering the application of forest management practices for attempting to increase recoverable water yields from snow, two basic options are available.

1. Reducing Forest Densities - thinning practices, including various intensities and combinations of intensities.
2. Removing Forest Overstories - clearing practices, including different arrangements and patterns.

Water yield improvement experiments on experimental watersheds (Brown, 1969; Hewlett and Hibbert, 1961; Reinhart, 1965) have demonstrated that increased snowmelt runoff may result from a reduction or removal of forest overstories, although the hydrologic mechanisms involved have not been completely identified and quantified. It is known that more snow accumulates in sparsely stocked forest stands, and in clearings in the forest overstory (Anderson, 1963; Goodell, 1965; Hansen and Ffolliott, 1968; Packer, 1962; Rothacher, 1965). The greater accumulation of snow in forest clearings may be a contributor to the increased runoff from experimental cuts. If this hypothesis is accepted, and if water equivalent of the snowpack can be maximized just prior to spring runoff by forest management practices, then perhaps the quantity of usable runoff can be maximized.

The assumption that maximum runoff occurs from maximum snow accumulation provides a basis for testing a variety of thinning and clearing options in varying timber stocking conditions, because changes in snow accumulation on site resulting from forest management practices can be measured. By this means, the management practices that will cause the greatest increase in snow accumulation prior to spring runoff can be identified for given timber stocking conditions.

Another consideration in developing forest management guidelines for increasing snowpack water yields is concerned with the identification of physiographic and climatic factors which partially determine the quantity of runoff yielded. Conceivably, comparable forest management practices on two sites of equivalent vegetative characteristics may yield different amounts of runoff if the sites have differing slope-aspect combinations, soil characteristics, or precipitation regimes. The land manager may wish to first implement water yield improvement programs on sites with the greatest apparent water yield. In this case, the decision would be based on physiographic, and possibly, climatic factors, since vegetation conditions are the same.

One measure of the effect of physiographic and climatic factors on the amount of runoff yielded is runoff efficiency, defined as the percentage of snowpack water equivalent at peak accumulation that appears as runoff (Garn, 1969). Runoff efficiency on small watersheds in the ponderosa pine forest of Arizona can vary from less than 20 to over 90 percent (Ffolliott, 1970). Conceptually, both fixed and variable factors determine runoff efficiency. Fixed factors include soil depth and type, slope percent, aspect, and basin configurations.

Variable factors include year-to-year differences in antecedent soil moisture conditions and rates of snowmelt.

DEVELOPMENT OF INVESTIGATION FRAMEWORK

To establish a framework for study which may ultimately lead to forest management guidelines for increasing snowpack water yields, alternative courses of action were simulated. The simulation technique used to achieve an effective and efficient program was based on PERT (Program Evaluation and Review Technique) analyses (Davis, 1968). Essentially, a PERT system identifies the relationships between activities comprising a project, the estimated time required to complete each activity, and the probabilities of success in completing the activities and project within the time constraints specified. At this stage of the research effort, only the relationships between activities in the project have been considered.

The investigation framework of the research project as established by a PERT analysis indicates the required activities within the project and the general ordering of prerequisite activities. Diagrammatically, study activities are arrows (directed arcs) ending at specified events (Figure 1). Several activities may end at one event, in which case the event occurs only when all activities are completed. Once an event has occurred, succeeding activities may begin.

In the investigation framework, study activities consist of the following:

1. Identifying pertinent populations.

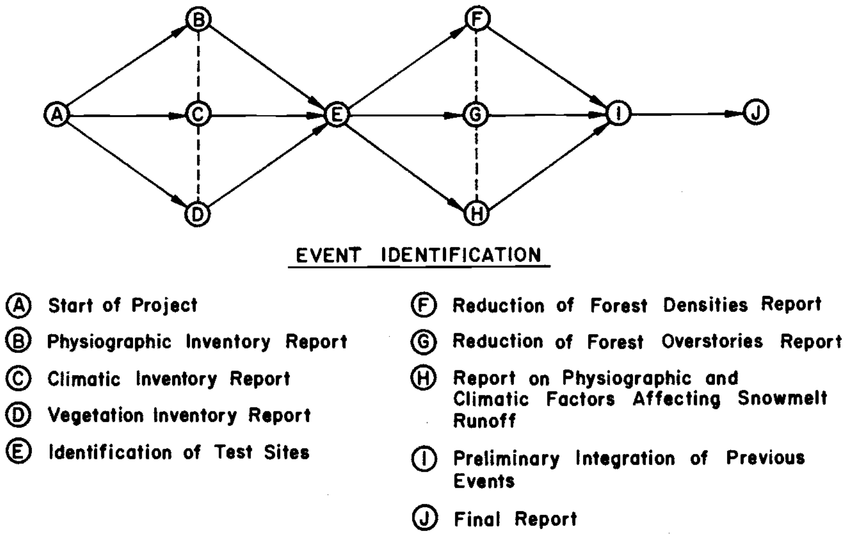


Fig. 1. A PERT network illustrating the investigation framework for a research effort designed to develop forest management guidelines for increasing snowpack water yield.

a. Physiographic (arc AB).

b. Climatic (arc AC).

c. Vegetative (arc AD).

2. Delineating test sites

a. In terms of physiographic features (arc BE).

b. In terms of climatic features (arc CE)

c. In terms of vegetative features (arc DE).

3. Implementing experiments.

   a. Reducing forest densities (arc EF).

   b. Removing forest overstories (arc EG).

   c. Effect of physiographic and climatic factors on runoff (arc EH).

4. Developing preliminary evaluations.

   a. Reducing forest densities (arc FI).

   b. Removing forest overstories (arc GI).

   c. Effect of physiographic and climatic factors on runoff (arc HI).

5. Preparing comprehensive report (arc IJ).

IMPLEMENTATION OF INVESTIGATION EFFORT

As indicated by the PERT network, identification of pertinent descriptive populations (physiographic, climatic, and vegetative) is a necessary initial activity. This step is needed to establish sideboards on the array of potential test sites for evaluation. With the completion of this event, priorities regarding the experimental development of forest management practices designed to increase snowpack water yields may be formulated. Given a fixed research effort, these priorities will delineate areas of initial and primary concern.

Three inventory evaluations are being conducted to attempt identification of pertinent populations for investigation. A physiographic evaluation of the ponderosa pine forest on the Salt-Verde River Basins has been initiated to describe slope, aspect, elevation, and soil interactions associated with this study area. The results of this inventory will provide a basis for estimating proportions of these Basins exhibiting specific physiographic features.

Concurrently, climatic and vegetative evaluations are being conceived and implemented. Zones of similar precipitation input, radiant energy components, snowpack accumulation, and snowmelt will be spatially located. Vegetatively, proportions of the study area that support given forest overstory densities that may affect the snowpack and runoff will be quantified to estimate the operational feasibility of proposed management systems.

Once the inventory evaluations are completed, and pertinent populations are identified, test sites can be established to represent the hydrologically significant physiographic, climatic, and vegetative features. Hopefully, test sites representing given interacting features can be replicated throughout the study area. As a minimum goal, however, test sites will be located on areas judged to be potentially high in snowpack water yields, as determined by observed contributions to the reservoir systems.

After appropriate test sites have been delineated, studies designed to evaluate (1) forest management options for increasing water yields from snow, e.g., reducing forest densities and removing forest overstories, and (2) physiographic and climatic factors which may help determine the quantity of snowmelt runoff yielded, will be implemented. Experimental evaluations will analyze a range of forest management opportunities on sites characterized by arrays of runoff efficiencies as described by physiographic and, possibly, climatic criteria. The ultimate goal of these evaluations will be the prescription of forest management opportunities that will maximize the water equivalent of the snowpack at peak accumulation on sites of high runoff efficiency.

Some studies of the snow regime as affected by forest density levels and clearings in forest overstories have begun, based on preliminary assessments of physiographic, climatic, and vegetative factors. Snow accumulation and melt have been measured for three years on study plots of different forest densities in the White Mountains and near Flagstaff. Additionally, the snow regime in forest openings and clearings has been measured on exploratory study sites this past winter. These efforts will be intensified on the basis of the above-mentioned inventory studies this coming year. In addition, the U.S. Forest Service is evaluating the effect of forest management practices on snow accumulation and melt in the Salt-Verde River Basins. Our work is coordinated with these efforts.

Preliminary assessment of physiographic factors that affect the magnitude of snowmelt runoff has also begun. This assessment utilizes the physiographic inventory (arc AB) to index fixed factors affecting runoff and the climatic inventory (arc AC) to index the variable factors. In addition, the combined effect of fixed and variable factors on runoff efficiency has been measured on small watersheds near Flagstaff. Although unique to these particular watersheds, these data provide some insight on the variability of runoff efficiency in space and time.

After field studies are completed, a preliminary and integrating evaluation will be prepared for the ponderosa pine lands that are potentially suitable for snow management. The relationships of proposed forest thinning and clearing practices to the production of timber, forage for livestock, and wildlife will be included in the evaluation. Impacts on recreational and esthetic values of the forest will also receive attention. The evalution will be submitted to federal, state, and private organizations that may have interest in such management guidelines. Review comments and criticisms from these organizations will be considered in the preparation of a final comprehensive report.

Acknowledgments. The authors express their gratitude to the U. S. Forest Service for assistance in establishing study sites and providing supplementary data. The assistance of the Salt River Project is also appreciated.

REFERENCES

Anderson, H. W., Managing California's snow zone for water, U.S. Forest Serv. Res. Paper PSW-6, 28 pp., 1963.

Berndt, H.W., Some influence of timber cutting on snow accumulation in the Colorado front range, U. S. Forest Serv., Rocky Mt. Forest and Range Exp. Sta., Res. Note 58, 3 pp., 1961.

Brown, H.E., The status of pilot watershed studies in Arizona, Paper presented at ASCE Irrigation and Drainage Specialty Conference, Austin, Texas, November, 1969, mimeo, 31 pp. 1969.

Davis, J.R., Why not PERT your next resource management problem?, Jour. Forest. 66, 405-408, 1968.

Ffolliott, P.F., Characterization of Arizona snowpack dynamics for prediction and management purposes, Unpubl. Ph.D. dissertation, Univ. of Arizona, 171 pp., 1970.

Garn, H.S., Factors affecting snow accumulation, melt and runoff on an Arizona watershed, Unpubl. M.S. thesis, Univ. of Arizona, 155 pp., 1969.

Goodell, B.C., Water management in the lodgepole pine type, Proc. Soc. Amer. Forest, 1964, 117-119, 1965.

Hansen, E.A., and P.F. Ffolliott, Observations of snow accumulation and melting in demonstration cuttings of ponderosa pine in central Arizona, U. S. Forest Serv. Res. Note RM-111, 12 pp., 1968.

Hewlett, J.D., and A.R. Hibbert, Increases in water yield after several types of forest cuttings, Internatl. Assoc. Sci. Hydrol. 6, 5-17, 1961.

Hoover, M.D., and C.F. Leaf, Process and significnce of interception in Colorado subalpine forest, In Internatl. Symp. Hydrol., Pergamon Press, New York, pp. 213-224, 1967.

Packer, P.E., Elevation, aspect and cover effects on maximum snowpack water content in a western white pine forest, Forest Sci. 8, 225-235, 1962.

