TEXAS WATER COMMISSION

BULLETIN 6512

SYMPOSIUM ON CONSIDERATION OF DROUGHTS IN WATER PLANNING

A Series of Technical Papers
Presented at the April 28-30, 1965 Meeting
Texas Section, American Society of Civil Engineers

April 1965

Published and distributed
by the
Texas Water Commission
Post Office Box 12311
Austin, Texas 78711

FOREWORD

In its report "A Plan for Meeting the 1980 Water Requirements of Texas," this Agency stated: "The legendary vagaries of Texas Weather, more amusing in folklore than actual experience, discourage any hope of relief through improvement in its natural behavior. If Texans cannot change the weather, they can at least, through sound, farsighted planning, conserve and develop water resources to supply their needs."

On August 12, 1964, Governor Connally requested the Water Commission to prepare a comprehensive State water plan. This plan will include not only the facilities necessary to meet all needs beyond the year 2000, but a means of implementation to provide the necessary facilities. This accelerated planning effort by the State will include consideration of over 170 potential reservoir sites and alternate locations for major water conveyance facilities. Intensive study will be given, also, to ground-water sources.

Some of the numerous technical questions to be resolved in this planning work relate to the hydrologic analyses of the effects of drought. The officers of the Hydraulics Division, Texas Section of the American Society of Civil Engineers have performed a distinct service to the Water Commission by arranging for a symposium of technical papers providing very useful information on the various aspects of drought. These papers were prepared for presentation at the Spring Meeting of the Hydraulic Technical Group of the Texas Section, ASCE, in Beaumont, Texas, April 29-30, 1965. They have been compiled and published in this volume to make these important papers available for distribution throughout the State.

The Commission wishes to acknowledge the assistance provided by the Texas Section, ASCE, and by the participants who have contributed their efforts in the preparation of the technical papers and discussions. As a variety of thoughts are included herein, the views expressed in the papers are those of the authors and do not necessarily reflect the views of the Texas Water Commission.

TEXAS WATER COMMISSION

John J. Vandertulip

John J. Vandertulip
Chief Engineer

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INTRODUCTION

By John J. Vandertulip,[1] M. ASCE

Droughts are one of the natural climatic phenomena which result when rainfall is below normal. Not every period of low rainfall, however, can be classed as a drought. It is only when the deficiencies in rainfall are great, or prolonged, that an area is experiencing a drought. Droughts are not new--man has had to contend with them throughout his existence.

As Tannehill[2] so aptly stated:

> "Drought belongs in that class of phenomena which are popularly known as 'spells of weather'. A drought is a spell of dry weather. Drought is unique among spells of weather; it creeps upon us gradually, almost mysteriously, but its consequences are a terrible reality."

Drought is one of the most devastating aspects of nature. It is also one of the climatic characteristics of the Temperate Zone in which the United States is situated. Since our climate is influenced by the circulation of the air around the earth, there will be changes in the precipitation pattern at any given spot. Droughts and floods represent extreme fluctuations in the precipitation pattern. Just as there have been droughts and floods in the past, there will be droughts and floods in the future.

The word drought means many things to many people. Drought is usually thought of in connection with agriculture. In terms of agriculture, drought can be defined as that deficiency in rainfall and soil moisture over a certain time which permits the wilting of plants, and which, if prolonged, can cause a complete loss of crops. Droughts, according to the above definition, can be serious when their duration is measured in years, months, or even weeks. Such periods of deficient rainfall occur frequently, even in the more humid sections of the State. It is in an effort to get relief from this irregularity of rainfall that irrigation works are built. The application of supplemental water at the proper time has been found to be a very successful means by which production of crops can be assured, with a corresponding increase in income.

Cities and municipalities usually associate droughts with deficiencies in rainfall and streamflow over longer periods of time. Cities in general are more prudent than individuals in providing their citizens with ample water, and

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1 Chief Engineer, Texas Water Commission, Austin, Texas.

2 Tannehill, I. R., Drought, Its Causes and Effects, Princeton University Press, Princeton, N. J., 1947, p. 1.

make every effort to keep supply in excess of demand. Such droughts are defined in the literature as hydrologic droughts as distinguished from agricultural droughts. Hence, shortages in water in the cities are not generally as frequent as local shortages in the rural areas.

In the minds of those who live in the larger population centers, the word drought does not have the same portent as it does to the individual in the rural area. Deficiencies in rainfall in cities do not become really significant until the available water supply is so depleted that water rationing becomes necessary. Usually this follows a period of years in which the deficiency in rainfall accumulates, but during which water is supplied from carry-over storage--thoughtfully provided before the drought became evident.

Drought has been defined by Webster as:

> "...constitutes dryness, want of rain or water, especially such dryness by weather or climate as effects the earth and prevents growth of plants."

Agricultural literature includes studies of drought effects, but a different definition is usually applied in each case. The common denominator among these agricultural studies appears to be the use of available soil moisture as an index of agricultural drought.

The lack of a generally applicable definition of drought is noted by Linsley, Kohler, and Paulhus[3] as follows:

> "A sustained period of time without significant rainfall is called a drought. Because of the variety of needs for water, it is not practical to define a drought specifically."

A meteorological basis for the determination of drought has been given by Hoyt[4] who concludes that in the humid and semi-arid areas drought conditions exist when there is an annual deficiency in precipitation of 15 percent or more. This definition was used by Lowry[5] in his investigation of droughts in Texas, which was prepared for the Texas Board of Water Engineers (now Texas Water Commission).

Lowry[5] determined from rainfall records maintained during the period 1889 through 1957 that 11 significant droughts had occurred in Texas. The most severe on a statewide basis occurred during the period 1954-1956. The second and third most severe droughts were 1916-1918 and 1909-1912 respectively. Lowry[5] rated the 1953 drought the fifth most severe and the 1950-1952 drought the seventh most severe. As these two droughts preceded the 1954-1956 drought, the most severe extended drought (7 years) was found to have occurred from 1950 through 1956. The general exception to this was eastern Texas when rainfall

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[3] Linsley, R. K., Jr., Kohler, M. A., Paulhus, J. L. H., Applied Hydrology, McGraw-Hill Book Co. Inc., New York, N. Y., p. 51.

[4] Hoyt, J. C., U.S. Geological Survey Water-Supply Paper 820, p. 2.

[5] Lowry, R. L., Jr., A Study of Droughts in Texas, Texas Board of Water Engineers, Austin, Texas, Bull. 5914, 76 p.

(and runoff) were above average in 1953. The grouping of the 1950 through 1956 period as a single drought results in a total of 9 significant droughts during the 1889-1957 period.

From a meteorologic standpoint, Lowry[5] demonstrated that during drought periods in Texas a combination of the following occurred: (1) rainfall was deficient and substantially below the average; (2) air temperatures were above average; (3) the relative humidities were lower than the average; and the combination of (1), (2), and (3) resulted in greatly increased net evaporation rates (gross evaporation less effective rainfall). This rather lengthy statement was more simply stated over 3000 years ago as "Drought and heat doth consume the snow waters." (Job 24:19).

The development of a quantitative definition of drought applicable for all purposes would be too generalized for use, even if such a definition were possible. As the discussions which follow this paper generally deal with surface-water supplies and reservoirs, the definition of drought to be developed herein will be directed towards surface-water supplies.

During a sustained period of deficient rainfall, there is a gradual depletion of water in the soil mantle through transpiration by vegetation, evaporation, downward percolation, and lateral drainage. Floodflows of streams from previous excessive rainfalls have long since passed out of the drainage area, and the low flow or dry-weather flow of the streams is made up of ground-water discharges. These dry-weather flows are termed "base flows."

The residual base flow in a stream usually varies with the season of the year, being highest in the winter when evaporation and transpiration rates are lowest, and is lowest in the summer when the natural losses are greatest. When rainfall deficiencies occur in several successive years there is a gradual reduction in the base flows as ground-water storage is depleted.