Reinhart, K.G., Increasing water production through manipulation of vegetation, Proc. Municipal Watershed Manage. Symp., Univ. of Massachusetts, Coop. Ext. Serv. Publ. 446, pp. 17-21, 1965.

Rothacher, J., Snow accumulation and melt in strip cuttings on the west slope of the Oregon Cascades, U.S. Forest Serv. Res. Note PNW-23, 7 pp., 1965.

OPTIMAL UTILIZATION OF PLAYA LAKE WATER IN IRRIGATION

M. J. DVORACEK

Hydrology & Water Resources, University of Arizona

T. G. ROEFS

Hydrology & Water Resources, University of Arizona

INTRODUCTION

Under present conditions of increasing demands on water and an overall concern for optimum utilization and conservation of this basic resource, there still remain large quantities of water which have not been so allocated. Two quantities standout rather dramatically to, particularily, residents of the Southwest. These two are: the outflow from major rivers in the South (Mississippi) and Northwest (Columbia) regions and the water stored in the playa lakes primarily in the plains or midwest region.

Playa lakes are known to exist in many regions of the world. All have the same basic physiographic and climatic features. Most occur where lands are relatively flat and there is an absence of well developed surface drainage nets. Also most are found in regions where the climate would be categorized as either arid or semi-arid. Many definitions have been rendered for a playa lake with one being "the sandy, salty, or mudcaked flat floor of a desert basin having interior drainage, usually occupied by a shallow lake during or after prolonged heavy rains. - Webster."

In the High Plains of Texas, there exist approximately 20,000 such shallow lakes or playas [*Schwiesow*, 1965]. The size of these playas vary in size from small shallow depressions with minimal storage potential to very large deep basins providing storage for hundreds of acre feet of water. These playas are filled by surface runoff from the highly erratic precipitation patterns common to the High Plains area.

The volume of potential storage in these playa lakes is an estimated 2.5-3 million acre feet. The occurrence of attaining this volume of storage is a function of precipitation and the antecedent moisture on the watershed but the probability of filling the lakes once a year is relatively high. The probability of filling two or more times is moderately high during years of normal precipitation. Periods of highest probability exist during the spring (May and June) and the late summer (August and September).

At present waters collected and stored in the playa lakes on the High Plains of Texas present a peculiar problem associated with beneficial use. Natural recharge through deep percolation is very low with only 10% being infiltrated. The reason for this minimal amount is the extremely low infiltration rate through the heavy, predominantly clay soils in the bottom of the playas. Rates increase when the lake fill level is high as peripheral infiltration rates are considerably higher. The remaining 90% is generally lost to evaporation except for the small amounts used for irrigation or artificial recharge [*Clyma*, 1964].

As indicated, the present system (or lack of system) of playa lake operation results mainly in evaporation and a limited amount of beneficial uses. There are three possible beneficial uses associated with this storage

- irrigation, artificial recharge, and recreation. Each of these uses posses unique problems which may result in their non-selection. Timing of use is important to all because losses to evaporation are high due to climate and an unfavorable depth-area relationship.

The High Plains is presently being subjected to a problem common to most areas dependent primarily upon an underground water supply - a declining water table. The water source for the area is the Ogallala formation, a vast unconsolidated, hydrologically isolated aquifer. Any augmentation of the source through recharge or development of a surface source will delay and possibly preclude the arrival of an extremely critical situation.

A potential surface source exists within the playa lakes. Since approximately 5.5 million acres [*New*, 1970] are annually irrigated within the area, the use of a large percentage of potential storage within the playas would materially decrease the draft on the underground source. Several problems exist within this source; some of which are water quality, loss to evaporation, questionable depth-area relations and the stochastic nature of the source. If the waters are to be used for irrigation, the undesirable water quality (sediment content) is not a real problem.

The questionable depth-area relationship evolves around the characteristically shallow depths of the playa lakes. This results in the large surface area which proves undesirable. In addition to increasing the inundated lands, the large surface area increases an already high evaporation potential. Also difficulty in pumping from the playa exists because of the shallow depths. This problem can be alleviated in part by the simple excavation of a sump or other depressional area from which pumping could occur.

Losses due to evaporation and the stochastic nature of the source are problems which cannot be totally overcome because of the very nature of the problem. Both are related to climate and to date man has not been able to successfully manipulate climate. Measures can be taken to minimize the magnitude of the loss to evaporation through immediate utilization of the water or by modifying the area-depth relationship of the playa. Unfortunately both measures present unique problems. Immediate utilization for irrigation is questionable as the soil moisture content will be high and additional water applications to the land will not be highly beneficial. Modification of depth-area relations will require extensive earth movements to attain a small but deep storage reservoir or playa. Under present economic conditions, this would be infeasible.

The unpredictability of the occurrence of water in the playa may be the limiting factor in the utilization of playa water for irrigation. An irrigation enterprise must possess sufficient flexibility to utilize playas as an alternate source of water rather than total dependency upon playa water. In order to attain this flexibility, additional expenditures would be required. Many irrigators are reluctant, in view of tightening economic constraints, to adopt this flexibility. Only those with a marginal primary source are willing to take the chance.

This paper assumes that water is available and presents a dynamic programming model useful in determining the optimal utilization of the water collected and stored in playa lakes for irrigation.

REVIEW OF LITERATURE

The problem of optimal utilization of a stochastic water supply is not new to todays water analyst. High speed digital computers and the development of dynamic programming theory has simplified the task of arriving at solutions to this type of problem.

Hall and Buras [1961] presented the application of dynamic programming to the general class of water resource problems to permit optimum development with respect to all benefits. Application of dynamic programming to determine the optimum irrigation practices was utilized by *Hall and Buras* [1961 (Feb)] in presenting a simple graphical procedure for solutions. This procedure permitted the determination of an optimum policy for irrigation of homogeneous lands under conditions of a deficient water supply.

Another application of dynamic programming techniques was by *Hall & Butcher* [1968] in determining the timing of irrigation. The methodology described permitted farmers to determine the time and quantity of irrigation to correspond with critical stages of crop growth. It possesses a limitation in that data relative to critical periods for crops and the magnitude of the adverse effects of associated soil moisture deficiences is lacking for most commercial crops.

Hall and Howell [1970] reported procedures for allocating the degree of assurance of a supply of water rather than taking the water itself as a primary resource. Introduced was the stochastic concept or probability of occurrence of a water supply rather than the presumption of a certainty of supply as used by others. The stochastic feature very nearly approximates the conditions which exist within the playa lake waters.

DEVELOPMENT OF A DYNAMIC PROGRAMMING MODEL

Dynamic programming is a mathematical technique for solving certain types of sequential or time-staged decision processes [*Howard*, 1956; *Roefs*, 1968; *Wagner*, 1969]. In order to use dynamic programming, one must be able to distinguish between system states and decisions. A state variable is one whose value completely specifies the instantaneous situation of the system. The values of the state variables provide the analyst with enough information about the system permitting a decision to be made. A decision is an opportunity to change the state variables at any given stage.

Another prerequisite to the use of dynamic programming is that the principle of optimality cannot be violated. In order to prevent violation, one must be able to identify a value function for a current decision such that it is unrelated now or in the future on any decision except in ways expressed in the value function of the state variable.

Two principle types of dynamic programming are deterministic and stochastic or probabilistic. In deterministic programming, the assumption is that all events are certain and the magnitudes thereof are known. In stochastic dynamic programming, the events and magnitudes are represented by probability distributions.

DETERMINISTIC DYNAMIC PROGRAMMING

A two-state variable deterministic dynamic programming model was developed to determine the optimal utilization of playa lake water for irrigation. The objective of the model was to determine the amount of playa lake water to apply to the land, through conventional irrigation, as well as timing of irrigation to obtain a maximum benefit in terms of crop response.

Let S represent the total amount of storage or water available in the playa lake. The quantity S cannot be considered a fixed quantity as evaporation will decrease this quantity for each subsequent time period. The amount lost to evaporation is a function of the playa surface area and surface area is a function of the amount in storage. The amount in storage is also reduced by the amount of irrigation x, if any, within each time period. Thus the model must be solved for any variable quantity s, where $0 \leq s \leq S$. The quantity remaining in storage in any time period can be calculated using

$$s_t - x_t - e\,[\,f(s_t + s_{t+1})/\,2\,] = s_{t+1} \quad \ldots\ldots\ldots\ldots\ldots\ldots [1]$$

where s_t, x_t, $e(f)$ are storage available, amount of irrigation, and evaporation rate per unit area for the average surface area $[\,(s_t + s_{t+1})/\,2\,]$ respectively during the t-th time period. Recharge is assumed to be nonexistant.

The amount of water applied through irrigation is a function of the antecedent soil moisture and is subject to the following constraint

$$\Sigma_{i=1}^{n}\, x_t \leq s_t \quad \ldots\ldots\ldots\ldots\ldots\ldots [2]$$

Realistically, discretizations of irrigation should be compatible with the mode of irrigation in order to eliminate minimal and infeasible amounts. Irrigation efficienc is assumed to be 100%.

Soil moisture content is a function of precipitation, consumptive use, and amount of irrigation. Since the model is deterministic, precipitation was not considered. Moisture available at any time is

$$w_t + x_t - c_t = w_{t+1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [3]$$

where w_t , x_t, and c_t are moisture content, amount of irrigation, and consumptive use during t-th period respectively. Soil moisture content is also subject to the constraint

$$w_p \leq w_t \leq w_f \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [4]$$

where w_p , w_t , and w_f are moisture contents at wilting point, during t-th period, and at field capacity respectively. Although field capacity is the upper limit on moisture content, it does not necessarily correspond to the moisture content resulting in maximum crop response.

Maximum crop response generally results from the combined effects of soil tilth, climate, variety, moisture content, etc. The model assumes response is a function of soil moisture only. Let a represent the crop response with values ranging from 0 to 1. Values for a can be synthesized from experience or from actual observations of the crops in question.

Keeping in mind the variable nature of soil moisture, a recursive relationship was developed to determine crop response corresponding to some given irrigation during a given time period. The relationship is defined by

$$f_{t+1}(s,w) = \max_{x_t} [a(w_t,w_{t+1}) \cdot f_t(s,w)] \quad \text{.......................... [5]}$$

In examing equation [5], it is important to recall that x_t takes on all values from 0 to s_t in order to increase soil moisture content to w_f or a maximum value of w_t. The production function $[a(w_t,w_{t+1})]$ represents the response for average moisture content during the time periods t and t+1 and the function $[f_t(s,w)]$ represents the response due to all previous values of storage and moisture content.

The solution to equation [5] gives an optimum policy since it specifies the decisions to be made at this stage to obtain a maximum crop response. For each value of s and w, there will be a value of x which will maximize the response for each state of the system.

Enumeration of equation [5] for each succeeding time period, or until water in storage is exhausted, will yield optimum values of x for each period. Analysis of the resulting values will determine the time period during which an irrigation application would yield maximum response.

To demonstrate the feasibility of the model in utilization of playa lake water for irrigation, sample calculations were carried out using assumed data for crop response as a function of moisture content. The model presented herein utilizes synthesized values with response less than 1 at w_f, increasing to 1 at $0.75w_f$ and diminishing to 0 at w_p. The sample calculations were run for 25 stages with each stage equal to one day. Other time discretizations could have been chosen but days were consistent with time units of evaporation and consumptive use.

Irrigation applications were discretized into 0.25 inch increments. Evaporation and consumptive use were taken as constants equal to 0.25 inches per day. Results were readily developed although the actual use of this model would require more specific crop response information and consideration of evaporation and consumptive use as variables rather than constants.

STOCHASTIC DYNAMIC PROGRAMMING

A more representative model of this problem would be a stochastic dynamic programming model. In the stochastic dynamic programming model, precipitation would be treated as a random variable $P_{i,t}$. The subscript i refers to the amount of rainfall and P is the probability thereof. This random variable would be introduced into both of the state transformation equations and would require the use of expectation summations in the recursion equation. Equation [1] would be modified to read

$$s_{i,t} - x_t - e\,[f((s_t+s_{t+1})/2)] + f(P_{i,t}) = s_{i,t+1} \quad \ldots\ldots\ldots\ldots\ldots \forall i \qquad [6]$$

for a particular i and where $f(P_{i,t})$ is the inflow resulting from the precipitation i during time period t.

Equation [3] would be modified to read

$$w_{i,t} + x_t - c_t + g(P_{i,t}) = w_{i,t+1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \forall i \qquad [7]$$

for a particular i where $g(P_{i,t})$ is the increase in soil moisture resulting from a precipitation i during time period t.

The recursion equation would read

$$f_t(s_i,w_i) = \max_{x_t} [a(w_{i,t} \sum_i P(w_{i,t+1})w_{i,t+1}) \cdot$$

$$\sum_i P(s_{i,t+1}, w_{i,t+1}) f_{t+1}(s_i,w_i)] \quad \ldots\ldots\ldots \quad [8]$$

SUMMARY

The optimal use of available playa lake water is essential to sound water resources management. Optimal use is not restricted to irrigation but could include artificial recharge and/or recreation. If irrigation is the predominant use, timing of irrigation will be important in order to maximize crop response and utilization of the diminishing supply of playa water.

The deterministic dynamic programming model presented will provide the time and amount of irrigation required to maximize crop response. Two state variables utilized by the model are antecedent soil moisture and amount of water in the playa available for irrigation. Evaporation is the primary factor which will reduce the amount of water available and could become very significant if timing was not considered. The results could be materially refined by utilizing accurate data relative to crop response, evaporation and consumptive use.

A better model is the stochastic dynamic programming model presented which considers the probability of precipitation and resulting filling of the playa lakes. Expectation summations are required in the recursion equation in order to include the probability distributions. The model presented is a first attempt and has not been validated at this time.

It is recognized that neither model includes all of the variables which could possibly be included. Variables such as cost of application of irrigation water, crop diversity, value of crop, time of season, and acreage limitations would materially add to the model. Also incorporation of other uses such as artificial recharge and recreation and their associated benefits would provide a more accurate realization of optimal utilization of the playa lake water.

REFERENCES

Clyma, W., "Artificial Groundwater Recharge by a Multiple-Purpose Well," Texas Agricultural Experiment Station Publ. No. MP-712, 1964.

Hall, W. A. and N. Buras, "Optimum Irrigated Practice Under Conditions of Deficient Water Supply," Trans. ASAE, v 4, n 1, 1961.

Hall, W. A. & N. Buras, "The Dynamic Programming Approach to Water Resource Development," Jour. Geophysical Research, v 66, n 2, Feb. 1961.

Hall, W. A. & W. S. Butcher, "Optimal Timing of Irrigation," Jour. Irrig. & Drainage Div., ASCE, v 94, n IR2, June, 1968.

Hall, W. A. & D. T. Howell, "Optimal Allocation of Stochastic Water Supply," Jour. Irrig. & Drainage Div., ASCE, v 96, n IR4, Dec. 1970.

Howard, R. A., "Dynamic Programming," Management Science, v 12, n 5, Jan. 1956.

New, L., "1970 High Plains Irrigation Survey," Agricultural Extension Service, Texas A & M University, 1970.

Roefs, T. G. "Reservoir Management: The State of the Art," Washington Scientific Center Pub. 320-3508, July, 1968.

Schwiesow, W. F., "Studies of Playa Lakes in the High Plains of Texas," Texas Water Development Board Report No. 10, Dec. 1965.

Wagner, H. M., Principles of Operations Research with Applications to Managerial Decisions, Prentice-Hall, 1969.

COLLECTIVE UTILITY: A SYSTEMS APPROACH FOR THE UTILIZATION OF WATER RESOURCES

Edwin Dupnick and Lucien Duckstein

Systems Engineering Department, University of Arizona

INTRODUCTION

In regions where water is a scarce resource, such as in the semiarid southwestern United States, the competition for water between various users is often fierce. The purpose of this paper is to develop a model for optimal allocation of water resources. Where no regional agency controls water allocation, the distribution is regulated by antiquated water rights laws and negotiation between competitive water users often results in court litigation. Such is the case in the Sahuarita-Continental critical groundwater area south of Tucson. In November of 1969, the largest farming interest in the Sahuarita-Continental area filed a Superior Court suit in Tucson seeking first to cut back the amount of groundwater used by four nearby copper mines, then to allocate that water among the mines, the farmers, the ranchers, three independent water companies, and presumably, the City of Tucson (Donahue, 1969). The farming interest maintains that the mines' drawdown on the groundwater table will deplete the supply to the point where the farming land will revert to barren wasteland. The copper companies contend that they are using less water for mining than would be necessary to irrigate the Santa Cruz River Basin property which they own and which at one time was used for farming. This problem is used as a case study to formulate a system approach for the utilization of water resources. A collective utility calculus including the consideration of externalities is developed and leads to an optimal policy for allocating groundwater resources. The policy strives to maximize the variation of change in the collective utility of the firms in the Sahuarita-Continental area over an arbitrary time horizon.

COLLECTIVE UTILITY

Conceptual Framework

The concept of collective utility developed by Lesourne (1964) postulates the existence of an Economic Decision Maker (EDM) who can construct a real valued functional of the net revenue function R_h of firm h. Given a limited number of firms, determination of the net revenue functions would be a formidable task (see, for example, Dupnick, 1970). Further, determination of the functional form of the collective utility U would be extremely difficult if not impossible. To get around these difficulties, the theory of collective utility usually deals with marginal transformations, that is, it compares the relative desirability of neighboring economic states. An economic state consists of a price structure for all goods and services, a tax structure and the amount of goods that are exchanged. The EDM has the power to impose groundwater-use taxes, structured in such a way as to maximize the overall growth of collective utility in the Sahuarita-Continental area over a given time horizon.

The following indices and symbols are used in the basic model:

- i: a given type of good or service; $i = 1, 2, \ldots, I$
- h: individual firms; $h = 1, 2, \ldots, H$
- Q_{ik}: quantity of good or service of type i consumed ($Q_{ih} < 0$) or produced ($Q_{ih} > 0$) by firm h per unit time

p_{ih}: price of good if for firm h

$R_h = \sum_h p_{ih}Q_{ih}$; firm net revenue function

$f_h = f_h(Q_{1h}, Q_{2h}, \ldots, Q_{Ih}) = 0$: firm production function relating how consumed goods and services are transformed into produced goods and services

$U = U(R_1, R_2, \ldots, R_H)$: collective utility function

Hypotheses

The basic hypotheses of this model are:

H-1. The collective utility function, U, firm revenue function R_h, and firm production function, f_h, do not change in form during the time horizon considered.

H-2. Each firm is a "price-taker." The price structure is established by forces outside the economic area under consideration. This price structure is considered to be time-varying.

H-3. Each firm seeks to maximize its net revenue subject to its production function constraint. Accordingly, given a price and tax structure, an equilibrium state of goods flow will be established.

H-4. The EDM dictates that the monetary value of the flow of goods shall determine the collective utility of an economic state. Furthermore, he assigns the same real value to a dollar of goods regardless of the firm who produced or consumed that good.

H-5. The price of any good or service i consumed depends on the quantity Q_{ih} only.

With these hypotheses a marginal transformation is given by:

$$\frac{dU}{dt} = \sum_h \frac{\partial U}{\partial R_h} \frac{dR_h}{dt}$$

or

$$\dot{U} = \sum_h \frac{\partial U}{\partial R_h} \dot{R}_h \tag{1}$$

$\dot{R}_h$ is given by

$$\dot{R}_h = \sum_i \frac{\partial R_h}{\partial Q_{ih}} \dot{Q}_{ih} \tag{2}$$

where $\partial R_h / \partial Q_{ih} = p_{ih}$ (since $R_h = \sum_i p_{ih} Q_{ih}$)

Substitution of (2) into (1) yields:

$$\dot{U} = \sum_{i,h} \frac{\partial U}{\partial R_h} p_{ih} \dot{Q}_{ih} \tag{3}$$

From H-4, we may set by an appropriate choice of units

$$\frac{\partial U}{\partial R_h} = \frac{\partial U}{\partial R} = 1$$

Hence, the time change in collective utility is given by,

$$\dot{U} = \sum_{i,h} p_{ih} \dot{Q}_{ih} \tag{4}$$

The necessary conditions for the maximization of firm revenue subject to its production function is given by,

$$p_{ih} - \lambda_h \frac{\partial f_h}{\partial Q_{ih}} = 0 \tag{5}$$

$$f_h = 0 \quad , \tag{6}$$

where λ_h is the unique Lagrange multiplier for each firm. By using (5) we may substitute the marginal value of production, $\lambda_h \frac{\partial f_h}{\partial Q_{ih}}$ into (4) to obtain,

$$\dot{U} = \sum_{i,h} \lambda_h \frac{\partial f_h}{\partial Q_{ih}} \dot{Q}_{ih} \tag{7}$$

Then the policy that the EDM wishes to impose is to maximize

$$\sum \dot{U} \; dt$$

where T is the time horizon, or equivalently,

$$\sum_{i,h} p_{ih}\dot{Q}_{ih}dt \tag{8}$$

However, the policy can only be implemented through the imposition of a groundwater use tax whose purpose is to control externalities as discussed below.

Externalities

An externality between firms can be defined as those effects of the interdependence of consumer goods of different firms which are not taken into account by the managements of the various firms. In other words, the action of producing or consuming a good by a firm may affect the ability of other firms to produce their goods or else, it may affect the revenue of consumers through means other than market prices and availability of goods. An externality is defined to be *horizontal* when it primarily affects present generations, and *vertical* when it primarily affects future generations. For example, an externality may cause a lowering of the total income of an economic area or the foreclosure of alternative courses of action for future generations. Writers have either considered horizontal externalities (e.g., Buchanan and Stubblebine, 1962) or vertical externalities (e.g., Brown and McGuire, 1967) but seemingly not both. It should be noted that generally, externalities exist in both the horizontal and vertical sense.