Drought periods, or periods of deficient rainfall, are not necessarily periods of absolute deficiency or no rainfall. In some instances of drought, rainfall occurs in sufficient quantity to produce surface runoff, and stream discharges increase into the "floodflow" or above base flow stages.

Streams in Texas during the 1950 through 1956 drought exhibited gradual reductions in base flows and ceased to flow. Water uses had also increased and the unregulated base flows (without reservoir storage to supplement them) were woefully inadequate to meet the water demands of municipalities, industries, and agriculture. <u>This drought demonstrated that reservoirs were needed to provide for both existing and future water needs</u>.

When a conservation reservoir is created and is initially filled, it is ready to serve its intended purpose--providing a regulated supply of water. During the day-to-day, month-to-month, and year-to-year operation of the reservoir, fluctuations will occur in the level of the reservoir water surface. Declines in the quantity of water stored usually result from a combination of: (1) reservoir withdrawals; (2) reduced inflows; and (3) natural losses by evaporation from the water surface and transpiration by adjacent vegetation. The extent of the variations in the reservoir water level is a parameter which may be used as an indicator of drought.

Declines in the reservoir contents will occur gradually, usually over a period of many months, and in Texas, often over a period of two or more years. Such a lengthy period suggests that the element of time might appropriately be a part of the drought definition. As the length of the drought period is a factor in determining the yield of a reservoir, and therefore enters into economic feasibility determinations, the time element must be given full consideration.

One possible method of defining droughts would be to relate the definition to the reservoir content as a percentage of the total conservation storage capacity. Although the beginning of a drought period may coincide with the first month a reservoir was less than 100 percent of capacity, many short periods of several months duration would then be termed droughts. These periods would be followed with reservoirs having been filled by runoff greater than reservoir contents depletion, and the designation of such short term droughts would have little or no significance.

For a particular reservoir, a definition of drought based upon actual contents being less than a given percentage of conservation storage capacity would have inherent in it several assumptions. It would be based upon the historic patterns of inflows and demands, insofar as these historic patterns are not altered by man's activities.

A general definition of drought as related to reservoirs does not appear possible because of the numerous variables involved with reservoir purposes and the relation of a given reservoir unit to a system of reservoirs. This would be particularly evident in either an optimizing or maximizing system operation of reservoirs in a large area, and when inter-basin transfer of water is considered.

The determination of the amount of water which can be obtained from a reservoir with a given capacity at a given site is termed the "reservoir yield." Studies of reservoir yields usually involve consideration of several drought periods to determine the minimum yield for each assumed reservoir capacity. The drought period which provides the resulting minimum yield for a given reservoir capacity is termed the "critical drought."

From the viewpoint of hydrologic analyses of proposed reservoirs, the critical drought has the greatest significance. Other drought periods then are of significance in project operations and the month-to-month scheduling of releases.

The critical drought analyses when used in system operation studies to obtain optimum reservoir yields will provide information necessary for planning. Such studies will then form a foundation for determining the operation of the reservoirs after construction.

PREDICTING DROUGHTS

PREDICTING DROUGHTS

By John T. Carr, Jr.,[1] PM. AMS.

ABSTRACT

Drought prediction methods are based mainly on three premises. The first premise supposes that happenings of the past can be extrapolated into the future. Advocating this premise is a group of investigators who believe weather occurs in cycles, and if one only has a long and dependable record of weather happenings of the past, he can forecast climatic changes far into the future. The second premise is that drought occurrence is a random thing, and droughts occur whenever the right combination of drought-producing weather factors come together at the same time and place. Forecasted long-range climatic changes based on statistical probabilities are usually produced by a group of investigators backing this premise. The third assumption is that climatic variations are somehow connected with fluctuations in the amount, or the rate, of radiation the earth receives from the sun because of sunspots, corona, faculae, and other solar activity.

Illustrations of long-range precipitation forecasts based on these three major premises will be shown and discussed. The relationships of mean temperature departures to volcanic eruptions and sunspot numbers will also be discussed.

GENERAL

In general, people just don't want to be known as "drought forecasters," but some don't object to being called "long-range climate" or "long-range precipitation" forecasters. There are not very many of them, either. Drought forecasting as such seems to be taboo. On the other hand, classifying and defining the intensity of droughts of the past, or working out formulas for determining the severity of droughts of the future seems to be acceptable. Also, it seems acceptable to analyze the causes of past droughts and to postulate about the causes of future droughts. And I'm no different from the rest; I can't forecast droughts, either. So, this paper assumes somewhat of a negative attitude. Little wonder, though--the success record among drought forecasters has been nothing to brag about. Almost invariably one lives to see his drought forecast fail to verify.

Actually, though, it's no real trick to take any mixed group of 60 men, women, and children and come up with <u>one</u> apparently successful drought

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[1] Hydrometeorologist, Planning Division Research Program, Texas Water Commission, Austin, Texas.

forecaster. For instance, the most historic south-central Texas drought of recent times lasted for the six-and-a-half-year period October 1950-February 1957[2]. The last severe drought before that one ended in May 1940. Now, if in June 1940, the next month after the May 1940 drought ended, 60 people had been asked to forecast the year of the beginning of the next drought in south-central Texas within the next 10 years, the chances are that six guesses would have been correct. Then, when the drought began in 1950, we might again ask the six correct guessers to say in which year of the next 6 years the drought will end. Statistically, one of them would guess correctly. There may actually be a successful drought forecaster among us here today.

This very "iffy" little example of successful drought forecasting is not offered just to take up time. Instead, it is intended as a slightly humorous example of how any one of only 60 perfectly sincere and conscientious meteorologists might apparently come up with what seems to be a sure-fire method of forecasting the beginning, duration, or ending of droughts. Considering that meteorologists have technical training which qualifies them to filter out the obvious non-contributing drought producing parameters, it might be that one out of only 30 meteorologists who really work at it can come up with a plausible looking drought forecasting method. Consider, then, the many cycles and periodicities "discovered" by cycle hunters while investigating graphs of sunspot activity, lunar synodical periods, and long-time series of precipitation cycles. When considering this lush pasture to graze in, is it any wonder someone once in a while "hits" a couple of drought forecasts?

Dr. Murray Mitchell[3] of the Office of Climatology at the U.S. Weather Bureau in Washington, authored the paper, "A Critical Appraisal of Periodicities in Climate." He presented this paper in May 1964 at a conference in Ames, Iowa, sponsored by the Center for Agricultural and Economic Development, Iowa State University. Some of you may have attended the conference and heard Dr. Mitchell offer his views on Harmonic Analysis and Cycle Hunting.

Mitchell has experimented extensively with the POWER SPECTRUM APPROACH to the problem of handling a time series--an approach that presupposes nothing at all about the periodic elements in the time series. High-speed electronic equipment is employed to process the mass of data used in his POWER SPECTRUM approach.

In his paper, Mitchell outlines some of the means by which would-be cycle finders might have checked their results before publishing the discovery of their pet weather cycle. Here is what Mitchell says:

> "From the historical viewpoint, if all cycle hunters had checked their results by these means, very few of their publications would ever have been written. Hasty and uncritical acceptance of the reality of evidence of cycles in climate has evidently been the source of more wasted effort in meteorology than any other kind of scientific misjudgement. Beyond a doubt, meteorology has not been alone in this experience either."

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[2] According to the Palmer (1961) drought classification and indexing system.

[3] Mitchell, J. M., A critical appraisal of periodicies in climate, Ames, Iowa, Proceedings of a Conference, May 3-6, 1964, sponsored by the Center for Agricultural and Economic Development, Iowa State University, pp. 189-227.

Mitchell is not altogether against weather cycles; he accepts two as being genuine and meeting the power spectrum test: the first is a very weak precipitation periodicity following the lunar synodical period of 29.53 days[4], consisting essentially of a semi-lunar variation having a period of about 15 days; the second is an oscillation with a period of approximately 2 years--it is known as the BIENNIAL OSCILLATION and is so conspicious in wind and temperature at high altitudes over the tropics that there can be no doubt about its reality. Mitchell also points out that some other real cycles may exist, but they have not yet been adequately proved. Two have to do with sunspots--an 11-year cycle and an even longer 80- or 90-year solar cycle.

EXTRAPOLATION OF A TIME SERIES

Without further talk about cycles and cycle hunters, let me now turn to the three illustrations of the three major premises upon which long-range weather forecasts are based. The first one illustrates the Abbot[5] long-range precipitation forecasts for El Paso and for Abilene. Abbot was for many years a Research Associate with the Smithsonian Institution. Figure 1 and Table 1 illustrate the premise that cyclic-appearing weather phenomena of the past can be successfully extrapolated into the future. The upper portion of Figure 1 shows Dr. Abbot's forecasts for the 4-month period January-April 1965. The complete set of maps covers the 9-year period January 1959-December 1967, in 4-month increments. Only one of the 27 maps is discussed here.

The figures scattered about on the map of the United States represent Abbot's precipitation forecasts for 32 cities. The forecasts are given in percentage departure from the two normals calculated by him separately for periods when Wolf sunspot numbers[6] are less than 20 and for periods when Wolf sunspot numbers are greater than 20. Thus, two normal precipitation figures were calculated for each city. The only Texas cities used by Abbot in his forecasts were Abilene and El Paso.

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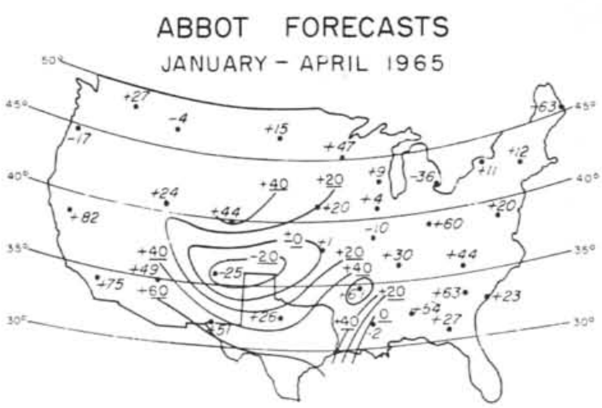
4 The period between two successive astronomical conjunctions of the moon and the sun--sometimes called a lunar synodical month, or a moon-month.

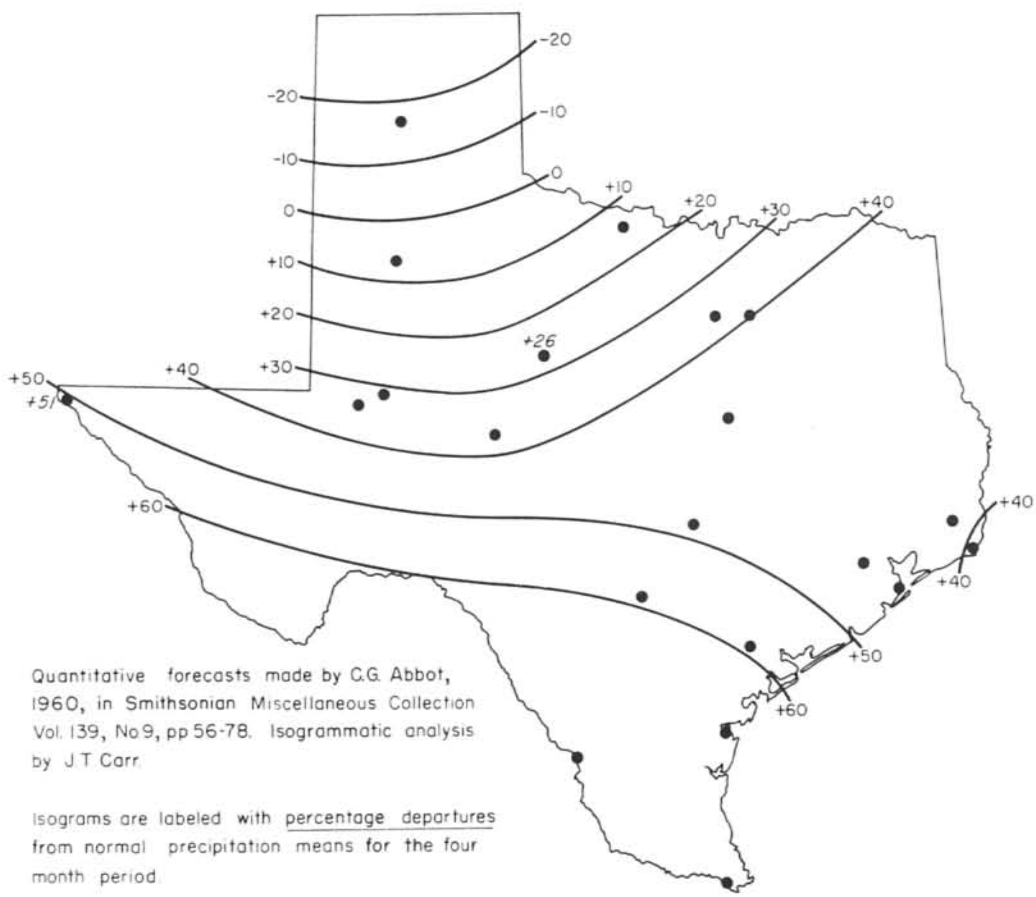
5 Abbot, C. G., A long-range forecast of United States precipitation, Washington, Smithsonian Miscellaneous Collections, Vol. 139, No. 9, 1960, 78 p.

6 Sunspot Numbers.--As a measure of the frequency of sunspots, R. Wolf of Zurich introduced his "sunspot number" defined by K. O. Kiepenheuer (in "Solar Activity," The Sun, The University of Chicago Press, 1953, p. 323) as follows: If there are on the solar disc f individual spots which are collected into g groups, the Wolf number R is

$$R = K\ (10\ g + f).$$

The factor K depends on the observer, the instrument used, and the method of observation (eyepiece, projection screen, photograph). Wolf set K = 1.0 based on his instrument. Efforts to keep the scale homogeneous have resulted in values of K from 0.91 to 0.64 at various observatories. This footnote is adopted from C. W. Morgan (doctoral dissertation for The University of Texas, "Surface Runoff in the Gulf Coast Area in Relation to Solar Activity," May 1958, 91 p.). (Monthly means of Wolf sunspot numbers, based on observations made at Zurich Observatory, Zurich, Switzerland, are published in the first issue each month of the Journal of Geophysical Research, as Geomagnetic and Solar Data.)





Quantitative forecasts made by C.G. Abbot, 1960, in Smithsonian Miscellaneous Collection Vol. 139, No 9, pp 56-78. Isogrammatic analysis by J.T. Carr.

Isograms are labeled with percentage departures from normal precipitation means for the four month period.