We will specify that a horizontal externality for firm h exists, whenever,

$$\int_0^{Q^*_{ig}} \frac{\partial R_h}{\partial R_{ig}} dQ_{ig} \neq 0$$

where good i is under the (at least) partial control of some other firm g and Q^*_{ig} indicates the equilibrium value for the revenue offering R_g to be maximum. To compensate for this, the EDM levies a Horizontal Externality Tax, HET_{ig}, (good i, firm g)

$$HET_{ig} \triangleq \int_0^{Q^{**}_{ig}} \frac{\partial R_h}{\partial R_{ig}} dQ_{ig} \tag{9}$$

and subsidizes firm h in the form of a compensation B_h

$$B_h \triangleq - HET_{ig} \tag{10}$$

in (9) Q^{**}_{ig} indicates the new equilibrium value of Q_{ig} when firm g considers the tax.

A vertical externality often results when present and future generations are not given equal consideration for the consumption of goods. This can be corrected by the use of discounting. Rather than allowing each firm to maximize its revenue over a given time horizon without consideration of future generations, the EDM dictates that each firm shall instead, maximize

$$\int_0^T R_h e^{-rt} dt$$

subject to

$$f_h = 0 \tag{11}$$

where r is the accepted discount rate. Then the necessary conditions for the maximization of revenue become:

$$p_{ih}e^{-rt} - \lambda_h \frac{\partial f_h}{\partial Q_{ih}} = 0 \tag{12}$$

$$f_h = 0 \tag{13}$$

On comparing (5) with (12) we note a difference of $p_{ih}(1 - e^{-rt})$. Thus, if a resource-use tax or Vertical Externality Tax VET_{ih} (good i, firm h)

$$VET_{ih} \triangleq - (1 - e^{-rt}) \lambda_h \frac{\partial f_h}{\partial Q_{ih}} \tag{14}$$

were added to the marginal value of product in (5), the effect would be to force each firm to follow the optimal policy indicated by (12). The net effect of the tax VET_{ih} is therefore, the removal of vertical externalities. The problem of combining horizontal and vertical externality taxes to optimize resource allocation over space and time can now be examined.

Optimal Policy of Water Resources Utilization

The EDM can accomplish his goal to maximize

$$\int_0^T \dot{U}dt$$

by imposing taxes such that

$$p_{ih} + HET_{ih} + VET_{ih} = \lambda_h \frac{\partial f_h}{\partial Q_{ih}} \tag{15}$$

$$f_h = 0$$

The net revenue function of each firm is given by

$$NR_h = \sum_i (p_{ih} + HET_{ih} + VET_{ih}) Q_{ih} + B_h \tag{16}$$

the horizontal and vertical externality taxes are respectively

$$HET_{ih} = \int_0^{Q_{ih}^{**}} \frac{\partial R_g}{\partial Q_{ih}} dQ_{ih} \tag{17}$$

and

$$VET_{ih} = -(1 - e^{-rt}) \lambda_h \frac{\partial f_h}{\partial Q_{ih}} \tag{18}$$

It should be noted that the revenue function R_g of firm g appearing in (17) is *not* the same form as the function NR_h indicated by (16), R_g indicates that the revenue of firm g *without* h or subsidies.

The Sahuarita-Continental Area problem presented at the beginning of this paper will be used to develop an example in the next section.

CASE STUDY

The optimal policy of groundwater use derived above will be limited to two identical farming concerns, raising an identical crop with irrigation water pumped from a common groundwater pool. Hence, horizontal and vertical externalities will be present.

Let the simplified net revenue function for each firm be given by

$$\text{Net Revenue} = \text{Crop Revenue} - \text{Pumping Cost} \tag{19}$$

the production function by

$$\text{Crop Yield} = \sum_{i=0}^{2} [a_i(\text{Water per Acre})^i] \text{ Acres} \tag{20}$$

and the pumping cost by

$$C_0 + C_1(\text{Pumping Lift})(\text{Total Water Consumption}), \tag{21}$$

where

$$\text{Pumping Lift} = \int_0^T [-K_0 + K_1 \sum_{s=g,h} Q_s]dt + \text{Initial Lift} \tag{22}$$

and

$$\text{Total Water Consumption} = (\text{Water per Acre})(\text{Acres}). \tag{23}$$

The quantities C_0 and C_1 are, respectively, a fixed and a variable cost of pumping; K_0 and K_1 are hydrological parameters. K_0 denotes the annual recharge of the aquifer, measured in feet of rise of the groundwater table and K_1 denotes the decline of the groundwater table per unit of water pumped from the aquifer.

Since the only good to be considered will be the groundwater consumed, we will simplify the notation to the following:

Q_h: rate of groundwater consumption by firm h at time t,

p: unit crop price;

PL_h: pumping lift at time t, for firm h

HET_h: horizontal externality tax for firm h at time t,

VET_h: vertical externality tax for firm h at time t,

PL_{0h}: initial pumping lift (at t = 0),

PC_h: pumping cost for firm h at time t,

λ_h: total crop yield for firm h at time t,

A: number of acres on each farm (the same for all farms).

We can rewrite the net revenue function and the production function (2) as

$$R_h = (p + HET_h + VET_h)\ Y_h - PC_h$$

$$f_h = Y_h - \sum_{i=0}^{2} [a_i (Q_h/A)^i]A = 0 \tag{24}$$

The necessary conditions for a maximum net revenue for each firm is given by

$$(p + HET_h + VET_h)\ \frac{\partial Y_h}{\partial Q_h} + Y_h\ (0 + \frac{\partial HET_h}{\partial Q_h} + \frac{\partial VET_h}{\partial Q_h})$$

$$- \frac{\partial PC_h}{\partial Q_h} = \lambda_h \frac{\partial f_h}{\partial Q_h} \tag{25}$$

and

$$f_h = 0,\ h = 1,\ 2$$

where

$$\frac{\partial Y_h}{\partial Q_h} = a_1 + 2a_2 Q_h \qquad \text{(the a's are given by (20))} \tag{26}$$

$$\frac{\partial HET_h}{\partial Q_h} = \frac{\partial R_g}{\partial Q_h} \qquad \text{(g is the "other" firm)}$$

$$= - \frac{\partial PC_g}{\partial Q_h}$$

$$= - C_1 Q_g \frac{\partial PL_g}{\partial Q}$$

$$\frac{\partial HET_h}{\partial Q_h} = - C_1 Q_h Q_h \tag{27}$$

$$\frac{\partial VET_h}{\partial Q_h} = - (1 - e^{-rt}) \frac{\partial}{\partial Q_h} (\lambda_h \frac{\partial f_h}{\partial Q_h}) = - (1 - e^{-rt}) \lambda_h \frac{\partial^2 f_h}{\partial Q_h^2} \tag{28}$$

$$\frac{\partial PC_h}{\partial Q_h} = C_1 (K_1 Q_h^2 + \int_0^T [- K_0 + K_1 \sum_{S=1}^{2} Q_s] \, dt + PL_{0h}) \tag{29}$$

$$\lambda_h = p/(\partial f_h/\partial Q_h) \tag{30}$$

$$\frac{\partial f_h}{\partial Q_h} = - a_1 - 2a_2 Q_h \tag{31}$$

$$\frac{\partial^2 f_h}{\partial Q_h^2} = - 2a_2 \tag{32}$$

Upon substitution of Equations (26) - (32) into (25) we obtain

$$(p + HET_h + VET_h)(a_1 + 2a_2 Q_h) - \sum_{i=0}^{2} [a_i (Q_h/A)^i] A [C_1 Q_g Q_h - 2a_2 (1 - e^{-rt})] - C_1 (K_1 Q_h^2 + PL_h) = p \tag{33}$$

with

$$HET_h = \int_0^{Q_h} C_1 Q_g dQ_h = - \frac{C_1 Q_g Q_h}{2} \tag{34}$$

$$VET_h = - (1 - e^{-rt}) p \tag{35}$$

The optimal consumption of groundwater for each firm will result from the simultaneous solution of (33), (34), and (35).

It can be readily seen that the consideration of more than one good would have led to a rather complicated system of equations. By considering such a simplified production function, we have eliminated other factors such as labor, farm implements, gasoline, and so on. To realize a closer approximation of the collective utility concept other firms (copper mines, ranchers) should be included in the model. Such an analysis would be warranted to evaluate several different possible actions of the State (in addition to the EDM's actions) to monitor the growth of collective utility. Each action would be evaluated by calculating the value of the maximized integral of $\dot{U}$ of that action. The most desirable action of the State would correspond to the maximum value of that integral.

CONCLUSIONS

The collective utility model enables one to approach the utilization of water resources in a global manner: in this sense it is a systems approach. In particular, this model allows a simultaneous elimination of vertical and horizontal externalities. The technique has sufficient flexibility to encompass the diverse activities of individuals and firms that usually compose an economic area. However, the level of detail of the analysis is limited by the complexity of the resulting system equation.

An example taken from a case study has suggested how the utility approach can be used to make sequential decision for optimal economic states, the EDM is able to derive an optimal policy of water utilization taking into account the externalities that usually accompany any resource consumption.

Acknowledgments. The research described in this paper was partially supported by Allotment Grant Number 5010-5351-71 of the Water Resources Research Center, The University of Arizona. The computations were done at The University of Arizona Computer Center on the CDC-6400 installed there.

REFERENCES

Brown, G., Jr., and C. B. McGuire, A Socially Optimum Pricing Policy for a Public Water Agency, *Water Resources Research*, *3*(1), 33-43, 1967.

Buchanan, J. M., and W. C. Stubblebine, Externality, *Economica*, *29*(116), 371-384, 1962.

Donahue, N., Farmer Investment Files Suit to Limit Pumping by Mines, *Tucson Daily Citizen*, *99*(280), 40, 1969.

Dupnick, E., Water Reallocation in the Sahuarita-Continental Area, File Report 324-H, Systems Engineering Department, The University of Arizona, Tucson, 1970.

Lesourne, J., *Le Calcul Economique*, Dunod, Paris, France, 1964.

Comparison of Water Pricing Structures from a Collective Utility Viewpoint

by

Bill Metler and Lucien Duckstein
Systems Engineering Department
University of Arizona
Tucson, Arizona 85721

INTRODUCTION

As a result of continually lowering water tables in the arid regions of the West, researchers on water resource projects have begun realizing that it would be a good idea to consider water as any other rare resource and to let economic factors regulate its distribution (supply and demand). The control or balance of the economic factors is in the power of the public domain as represented by a city water management agency. This agency establishes some price rate structure for the collection of revenues. Metering is found to be a reliable, practical means of measuring the water consumption of users, and revenues are collected according to the measured consumption.

Historically there are four basic areas or categories of consumption. There are agricultural, industrial, commercial, and residential. Each category has its own rate structure. The revenue collected by the city water management agency then is a function of the category and the rates assessed in that category. In a study of public utilities, Whitford (1970) found that on the average of 41% of the consumed water occurred in the residential category.

24% in industrial, 18% in commercial, and 17% elsewhere. Thus, depending on the rate structure of the residential category, a good percentage of the revenue collected by the water agency occurs from residential consumption.

At present, Tucson's only source of water lies underground, and as Tucson's population grows, the pumping of water from this source will increase if no other source becomes available. The concern here is how a water agency can best accomplish the distribution of water to maximize benefits to the community. It may be desirable to decrease not only average consumption, but also peak consumption, which in Tucson, occurs during the summer because of sprinkling, evaporative coolers and swimming pools. To conserve water, the agency itself must practice a sound economic policy which is expressed as a price structure. We propose in this investigation a model for comparing two price structures from a collective utility standpoint in an effort to define a monetary value for the conservation of water.