Figure 1

Abbot Precipitation Forecast

Texas Water Commission
Planning Division
Research Program

TABLE 1.--VERIFICATION OF ABBOT'S FORECASTS FOR ABILENE AND EL PASO, TEXAS

		ABILENE		EL PASO	
		PRECIPITATION, IN INCHES		PRECIPITATION, IN INCHES	
		FORECASTED	OBSERVED	FORECASTED	OBSERVED
1959	Jan. - Apr.	4.8	3.1	0.9	0.4
	May - Aug.	10.4	15.2	6.1	3.6
	Sept.- Dec.	6.5	9.0	2.6	1.0
1959	Total	21.7	27.3	9.6	5.0
1960	Jan. - Apr.	4.6	5.8	1.9	1.3
	May - Aug.	11.7	11.1	5.1	5.2
	Sept. -Dec.	10.5	8.3	2.3	2.6
1960	Total	26.8	25.2	9.3	9.1
1961	Jan. - Apr.	8.2	6.2	1.6	0.7
	May - Aug.	9.0	16.6	3.5	3.8
	Sept.- Dec.	7.6	12.7	2.0	3.1
1961	Total	24.8	35.5	7.1	7.6
1962	Jan. - Apr.	6.0	2.7	0.7	1.9
	May - Aug.	9.8	15.2	4.5	1.8
	Sept.- Dec.	7.1	9.2	1.5	4.6
1962	Total	22.9	27.1	6.7	8.3
1963	Jan. - Apr.	8.0	1.9	1.2	0.7
	May - Aug.	12.1	11.7	4.1	2.3
	Sept.- Dec.	6.5	4.2	0.9	1.8
1963	Total	26.6	17.8	6.2	4.8

		ABILENE		EL PASO	
		Col.A	Col.B	Col.A	Col.B
1964	Jan. - Apr.	6.4	5.8	1.1	1.3
	May - Aug.	11.7	13.5	5.4	5.4
	Sept.- Dec.	4.9	4.4	4.1	4.4
1965	Jan. - Apr.	7.6	6.9	1.8	2.0
	May - Aug.	13.7	15.7	8.0	8.0
	Sept.- Dec.	6.7	5.2	1.0	1.1
1966	Jan. - Apr.	8.3	7.4	0.4	0.4
	May - Aug.	6.7	7.7	2.9	2.9
	Sept.- Dec.	8.5	7.7	2.2	2.3
1967	Jan. - Apr.	7.8	7.0	1.2	1.3
	May - Aug.	11.0	12.6	3.8	3.8
	Sept.- Dec.	8.0	7.3	2.2	2.3

Verification of Abbot's forecasts for Abilene and El Paso, Texas, for the years 1959-63. Beginning with 1964, the precipitation forecasts shown under Columns A are for periods when Wolf sunspot numbers are less than 20; The precipitation forecasts shown under Columns B are for periods when Wolf sunspot numbers are greater than 20. Near misses and outstanding deviations from forecasted precipitation amounts are flagged.

Texas is a large state. Forecasts for only two cities in Texas are hardly adequate for a statewide precipitation outlook; so I have taken the liberty of drawing isohyetals over the entire State, taking into account not only the two cities, Abilene and El Paso, but also all other cities for which forecasts were made in nearby states. Missing, but badly needed, are forecasts for Brownsville and Houston. Without them the configuration of the plus 60 percent isogram is little more than a guess, but the plus 61 percent at Little Rock, Arkansas, helps a little in determining where it should be placed.

Texas was lifted from the United States map and enlarged. Isograms were then drawn depicting percentage deviation from normal precipitation in 10-percent increments. Let me again point out that I have little confidence in any of the isograms drawn through the southern half of the State chiefly because of the absence of Brownsville and Houston data, that is, I have little confidence Abbot's forecasts are fairly depicted in the southern half of the State.

Backing out Abbot's percentage-deviation precipitation forecasts and converting percent to inches, the tabulated figures on Table 1 were obtained for the two Texas cities used: Abilene and El Paso. Abbot forecasted percentage deviation from normal for each 4-month period for the years 1959-1967, but because when this paper was written sunspot data had not yet been distributed for all months in the years subsequent to 1963, it was possible only to verify Abbot's forecasts through 1963. Arrows indicate near misses and outstanding deviations from forecasted precipitation for the 4-month periods. On a yearly basis, results at Abilene ranged from a near miss in 1960 of only 1.6 inches (26.8 inches forecasted--25.2 inches observed) to a wide deviation in 1961 of as much as 10.7 inches (24.8 inches were forecasted--35.5 inches observed). The results appear to be inconclusive at this stage. Perhaps the results of Abbot's forecasts will be significant by the end of the 9-year forecast period.

DROUGHT AS A RANDOM OCCURRENCE

Dr. Don G. Friedman[7], a scientist at The Travelers Weather Research Center, in 1957 undertook the job of authoring a research paper entitled: "The Prediction of Long Continuing Drought in South and Southwest Texas." This 164-page paper meets the problem head-on, with special orientation toward the weather factor in the operation of a Farm Mortgage Loan Program, but perforce considers other aspects of drought as well--hence its value to us here today.

Friedman's approach was to make a statistical analysis using Texas rainfall data. The long drought of the early 1950's probably pointed up the need for the type of study made, but of interest were all cases of departure toward dryness for one or more years in succession, that is, a drought condition which was continuous for one or more years. To complete the drought index, rainfall data alone were chosen over other parameters such as geochronological data, erosion and alluviation, tree ring growth, etc. The records were used for more than 40 weather reporting stations in and near Southwest Texas during a period spanning roughly the first half of this century.

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[7] Friedman, Don G., The prediction of long continuing drought in South and Southwest Texas, The Travelers Weather Research Center, Occasional Papers in Meteorology, No. 1, The Travelers Insurance Co., Hartford, Conn., 1957, 164 p.

There was no immediately obvious regularity in the year-to-year variation of annual rainfall in South and Southwest Texas. The randomness of rainfall rendered statistical analysis of the data especially adaptable. Actually, this non-deterministic component can be handled best by the probability concept and the statistical approach. Three well-known statistical tests were applied to the data. The three tests were the "ranking," the "runs," and the "persistence" test.

By application of these tests to the climatic data Friedman determined:

1. There is no general indication that the climate of South Texas is getting dryer;

2. There is no general evidence of regular recurring cycles in the annual rainfall data of South Texas that cannot be explained by random fluctuations; and,

3. Regarding year-to-year persistence in wet and dry spells, the positive evidence at Brownsville is of no practical significance considering the other nine stations sampled were negative--the other nine stations were El Paso, Fort Davis, Amarillo, San Angelo, Del Rio, San Antonio, Laredo, and Corpus Christi, Texas and Roswell, New Mexico.

Friedman expressed his analysis of South Texas drought probabilities with a set of nine maps of Texas, each having over-printed isograms labeled with precipitation values. Each of the nine maps shows a percentage probability that the precipitation values represented by the isograms will be less than or equaled one or more years out of ten, depending on which of the nine maps one is interested in at the time.

Figures 2 and 3 consist of one of these probability maps--the probability of 0.3 (or 3 years out of 10)--and a similar map of Texas showing the average-annual rainfall at selected cities.

This is only one of nine maps in the set, each depicting a probability ranging from 1-out-of-10 years to 9-out-of-10 years. This one, the 3-out-of-10 years, was chosen to illustrate how the system can be used. For example, Laredo had an average-annual rainfall of 19.3 inches during the 42-year period 1914-1955. There is a probability of 0.3, 3-years-out-of-10, that the average-annual rainfall at Laredo will be equal to or less than 15 inches. In other words, in 3-out-of-10 years, the annual rainfall at Laredo can be expected to be less than three-fourths normal.

Similar use can be made of any of the other eight maps in the set. For instance, on the 7-out-of-10 year map, the 22-inch isohyet passes close by Laredo. Therefore, in 7 of 10 years, the annual rainfall at Laredo can be expected to be less than 22 inches.

THE INFLUENCE OF LUNAR AND SUNSPOT VARIATIONS

There seems to be more speculation but less proof about the part sunspots play in climatic variations on earth than about any other extraterrestrial influence. A close second is the moon and its influence. The literature is saturated with sunspot and moon-phase charts, graphs, and tabulations. Most are not explained; the data simply are offered and the reader can make up his

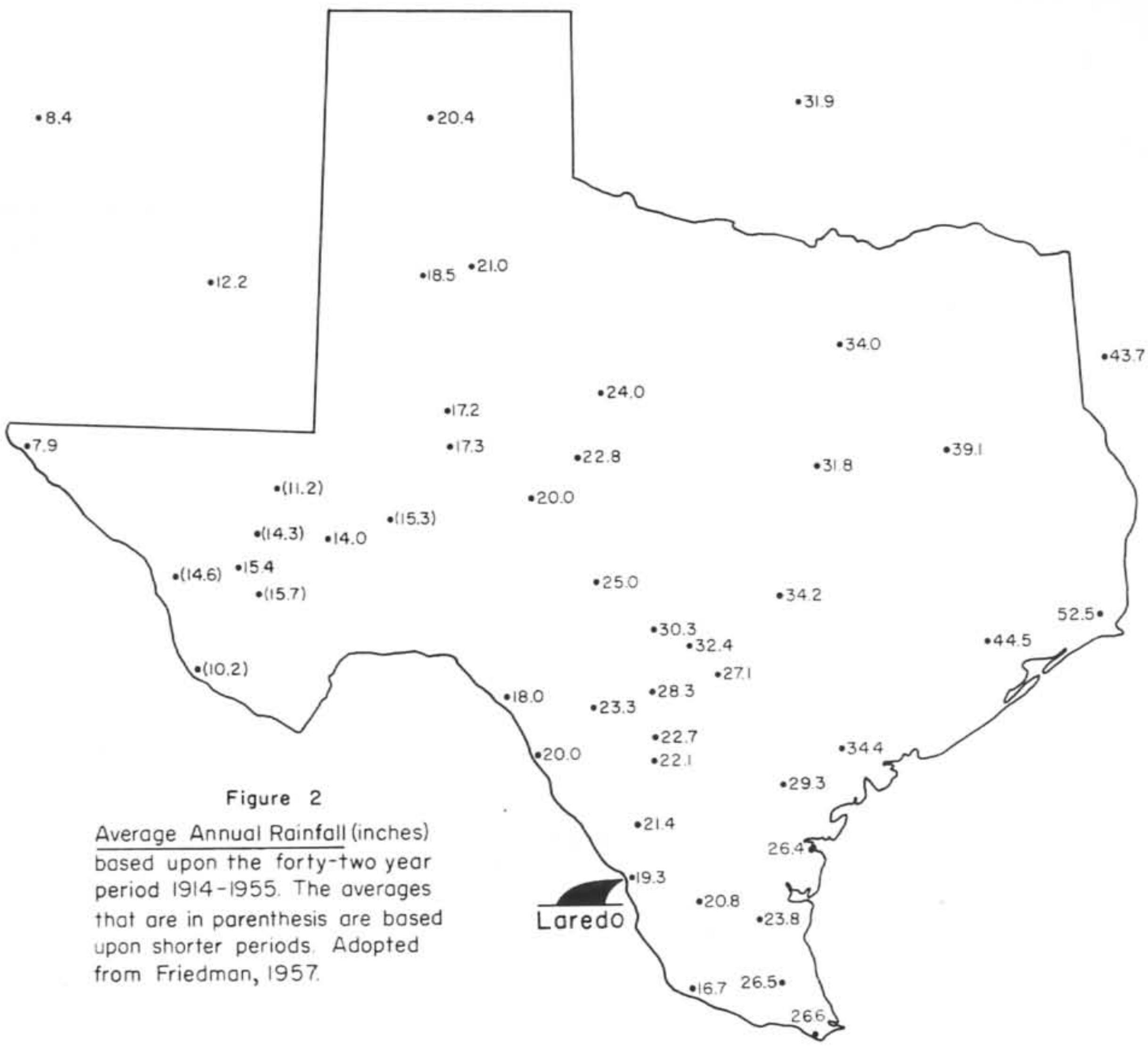

Figure 2

Average Annual Rainfall (inches) based upon the forty-two year period 1914-1955. The averages that are in parenthesis are based upon shorter periods. Adopted from Friedman, 1957.

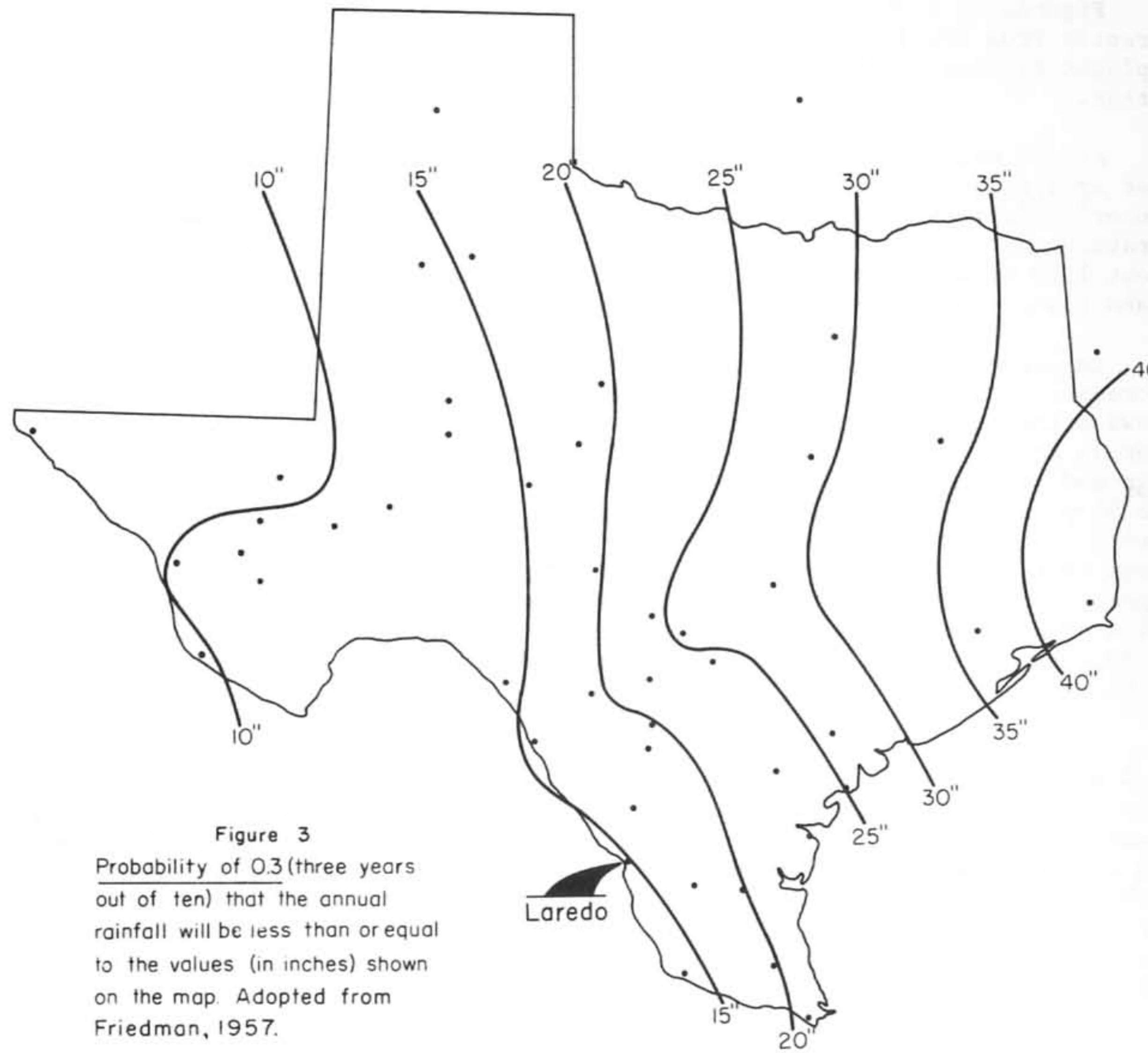

Figure 3

Probability of 0.3 (three years out of ten) that the annual rainfall will be less than or equal to the values (in inches) shown on the map. Adopted from Friedman, 1957.

own mind about how they can be interpreted. This open invitation to cycle hunting results in the discovery of more and more cycles, oscillations, sub-oscillations, and the like. It's a fascinating pastime. Figures 4, 5, 6, and 7 provide all the materials necessary to discover a cycle of your own.