TYPES OF PRICE STRUCTURES

There are basically three price structures for assessing water rates. One is called the flat rate. The flat rate system assesses upon the consumer a fixed price per billing period which is dependent upon many factors, e.g., type of dwelling (apartment, farmhouse), business establishment, or type of plumbing fixtures. Another structure is the step rate system. Under this system the unit rate is dependent on the total quantity consumed. The last type of price structure is the block rate. Under this system a new unit price is prescribed for each block of the total quantity consumed.

Each of these structures may be regressive or progressive. In a regressive pricing structure, rates decrease as quantity increases (a policy of marginal pricing and non-conservation). In a progressive pricing structure, rates increase as consumption increases (a policy of conservation). The City of Tucson presently uses a regressive block rate pricing structure.

This paper will consider a change of pricing structures for each of two periods from a collective utility standpoint. The collective utility is examined for a change in the present regressive rates to a permanent and seasonal progressive block rate pricing structure.

Before discussing collective utility in terms of a change in water pricing structure, we will try to present a brief theoretical overview of collective utility.

THE MODEL: THEORY

What is collective utility? Collective utility is an idealized measure of the worth of an economic state. We can only calculate the value of a change in collective utility which is then a measure of the value of a change from one economic state to another. We can consider four classes or sectors of the economy contributing to the economic state within jurisdiction of the agency. These four classes are residential, industrial, commercial, and agricultural. Each of these sectors is in an economic state and each can be measured in terms of collective utility.

For purposes of our mathematical model we define our variables with the following indices:

i	goods or services
k	persons, individuals
h	firms, companies
Q(i,k)	quantity of good or service of type i consumed by individual k
Note:	Q(i,o) is the initial quantity of i Q(i) is the total quantity consumed $Q(i) = \sum_k Q(i,k)$
Q(i,h)	quantity of good or service of type i produced by firm h
p(i,k)	price of good i paid or obtained by k
p(i,h)	price of good i paid or obtained by h
r(k)	revenue or income obtained by k
u(k)	real income of k
r(h)	revenue or income obtained by h

The satisfaction function of individual k is defined to be (Lesourne, 1964)

$$S(k) = S[k, Q(1,k), Q(2,k), \ldots, Q(I,k)].$$

The production function of firm h is a function of the goods and services consumed and produced by the firm:

$$f(h) = f[h, Q(1,h), \ldots, Q(m,h)] = 0.$$

This function, which may be vector valued, describes technological and other constraints.

An indifference curve for individual k describes the trade-off of good i versus good j for a given value of satisfaction, S(k). Thus, individual k receives as much satisfaction by consuming x units of good i and y units of good j as by consuming x' units of i and y' units of j. A set of indifference curves for individual k may thus be defined by considering different values of satisfaction; each curve of constant satisfaction represents the trade-off of i for j. We assume that S(k) is constrained by k's income, r(k). If the society consists of two individuals, k and m, we may find that, by a proper redistribution of goods i and j, k may rise to a higher level of satisfaction, from $S_1(k)$ to $S_2(k)$, while m remains on his current indifference curve (satisfaction unchanged).

Extending this argument to a multi-dimensional concept, where each dimension represents a good, we may define an indifference hypersurface which gives the trade-off between all goods included in the satisfaction function of individual k.

An economic state can then be defined as the Cartesian product of the set of indifference hypersurfaces (one element per individual k).

The collective utility is a function of the indifference surfaces which in turn depend on the individual satisfaction functions.

$$U(S) = U(S(1), S(2), \ldots, S(k))$$

The collective utility function then provides a measure of the total flow of goods within a given economic state because each satisfaction function gives a relationship among these goods. As stated earlier, individual k's consumption is limited by r(k):

$$f(k) = \sum_i p(i)Q(i,k).$$

A change in collective utility, dU, then will measure the worth of the change from economic state 1 to 2. If dU is negative, the monetary value of the flow of goods is lessened; if dU is positive, the flow is increased relative to the initial state.

The basic expression for dU will be derived using the following working hypotheses.

H-1. For each fixed distribution of income, r(k), a system of prices and a set of quantities exist so that each individual's satisfaction is maximized. Each individual feels satisfied that he is getting the "most" for his money.

H-2. p(i,k) depends only on Q(i,k), i.e., the price of good i depends only on the demand-to-offer ratio of good i and is independent of the flow of the goods. There is no discount on the price of good i for buying good j.

H-3. Every individual pays the same price for a given good there is no favor in price to anyone.

$$p(i,k) = p(i)$$

H-4. $\Delta r(k)$ equals $\Delta u(k)$, i.e., with a proper selection of units a change in the measure of k's economic state equals a change in k's purchasing power.

H-5. Assume k's taste for good i remains constant, i.e., the desirability of good i remains the same. From these hypotheses and the relationships:

$$S(k) = S[k, Q(i,k)]$$

$$r(k) = \sum_i p(i)Q(i,k)$$

$$U = U(S(1), S(2), \ldots, S(k))$$

we find,

$$dU = \sum_{i,k} [p(i,k) + \frac{dp(i,k)}{dQ(i,k)} Q(i,k)] \, dQ(i,k)] \qquad (1)$$

U is assumed differentiable to yield dU. S(k) is maximized by Lagrange multipliers, constrained by r(k) and substituted into the equation for dU.

Normally it would be necessary to continue the theoretical developments to derive an expression for dQ(i,k). In the collective utility theory dQ(i,k) must account for the substitution of goods upon a change in the system of prices and set of quantitites. dQ(i,k) may be computed by use of the Slutsky coefficients, which, however, is beyond the scope of this paper.

THE MODEL: IMPLEMENTATION

The expressions for dU imply a knowledge of p(i), Q(i,k), dp(i) and dQ(i,k). The last variable is the most difficult to obtain and the most controversial to define accurately. Assumptions (indicated by the letter A followed by a numeral) will enable us to implement the model:

A-1 There are no goods to be substituted for water. Thus, dQ(i,k) (normally computed using the Slutsky coefficients) may come from empirical data of past changes or inferred from demand schedules. We have chosen the latter means. That is, dQ(i,k) can now be determined by the proper selection of a value for the elasticity of demand n:

$$n = \frac{\Delta Q}{Q} / \left(\frac{\Delta p}{p}\right)$$

A-2 The value of n is the same for all individuals k.

A-3 The demand for water by industry is inelastic. Brown (1968) estimates that water costs account for about one percent of total production costs in industry, so water costs are relatively minor in minimizing total costs of production. This of course means that dQ(i,h) may be considered as having a small effect on conservation. Society can force industry's demand schedule toward elasticity by raising the price of water to a point where percentage of production costs by water becomes significant.

A-4 The demand schedule for commerce will be taken in first approximation as identical to that for industry.

Thus, in computing dU for purposes of studying conservation, we shall only be concerned with the residential sector of the community. This simplifying assumption will be removed in further studies to be published at latter date.

The Tucson Department of Water and Sewers is currently in the process of developing computer programs designed to estimate the revenue gained from water each month. Thus, there are some reliable data available, but at this time these data are not suited to our mathematical model, and are far from complete. Without having to go through each user's bill, it is possible to use the data from the computer print-out with some assumptions. A sample print-out is given for one month for one of four metered areas (inside Tucson, outside Tucson, South Tucson, and remote or special areas). There are three rates according to consumption groups; the first is a flat rate while the succeeding two are incremental.

A-5 The distribution of bills within a consumption group is uniform. We expect to construct frequency distributions for each type of service for each area in the continuation of this research, but a uniform distribution allows us to demonstrate the applicability of the model although the results will be inaccurate.

A-6 The elasticity of demand is -.5 for annual residential use in Tucson. Howe and Lineweaver (1967) give a weighted mean of -.405, Clausen (1970) gives -0.35 while stating that the Tucson value is much higher, and Whitford (1970) gives -0.5 as weighted mean from a John Hopkins study for western areas.

EXAMPLE OF IMPLEMENTATION

For this example we will only consider the dU for the month of February, 1970, for $\frac{3}{4}$ in. service pipe (residential in the Remote area). Data are presented below.

Let

$$i = \text{water rate } 1, 2, \text{ or } 3$$

$$p(i) = \text{price of water } i \text{ in state } 1$$

$$dp(i) = \text{change of price for water } i$$

$$Q(i,k) = k\text{'s consumption of water } i \text{ in state } 1.$$

$$dQ(i,k) = \frac{nQdp(i)}{p(i)}$$

$\frac{3}{4}$" Users Remote	Consumption	Rate	# Users
In state 1:	0 - 700 ft.^{3}	\$7.50	142
	800-3700 ft.^{3}	.40/100 ft.^{3}	425
	3800 - ft.^{3}	.40/100 ft.^{3}	30

Let us hypothesize 2 as follows:

0 - 700 ft.^{3}	\$7.50	to be determined
800-3700 ft.^{3}	.41/100 ft.^{3}	
3800 - ft.^{3}	.43/100 ft.^{3}	

In this problem the price paid for good i is not independent of the quantity consumed. Thus

$$\frac{dp(i)}{dQ(i,k)} \neq 0$$

and

$$dU = \sum_{i,k} \left[p(i) + \frac{dp(i)}{dQ(i,k)} Q(i,k)\right] dQ(i,k) \tag{2}$$

becomes

$$dU = \sum_{i,k} [p(i)dQ(i,k) + dp(i)Q(i,k)] \tag{3}$$

Since dp(i) is positive, dQ(i,k) is negative and an individual k in group i = 3 may, by reducing consumption, fall into i = 2. Thus, we must be careful to recognize this "shift" when performing the summation in (3).

Define H = {k|k is a user in the remote area of service type $\frac{3}{4}$"}

In state 1, H(1) = K1 + K2 + K3, with K1·K2·K3 = ∅;

for example, K2 = {k|k is a user in state 1 whose maximum consumption places him in rate i = 2}

In state 2, $H(2) = [K1 + \Delta K(2\text{-}1)] + [K2 + \Delta K(3\text{-}2) - \Delta K(2\text{-}1)]$

$+ [K3 - \Delta K(3\text{-}2)]$

where e.g., $K(2\text{-}1) = \{k|k$ is a user who shifts from rate $i = 2$ to rate $i = 1\}$

Now let us set up the dU formula with the proper summation sets

$$dU = \sum_{\substack{i=1 \\ k\epsilon H(2)}}^{3} [p(i)dQ(i,k) + Q(i,k)dp(i)]$$

for $i = 1$,

$$dU(1) = \sum_{k\epsilon K1 + K2 + K3 = h} [p(1)dQ(1,k) + Q(1,k)dp(1)]$$

(everyone pays $i = 1$)

$$dU(1) = Hdp(1)$$

since all k's must pay dp(1), dQ(1,k) is irrelevant because p(1) is a flat rate. Also there is no change hypothesized for $i = 1$ so, $dU(1) = 0$, i.e., there is no change in collective utility for $i = 1$. Now for $i = 2$

$$dU(2) = \sum_{k\epsilon K2 + \Delta K(3\text{-}2) - \Delta K(2\text{-}1)} [p(2)dQ(2,k) + Q(2,k)dp(2)]$$

$$+ \sum_{k\epsilon K3 - \Delta K(3\text{-}2)} [p(2)dQ(2,k) + Q_m(2,k)dp(2)]$$

where $Q_m(2,k)$ is the maximum consumable quantity in rate $i = 2$ for k in rate $i = 3$; also, $dQ(2,k) = 0$ for k in rate $i = 3$, therefore,

$$dU(2) = \sum_{k\epsilon K2 + \Delta K(3\text{-}2) - \Delta K(2\text{-}1)} [p(2)dQ(2,k) + Q(2,k)dp(2)]$$

$$+ \sum_{K\epsilon K3 - \Delta K(3\text{-}2)} Q_m(2,k)dp(2) \qquad (4)$$

now for i = 3

$$dU(3) = \sum_{k \in K3 - \Delta K(3-2)} [p(3)dQ(3,k) + Q(3,k)dp(3)] \quad (5)$$

To determine the ΔK sets, use A-2 and A-6 to obtain

$$\Delta Q = \frac{nQ\Delta p}{p} = \frac{(-.5)\ (41)\ (.03)}{.4} = 1.54$$

Thus each k paying rate i = 3 will reduce his consumption by an average of 154 ft.^{3}.

Using A-6,

$$\Delta K(3\text{-}2)(26.7)\text{ft}^3/\text{user} = 154\ \text{ft.}^3, \text{ yielding } K(3\text{-}2) = 5.$$

Thus of the k's paying rate i = 3 there will be 5 who shift from rate i = 3 to rate i = 2.

We can find by the same method all quantities in the above formulas. The computations are, for evaluating dU, found in Appendix A. The results are:

PERMANENT RATE CHANGE

1.	[ΔQ(2)] = 25 ft.^{3}	[ΔQ(3)] = -154 ft.^{3}
2.	dU(2) = $24.63	dU(3) =-$12.00
3.	K(2-1) = 4	ΔK(3-2) = 5
4.	Total dU = $12.63	
5.	Total dU for 12 months = $150	

Thus, if November is considered as an average month, the annual increase in collective utility would be about $150 for the Remote Area of service type $\frac{3}{4}$". Thus, the rate change would be recommended.

SEASONAL RATE CHANGE

Now let us examine the change in collective utility if the price rate structure is changed during the summer and remains as now during the winter.

We will make the same assumptions as for the preceding example and select the month of September as the sample month for the summer. Therefore, for the Remote Area of service type $\frac{3}{4}$", the following rates are to be charged during the six summer months:

Type	Consumption	# Users	Rate State 1	Rate State 2
$\frac{3}{4}$"	0 - 700 ft.^{3}	106	$7.50	$7.50
	800-3700 ft.^{3}	436	.40/100 ft.^{3}	.41/100 ft.^{3}
	3800 - ft.^{3}	41	.41/100 ft.^{3}	.43/100 ft.^{3}

The elasticity of demand during the summer will be taken to be -.7 (Howe and Linaweaver, 1967). For the summer then the results are as follows:

1. Q(2) = -38.5 ft.^{3} Q(3) = -251 ft.^{3}
2. dU(2) = $4.63 dU(3) = -$16.25
3. K(2-1) = 5 K(3-2) = 8
4. Total monthly dU = -$11.62
5. dU for 6 months = -$70

Thus a price rate structure changed only for the summer would apparently be detrimental to the economic state of the area in question. A closer scrutiny of such a seaonal rate change shows that it is still beneficial.

COMPUTATION OF ΔQ AND ΔR

Why is there a difference in the sign of dU for the proposed rate changes? To answer this question we will compute the change in revenue and the change in water consumption for both the permanent change and the seasonal change. In computing ΔR and ΔQ for both cases we use the preceding assumptions given in finding dU.

Because there is no change in the first rate, there will be no noteworthy changes in the consumption pattern of those users who only have to pay the first rate.

(a) For the permanent change,

$$\Delta R = \$216 \text{ for 12 months}$$

i.e., The revenue is increased by the change; and

$$\Delta Q = -200{,}000 \text{ ft.}^3 \text{ for 12 months}$$

i.e., water was conserved.

(b) For the seasonal change,

$$\Delta R = -136{,}800 \text{ ft.}^3 \text{ per season}$$

i.e., water would be conserved.

In tabular form,

Permanent Change	Seasonal Change
$\Delta R = \$216$	$\Delta R = -\$31.32$
$\Delta Q = -200{,}000$ ft.^{3}	$\Delta Q = -136{,}800$ ft.^{3}
$n = -.5$	$n = -.7$
$dU = \$150$	$du = -\$70$

Note that the signs of ΔR and dU are the same.

The computer was used to perform further tedious numerical calculations. Under our assumptions the following values for the month of November were obtained:

n = -.5	dU(2)$	dU(3)$	ΔR$	ΔQ/100 $ft.^3$
Remote $\frac{3}{4}$ in.	24.63	-12.00	18.32	-163
South $\frac{3}{4}$ in.	41.91	-28.16	-5.04	-431
Outside $\frac{3}{4}$ in.	138.09	-59.47	129.43	-1186
Inside $\frac{3}{4}$ in.	1593.55	-888.13	-896.26	-32671

Total dU	Total ΔR	Total ΔQ
810.43	-753.55	-34451

For the month of September:

n = –.7	dU(2)$	dU(3)$	ΔR$	ΔQ/100 $ft.^3$
Remote $\frac{3}{4}$ in.	4.63	-16.25	-5.22	-228
South $\frac{3}{4}$ in.	2.69	-32.94	-60	-603
Outside $\frac{3}{4}$ in.	-1.59	-73.66	-12.33	-1660
Inside $\frac{3}{4}$ in.	-1215.38	-257.18	-3714.11	-45740

Total dU	Total ΔR	Total ΔQ
-1589.68	-3791.65	-48232

DISCUSSION: RESULTS

With either suggested price structure the water utility agency under our hypotheses will lose money and water consumption will be lowered. However, under the permanent change the monetary value of the flow of goods would be be relatively greater while under the seasonal structure of the flow of goods would be relatively decreased. In economics the flow of goods indicates the "health" of the economy. Thus, under our hypotheses the permanent structure change would be recommended and the temporary would not be suggested. If it is deemed by the public to conserve water, then the temporary structure could be implemented although the "health" of the economy might suffer.

The reader might expect that $\Delta R = dU$, since the flow of goods exists only between the agency and the individuals. The value for ΔR and dU are different because ΔR is a function of the consumption levels and prices in State 1 versus State 2, whereas dU is a function of the consumption and price <u>changes</u> given the State 1 values. Since the price is increased in our example, Qdp gives a value for the flow when the consumption remains constant and the price remains constant and the price is changed, and pdQ gives a value for the flow when the price remains constant and the consumption changes. dU then reflects a trade-off between these two flows. A negative value of dU implies that pdQ is larger than Qdp; that is, the reduced consumption more than offsets the increase in price, thus water is conserved.

The phenomenon of shifting accounts for the difference between ΔR and dU. ΔR is computed <u>post facto</u> as a function of the state of nature and unit prices. dU, on the other hand, is computed on a marginal basis and so reflects the change of flow as a function of these marginal values and the given state of nature.

In the arid regions of the Southwest where water is among the scarcest resources, we see that dU is a better measure of a change in pricing than

ΔR. We note that it is possible to have a negative ΔR (indicating conservation on the basis of a loss in revenue) and a positive dU. The difference between ΔR and dU can be enlarged if the price break between rates is increased. Furthermore, industry and commerce can contribute nothing to conservation until society raises their elasticity to a point where the costs of water become a significant proportion of production costs.

If the agency adopts a policy of increasing the water rates on a programmed basis, collective utility provides a mechanism for considering the substitution of goods, e.g., refrigerated cooling instead of evaporative cooling and non-water consumptive forms of landscaping instead of lawns, shrubs, and trees.

Several criticisms can be raised about this model. The first concerns the abundance of assumptions. Perhaps the most significant assumption relating to implementation concerns a uniform distribution of users within a group because it forces us to define an upper limit in the third consumption group (in this case 4500 $ft.^3$). We are taking steps to construct a frequency distribution function which will obviate the need for the assumption of uniformity Once we have constructed a frequency distribution function we can consider the influence of commercial and industrial consumption.

The assumption of applying the same demand schedule to all individuals is plausible after considering certain factors. Those individuals who consume the most generally can afford to pay according to their consumption. Furthermore, few individuals know to which price rate group they belong; so no individual will lower his consumption more than the demand schedule indicates. Other elasticities could easily be considered according to the economic sector of the city in which the individuals live.

Higher rate change structures could be hypothesized to find which structure causes the value of a positive dU to change to a negative dU. Under our assumptions such changes in structure have been hypothesized and a sensitivity analysis conducted with the aid of a computerized model.

For this particular model we changed the limit in the third rate to 6100 ft.^{3}. We made two runs in computing dU and ΔR. The first run was on the present regressive rate structure with no increase in price for rate i = 1, a 0 to 50% increase within price for i = 2, and a 0 to 50% increase in price for i = 3 both in increments of 5% for each of the four billing areas in Tucson. This was repeated for elasticities from -.3 to -.65 in increments of -.05. The second run was on a progressive rate structure with no increase in price for rate i = 1, a 0 to 50% increase in increments of 5% for i = 2, and a 0 to 100% increase in increments of 10% for i = 3 for each of the four billing areas in Tucson. This also was repeated for elasticities from -.3 to -.65 in increments of -.05 . For both runs it was found that dU started with a positive value, increased to a maximum and then decreased for all elasticities except -.65. At -.65, for the regressive structure, dU started positive and decreased for each increase; for the progressive structure, dU started negative and decreased for each increase in price. The sensitivity analysis also shows that, for a given elasticity and level of percentage increase, dU for the progressive structure is always less than dU for the regressive structure, the difference being due to the greater shifting from i = 3 to i = 2 in the progressive structure. However, dU is seldom negative except at the higher values of elasticity and at the greater changes in price which are politically impractical. The analysis does substantiate the belief that a progressive price rate structure does encourage lower consumption of water than a regressive structure. It should be emphasized here that in all cases ΔR continued to increase in value well after dU had reached its maximum, i.e., the values of dU are more sensitive to shifting than the values of ΔR. The analysis also tends to indicate that once the community is on a progressive rate structure, the rates of $i = 2$ should be increased as much as the rates in $i = 3$ since the bulk of the residential consumers lies in $i = 2$. The consumer shift from group $i = 2$ to $i = 1$ would have even more impact on dU than the shift from $i = 3$ to $i = 2$. These results are illustrated in Figure 1 for a progressive pricing structure and in Figure 2 for a regressive one. The numbers labeling the lines represent the percentage of price increase in group $i = 1, 2, 3$, respectively.

CONCLUSIONS

The mathematical model for collective utility is intrinsically suited to a computer program. With the aid of the computer the user sets can easily be defined and a distribution function devised from available data. Such function could give the ΔK sets upon computation of ΔQ from a given n. These ΔK sets and distribution functions would of course give a more accurate value to the shift of users from one rate to another and lead to an accurate evaluation of a city-wide dU. Such a value of dU would enable the agency to evaluate the benefit of change of price rate when having to consider in their decision the benefit to the community of water conservation and the lowering of consumption peaks.