Figures 4, 5, 6, and 7 consist of a selected assortment of figures taken directly from the literature with the exception of a little scissor work and an explanatory line or two of my own. Each figure is identified by an added letter.

Almost everyone these days accepts the fact that increasing temperatures over an area as large as a continent go hand-in-hand with decreasing rainfall. Kincer[8] illustrates this point quite well with graph "A". Note that the temperature increased and the precipitation decreased in the United States from about 1909 to about 1934. Mitchell[9], however, has offered proof of a recent trend toward cooler global temperatures.

In graph "B", Noriega[10] partly supports the argument that precipitation decreases as temperature increases. Mitchell's graph (graph "G") quite clearly shows a temperature increase spanning many of the years when Noriega shows an overall precipitation decrease. Noteworthy in graph "B" is the likeness of the <u>sign</u> and the <u>magnitude</u> of the approximate 5-year precipitation plateaus during the 34-year period 1890-1923--when compared with similar incremental periods during the years 1927-1960. However, an overall decrease in precipitation in Texas averaging about 2.5 inches is illustrated on the 1927-60 curve. There appears to be an inverse rainfall-temperature correlation, and suspicion at least of an approximate 30-year precipitation cycle wherein the average amount of precipitation in Texas changes about every 5 years in some sort of sub-cyclic fashion.

Graph "C" shows quite good correlation between sunspot activity and precipitation at the coastal city of Los Angeles during the period 1770-1950. This kind of correlation is not at all unexpected at a west-coast city near a mountain range in a belt of prevailing westerly winds. This tends to support one of Tannehill's[11] postulations: that increased solar activity increases the global circulation, thus increases the flow of air from the Pacific Ocean on to the North American Continent. During periods of increased solar activity coastal areas near mountain ranges will get more rain because more moist air is forced against the mountain barrier, thrust upward, and forced to release its moisture through a cooling-condensation process.

Look now at graph "D" (Figure 4). The top section depicts sunspot activity since the year 1870. Drought periods in the Great Plains are represented by

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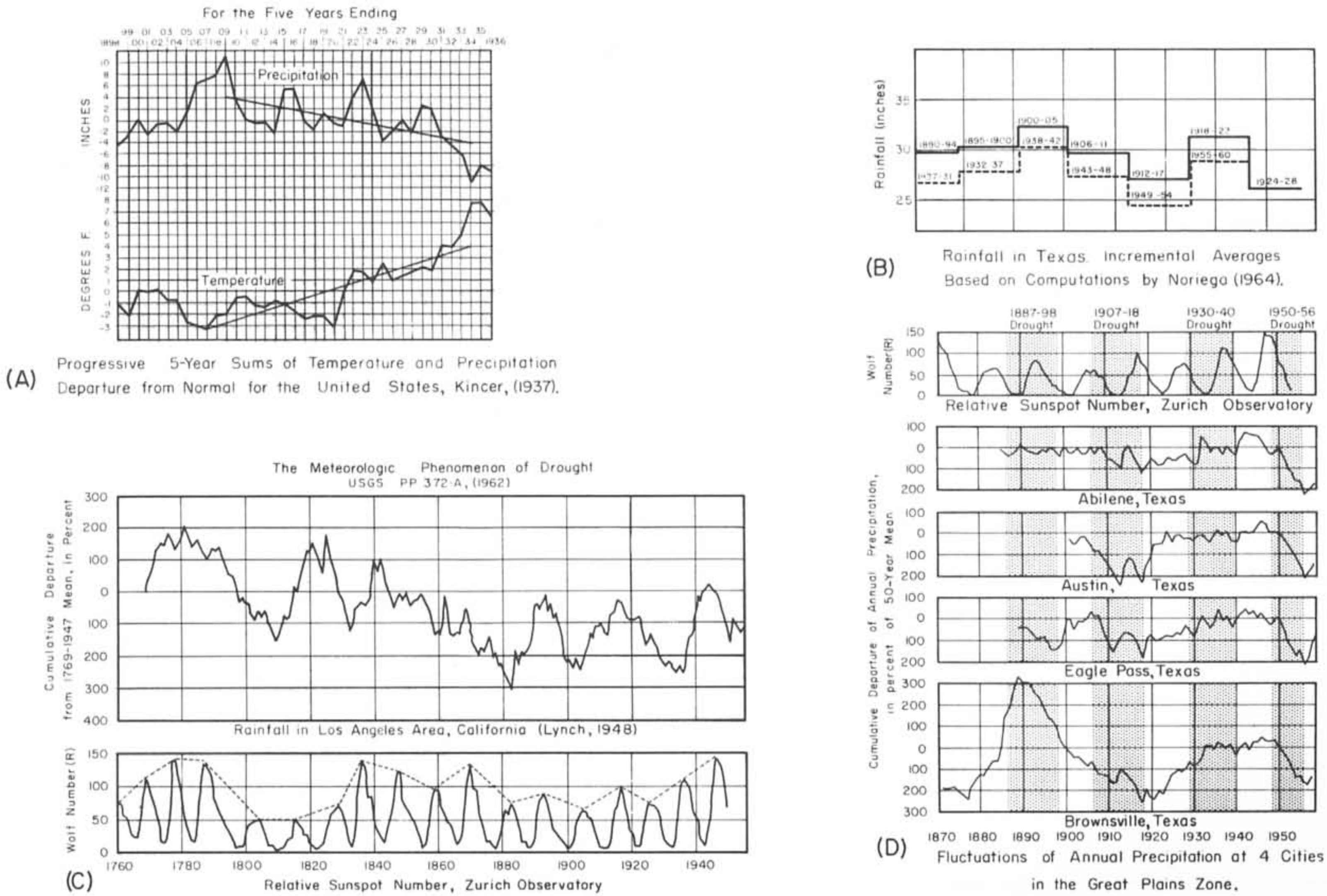
[8] Kincer, J. B., Is our climate changing, An address before the Illinois Farmers' Institute, Rockford, Ill., February 19, 1937.

[9] Mitchell, J. M., Recent secular changes of global temperature, Annals of the New York Academy of Sciences, Vol. 95, Art. 1, Oct. 5, 1961, pp. 235-250.

[10] Noriega, J. S., Private correspondence with Commissioner H. A. Beckwith, Texas Water Commission, Austin, Texas, Eng. Jose S. Noriega, A. de Musset 326, Mesico 5, D. F. 15 de Septiembre de 1964, 1 p. and 1 chart.

[11] Tannehill, I. R., Drought, Its Causes and Effects, Princeton University Press, Princeton, N. J., 1947, 264 p.



(A) Progressive 5-Year Sums of Temperature and Precipitation Departure from Normal for the United States, Kincer, (1937).