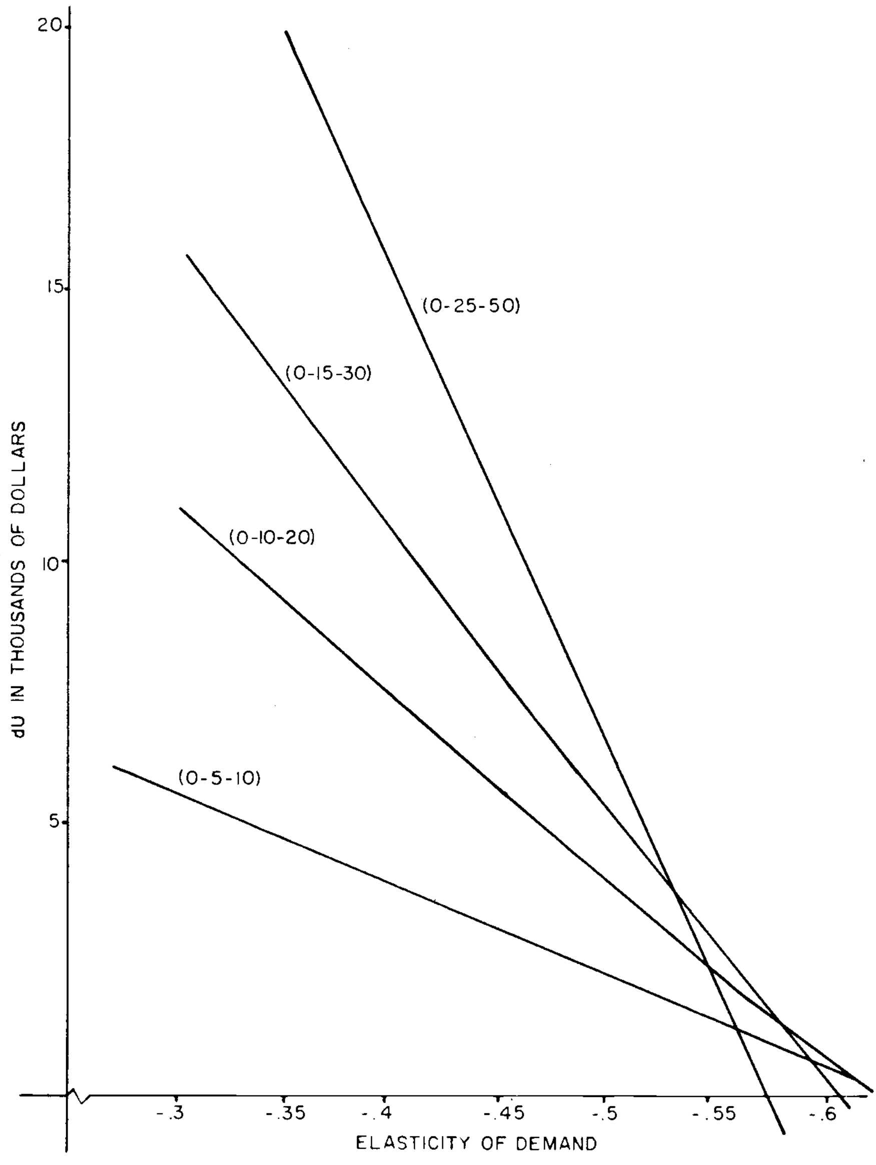


FIGURE 1

Collective utility change dU versus elasticity and price increase schedule for a Progressive Pricing Policy

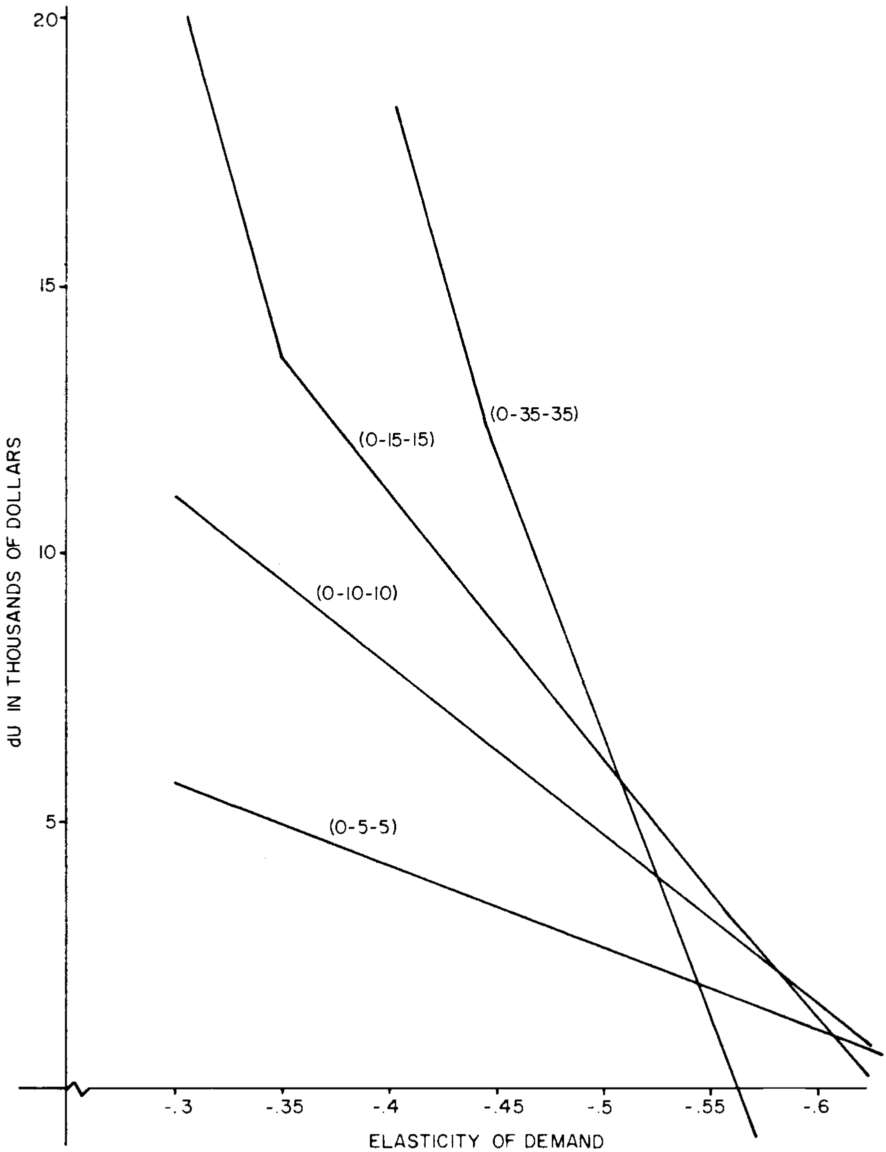


FIGURE 2

Collective utility change dU versus elasticity and price increase schedule for a Regressive Pricing Policy

APPENDIX A:

Numerical Evaluation of dU

We have shown earlier that dU for i = 1 is zero. For i = 2 then by A-5:

$$\frac{(3700 - 700)\text{ ft.}^3}{425} = 7 \text{ ft.}^3/\text{user}$$

$$E[Q(2)] = 2200 \text{ ft.}^3$$

by A-5 and A-6 $E[\Delta Q] = \frac{nQ\Delta p}{p} = \frac{(-.5)\ (22)\ (.01)}{.40} = 27.5 \text{ ft.}^3$

i.e., each k in state 1 in rate i = 2 will reduce his consumption by 27.5 ft.^{3} (this is on the average). By A-5 $\Delta K(2\text{-}1)$ (7 ft.^{3}/user) = 27.5 thus K = 4, i.e., there are k = 4 who will, by reducing consumption no longer have to pay rate i = 2. There are 4 k's in K(2-1). As computed in the main body, $\Delta K(3\text{-}2)$ = 5.7, by (3).

$$\begin{aligned}
dU(2) = & \sum_{k\epsilon K2} p(2)dQ(2,k) + Q(2,k)dp(2) \\
& + \sum_{k\epsilon \Delta K(3-2)} p(2)dQ(2,k) + Q(2,k)dp(2) \\
& - \sum_{k\epsilon \Delta K(2-1)} [p(2)dQ(2,k) + Q(2,k)dp(2)] \\
& + \sum_{k\epsilon K3} Q_m(2,k)dp(2) - \sum_{k\epsilon \Delta K(3-2)} Q_m(2,k)dp(2) \\
= & (.4/100)(-27.5)(425) + (2200-700)(.01/100)(425) \\
& + (.4/100)(-153.75/2)(5.7) + (3700-700)(.01/100)(5.7) \\
& - (.4/100)(-27.5)(4) - (2200-700)(.01/100)(4)
\end{aligned}$$

$$+ (3700-700)(.01/100)(30-4)$$

$$= -46.75 + 63.75 - 1.773 + 1.73$$

$$+ .428 - .5835 + 7.83$$

$$= \$24.63$$

by (4)

$$dU(3) = \sum_{k\epsilon K3} p(3)dQ(3,k) + Q(3,k)dp(3)$$

$$- \sum_{k\epsilon\Delta K(3-2)} [p(3)dQ(3,k) + Q(3,k)dp(3)]$$

$$= (.4/100)(-153.75)(30) + (4100-3700)(.03/100)(30)$$

$$- (.4/100)(-153.75)(5.7) - (4100-3700)(.03/100)(5.7)$$

$$= -18.45 + 3.60 + 3.54 - .69$$

$$= -\$12.00$$

$$dU(1) + dU(2) + dU(3) = \$12.63$$

Acknowledgements. The partial support of the research described in this paper by 1970-1971 Allotment Grant Number 5010-5351-71 of the Water Resources Research Center of the University of Arizona is gratefully acknowledged. The computations were done at the University of Arizona Computer Center on the CDC-6400 installed there.

BIBLIOGRAPHY

Brown, G.M., Forecasting Residential Water Demand , in W.R. Sewell and B.T. Bower, (eds) Forecasting the Demand for Water, Queen's Printer, Ottawa, 1968.

City of Tucson, Department of Water and Sewers, Water Utility (Report) November 1970.

Clausen, G.S. Optimal Operation of Water Supply Systems, Hydrology and Water Resources Interdisciplinary Report No. 1, The University of Arizona, Tucson, 1970.

Howe, C.W. and Linaweaver, F.P., The Impact of Price on Residential Water Demand and Its Relation to Systems Design and Price Structure, Water Resour. Res. 3(1), p. 13, 1967.

Lesourne, J., Le Calcul Economique, Dunod, Paris, 1964.

Whitford, P.W., Forecasting Demand for Urban Water Supply, Report ERP-36, Engineering Economic Analysis, Stanford University, California, June 1970.

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.