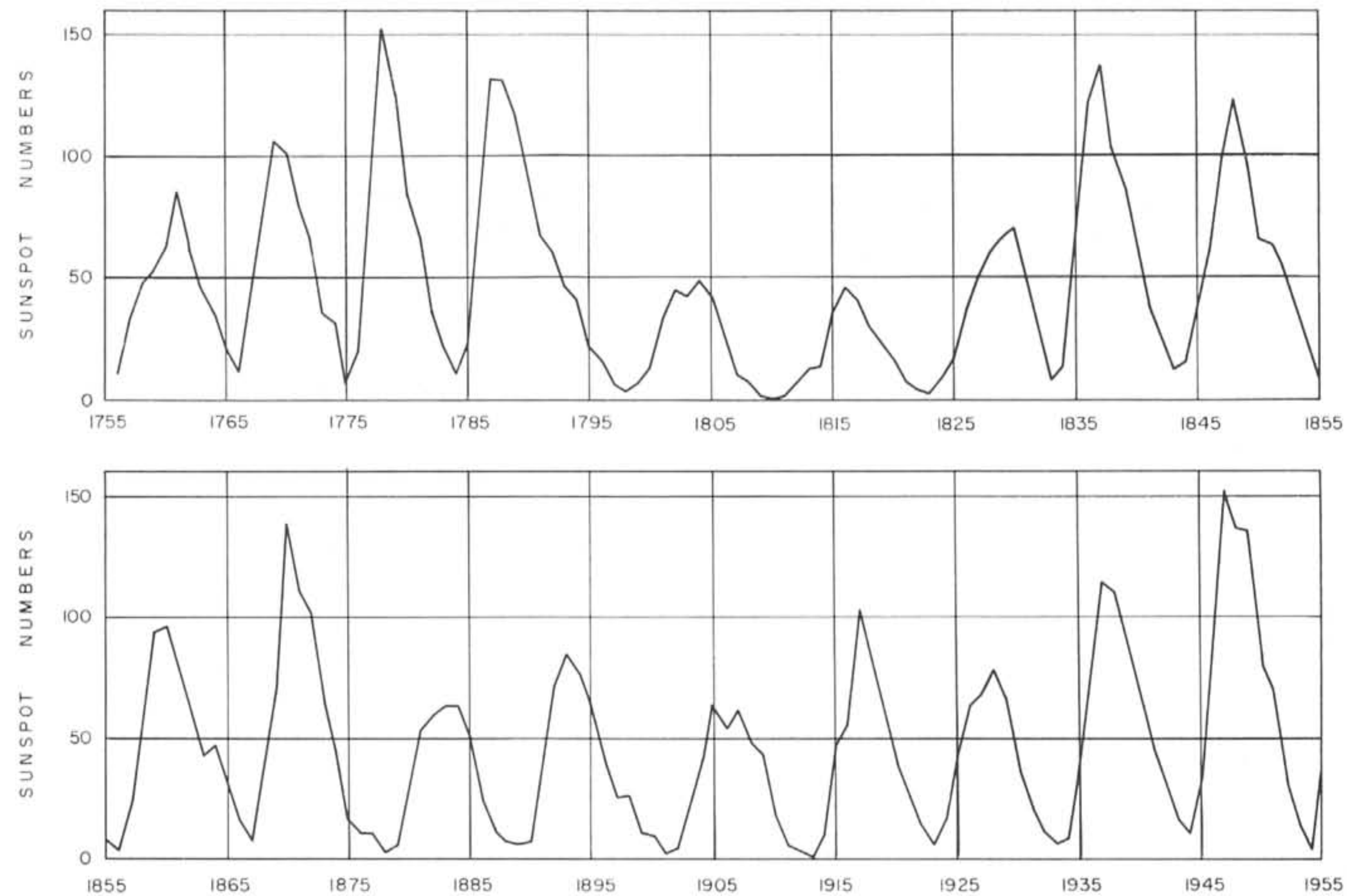
(B) Rainfall in Texas. Incremental Averages Based on Computations by Noriega (1964).

(C)

(D) Fluctuations of Annual Precipitation at 4 Cities in the Great Plains Zone.

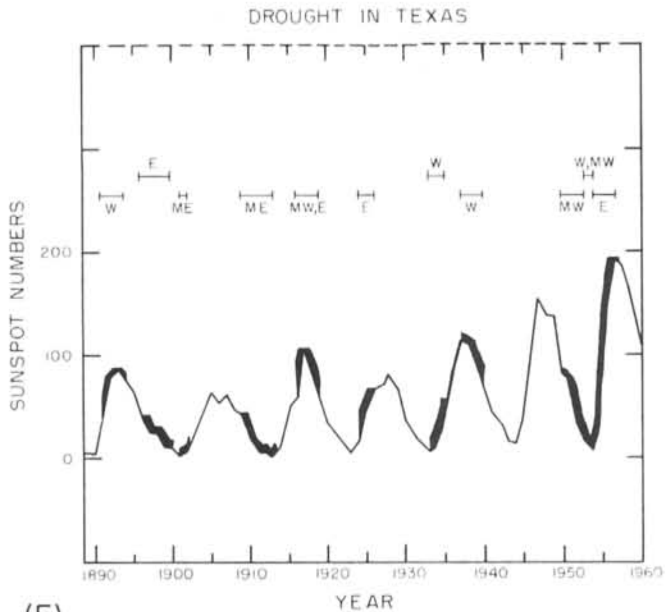
Figure 4

Climatic Trends



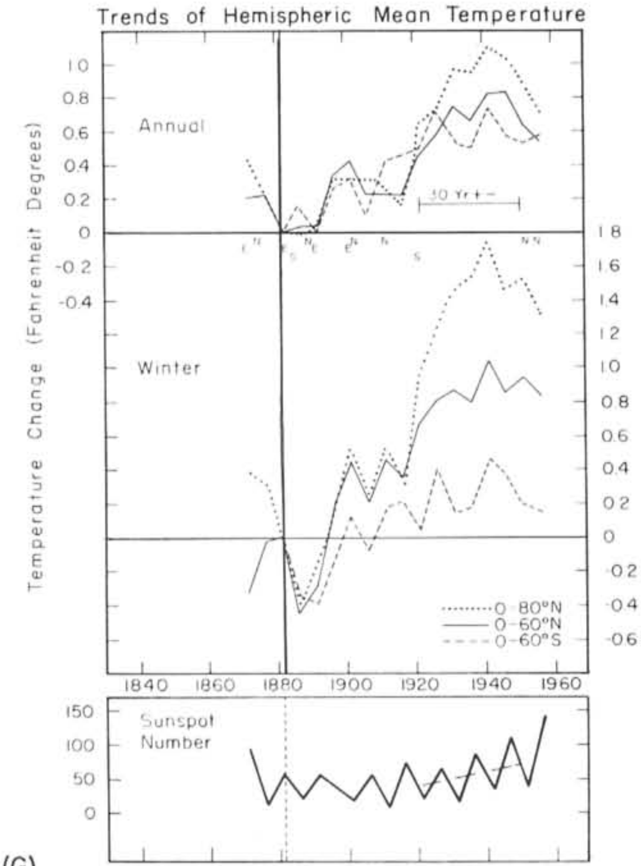
(E) Sunspot Numbers for 1755-1955 Based on a Tabulation by E.H. Munro.
Adopted from Friedman, (1957)

Figure 5
Sunspot Numbers for 1755-1955



(F)

Broad lines on sunspot graph denote years when drought occurred in Texas during the period 1891-1956. Letters above the sunspot graph show in which area of Texas the particular drought was the most severe. "W", West Texas; "E", East Texas; "ME", Mid-East; "MW", Mid-west. Severity, duration, and location of droughts are taken from Lowry (1959).