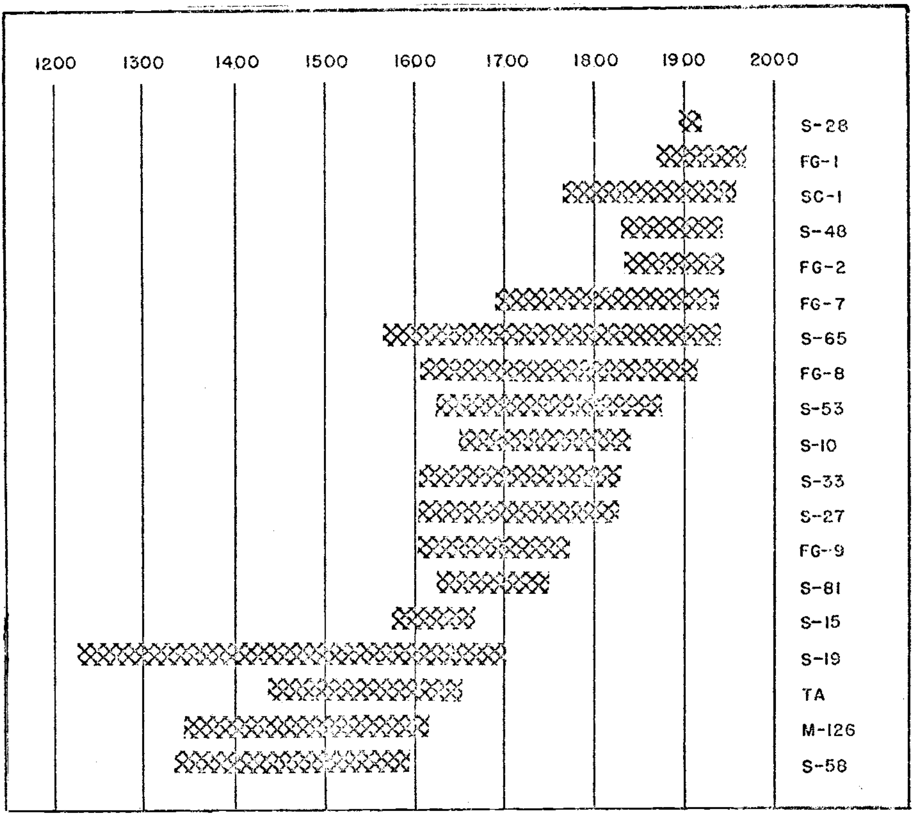


Fig. 1. Time intervals (A.D.) contained in 19 pieces of tree-ring dated driftwood from various sites along the Colorado River in the Grand Canyon.

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.

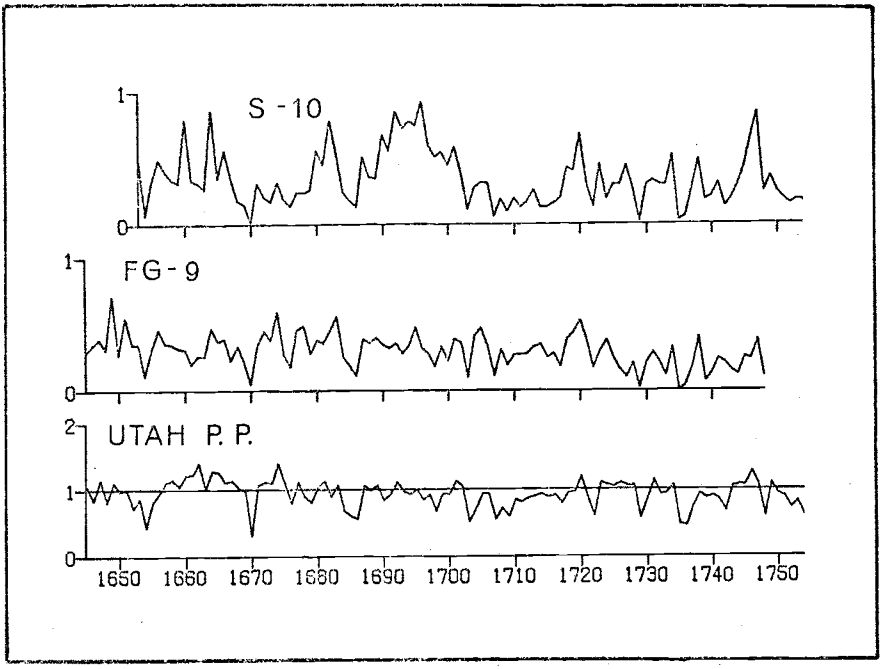


Fig. 2. Plotted ring measurements (0.0 - 1.0 mm) for S-10 (Douglas-fir) and FG-9 (Pinyon) shown in comparison with the standardized master chronology (percent) for Utah ponderosa pine for the interval A.D. 1645-1755.

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.

REFERENCES

Beaty, C. B., and C. W. Ferguson, Dating of alluvial surfaces: Possible use of tree-ring analysis. (Manuscript in preparation.)

Berger, Rainer, editor, Scientific Methods in Medieval Archaeology, U.C.L.A. Center for Medieval and Renaissance Studies Contributions: IV, 459 pp., University of California Press, Berkeley, 1970.

Euler, Robert C., Willow figurines from Arizona, Nat. Hist., 95(3), 62-67, 1966.

Euler, Robert C., and Alan P. Olson, Split-twig figurines from Northern Arizona: new radiocarbon dates, Sci., 148(3668), 368-369, 1965.

Ferguson, C. W., A 7104-year annual tree-ring chronology for bristlecone pine, Pinus aristata, from the White Mountains, California, Tree-Ring Bull., 29(3-4), 1-29, 1969.

Ferguson, C. W., and Austin Long, Radiocarbon dating and dendrochronological evaluation of driftwood in Stanton's Cave. (Manuscript in preparation.)

Olsson, Ingrid V., Editor, Radiocarbon Variations and Absolute Chronology, Proceedings of the 12th Nobel Symposium held at the Institute of Physics at Uppsala University, 652 pp., Almquist and Wiksell, Stockholm, 1970.

Schulman, Edmund, Dendroclimatic Changes in Semiarid America, 142 pp., The University of Arizona Press, Tucson, 1956.

Stokes, M. A., and T. L. Smiley, Tree-ring dates from the Navajo Land Claim II, the Western Sector, Tree-Ring Bull., 26(1-4), 13-27, 1964.

Stokes, M. A., and T. L. Smiley, An Introduction to Tree-Ring Dating, 73 pp., The University of Chicago Press, Chicago, 1968.

Stokes, M. A., et al., Tree-ring chronologies in Western America. (Accepted for publication by the Tree-Ring Bull.)

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 stretches of rivers could then be assigned values which might be weighed against their usefulness for engineering projects.

The Colorado River is the major drainage system of the Southwest. Its flow through a channel cross-section at Lees Ferry has been measured and added to the estimated depletion upstream to obtain the so-called virgin flow of the Colorado River over the past 75 years. Those measurements reveal an interesting disparity. The average annual flow of the Colorado River for the years 1896 to 1930 was about 17 million acre feet; during the years 1931 to 1965, the average annual flow was only about 13 million acre feet (an acre foot is the amount of water that will cover one acre to a depth of one foot) (National Research Council, 1968). The Committee on Water of the National Academy of Sciences suggests that the disparity is, most likely, due to differences in measuring methods, and that a figure of 15 million acre feet for the average annual virgin flow of the Colorado River at Lees Ferry is about right. If that is so, then something has to give, for there is not enough water in the river to fulfill the legal allocations under river law (including the Colorado River Compact, the Boulder Dam Project, and the Mexican Treaty). These legal allocations total 17.5 million acre feet per year of Colorado River water.

Present reservoirs along the Colorado River can store 60 million acre feet of water, or nearly five times the average annual flow (National Research Council, 1968). The loss, by evaporation from the lakes in the lower region, mostly behind dams, is well over one million acre feet per year (Water Resources Council, 1970).

While Southwestern river water is being allocated and dammed beyond reason, groundwater resources in the lowland parts of the Southwest are being literally mined, at a frightening rate. In some areas, the water table is being lowered at the rate of 20 feet per year. This water is ancient groundwater that took centuries to accumulate. It is not replaceable, not even by the Central Arizona Project. The Project, when implemented, will bring 1.2 million acre feet of Colorado River water into the Gila River basin, but this imported water will cancel only about half of the annual overdraft of groundwater in that area. The water table in central Arizona had dropped, by 1968, to 250 feet below the surface. Even if pumping were to stop completely, many centuries of desert rains would come and go before the water table could rise to its former depth of about 50 feet (National Research Council, 1968). It should be obvious to the most enthusiastic booster of growth for Arizona that the Central Arizona Project will not provide even enough water for present levels of usage in the central part of the state.

Unrealistic demands upon the water resources of the arid Southwest are not new. In the latter part of the ninetheenth century, John Wesley Powell tried to convince would-be settlers that only a small portion of the land could be reclaimed, even by irrigation. Rain, he said, would not follow the plow, as some ignorant folk believed. If Powell could see the Phoenix area today, he might warn that rain also does not follow the subdivider's bulldozer.

BIBLIOGRAPHY

Hunt, Charles B.
1967 "Physiography of the United States". Freeman and Company, San Francisco.

Leopold, Luna B.
1964 "Fluvial Processes in Geomorphology". W. H. Greeman and Company, San Francisco.

Morisawa, M. and M. Murie
1969 "Evaluation of Natural Rivers". U. S. Department of Interior Water Resources Research Project No. C-1314. Antioch College, Yellow Springs, Ohio.

National Research Council
1968 "Water and Choice in the Colorado River Basin, An Example of Alternatives in Water Management". Committee on Water of the National Research Council, publish No. 1689. National Academy of Sciences Washington, D.C.

Water Resources Council
1970 "Lower Colorado Region Comprehensive Framework Study". Preliminary Field Draft prepared by the Lower Colorado Region State-Federal Interagency Group for the Pacific Southwest Interagency Committee of the Water Resources Council.

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 particularily concerned with abuse.

References

Ayres, J.E., A prehistoric farm site near Cave Creek, Arizona, The Kiva, 32 (3), 106-111, 1967.

Dunbier, R., The Sonoran Desert, its geography, economy and people, pp. 220-221, The University of Arizona Press, Tucson, 1968.

Haury, E.W., The Hohokam, first masters of the American Desert, National Geographic, May, 691, 1967.

Woodbury, R.B., The Hohokam canal at Pueblo Grande, Arizona, American Antiquity, 26(2), 267-270, 1960.

Woodbury, R.B., and J.Q. Ressler, Effects of environmental and cultural limitations upon Hohokam agriculture, Southern Arizona, University of Utah Anthropological Papers, No. 62, pp. 41-51, 1962.

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.

Bibliography

Ellis, Florence H.
1970 Irrigation and Water Works in the Rio Grande. Paper presented at the 1970 Pecos Conference, Santa Fe.

Gaillard, D. D.
1896 A Gigantic Earthwork in New Mexico. American Anthropologist, O.S. Vol. 9, No. 9, pp. 311-313. Washington.

Lindsay, Alexander J., Jr.
1970 A Descriptive Summary of Soil and Water Conservation Devices and Settlement Patterns in the Kayenta Anasazi Region. Paper presented at the 1970 Pecos Conference, Santa Fe.

Plog, Fred
1970 Water Control in the Upper Little Colorado. Paper presented at the 1970 Pecos Conference, Santa Fe.

Rohn, Arthur H.
1970 Social Implications of Pueblo Water Management in the Northern San Juan. Paper presented at the 1970 Pecos Conference, Santa Fe.

Woodbury, Richard B.
1970 The Zuni Area. Paper presented at the 1970 Pecos Conference, Santa Fe.

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