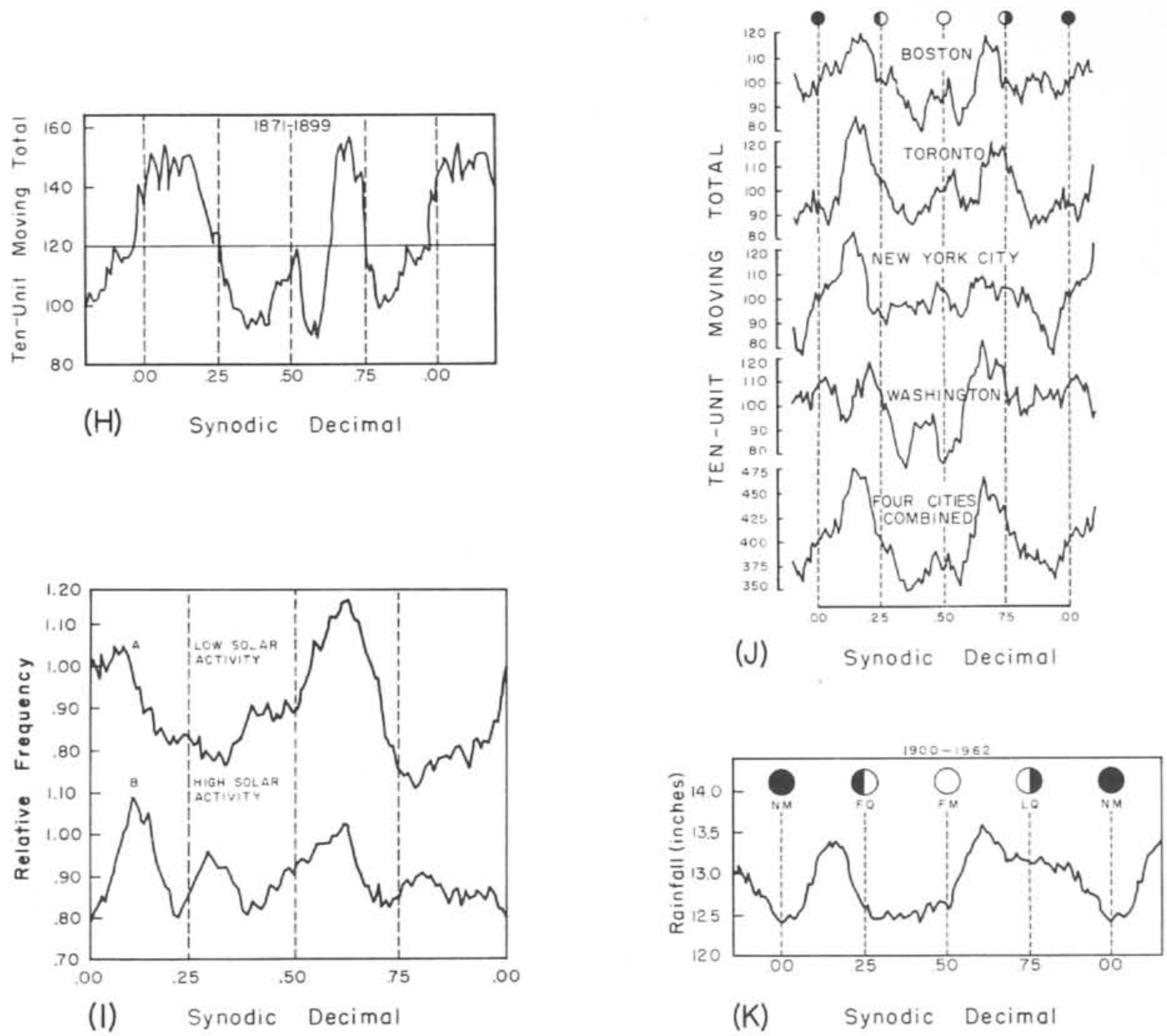


(G)

Trends of mean temperature in Northern and Southern Hemispheres, within indicated latitude limits. Annual average data above and winter-season data below. All curves are area-weighted averages of 10°-latitude band data. Dates of major volcanic eruptions shown in middle of the figure by E (for equatorial), N (for Northern Hemispheric), or S (for Southern Hemispheric). Adopted from Mitchell, 1961.

Figure 6

Sunspot and Volcano Influence



Adopted from Brier and Bradley, 1964

Figure 7

Lunar Influence

the vertical shaded areas. Thomas[12] has pointed out that there are similar alternating wet and dry periods indicated on all of the graphs except the one drawn for Brownsville (Brownsville is a coastal city). Also, the graphs show that these droughts began in years of maximum sunspot activity during the lower maximum of the double sunspot cycle.

If one cares to extrapolate into the future, and he believes the next Great Plains drought period will also begin just following the peak of the next lower maximum of the double sunspot cycle, he could with relative ease pick out the approximate year in which that peak on the sunspot curve will occur. These lower maximum peaks have been occurring at intervals averaging about 11 years after the higher maximum of the double sunspot cycle. The last higher maximum occurred in 1957. Indications now are that a lull occurred on schedule in 1964, so we should now be on the way to another maximum. These maxima have been occurring about 5 years after the primary minima. Five years added to 1964 equals 1969. By extrapolation then, the next major Great Plains drought period would begin in 1969 or in the year following 1969. Fascinating little game, isn't it?

Graph "E" is a plot of sunspot numbers for the period 1755-1955. All kinds of cycles might be envisioned here. One almost feels like taking a pair of scissors and cutting the graph in half, placing the two plots on a light table, and sliding them back and forth to see if an exact match can be found. Well, let's suppose an exact match could be found if we had a thousand years of reliable sunspot records. What would we then have? Accurate weather records don't go back that far. We wouldn't be able to match sunspot occurrences with weather occurrences any better than we can now. What we need to do now is insure that records are kept in the future. So, perhaps a thousand years hence, earth inhabitants may be living by a plan based on accurately forecasted climatic changes--or they may have by then thoroughly and soundly disproved any present-day theories about possible connections between sunspots and weather.

Graph "F" is a plot of droughts which have occurred in the four sections of Texas since about 1890 (See Lowry[13], p. 23). These droughts are plotted as broad lines along a graph of the sunspot activity during the same period of time. Severe droughts have occurred somewhere in Texas during all variations in sunspot activity. So, what was beginning to look like a pretty good case for sunspot-weather correlation now begins to break down. With only about 50 years of records, serious doubt is raised about a possible correlation.

Graph "G" may help explain a major problem standing in the way of better sunspot-weather correlation in past years, and may at the same time help explain much of the skepticism about possible future correlations. Keeping in mind the inversive effect a rising trend of world temperature is thought to have on precipitation (as illustrated with graphs "A" and "B"), it seems clear that any factor which reduces world-wide temperatures has a good chance of increasing world-wide precipitation.

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[12] Thomas, H. E., The meteorologic phenomenon of drought in the southwest, U.S. Geological Survey Prof. Paper 372-A, 1962.

[13] Lowry, R. L., Jr., A study of droughts in Texas, Texas Board of Water Engineers, Austin, Texas, Bull. 5914, 76 p.

There is a strong case made by Humphreys[14] and other investigators that the amount of the sunspot effect on weather and climatic changes is insignificant when compared with the effect caused by volcanic dust and dust in the atmosphere. Volcanic dust is said to reflect and scatter the radiant heat from the sun. Periods of glaciation and periods of mountain building have been independently proved to be coincident--the mountains having been formed by massive and widespread volcanic eruptions, which threw great quantities of dust into the atmosphere. The dust acted as a shield between the sun and the earth, reflecting away the sun's heat and causing cooling and deep snow that could not melt between seasons. The snow then grew into an expanding ice cap and another ice age was launched.

The solid line in the upper section of Graph "G" represents the annual temperature trend since about 1870 in the northern hemisphere between zero and 60 degrees latitude. The letters along the horizontal line indicate when and where major volcanic eruptions took place. "N" is for eruptions in the Northern Hemisphere, "S" for Southern Hemisphere, and "E" for Equatorial. The depressed temperature trend from about 1880 to about 1920 is accounted for in the graph by the numerous volcanic eruptions of the time, which threw dust into the atmosphere and reflected away the sun's heat. During a 30-year period between about 1920 and about 1950, no major volcanic eruptions occurred. The temperature trend was upward--possibly in response to the upward trend of the sunspot curve shown in the bottom section; possibly just because the normal heat from the sun could get to the earth through a relatively dust-free atmosphere. That ends the case for sunspots, but how about lunar effects?

Graphs "H" through "K" illustrate a thoroughly proven, small but nevertheless real, effect the moon has on precipitation. To warrant this conclusion, numerous rigorous statistical tests were applied to United States precipitation records for the 91-year period 1871-1961 (See Brier and Bradley[15]). The cycle is 14.765 days, one-half the lunar synodic month. The basic data used in the major part of the study were the dates of occurrence of the maximum 24-hour precipitation amounts for 1544 weather stations in the continental United States which continuously operated over the 50 years, 1900-1949 and were published by Jennings[16]. A total of 16,057 entries were used representing 6710 individual dates during this period. The average amplitude of this lunar affect is quite small, therefore is of little or no forecasting value for day-to-day rainfall.

On all these graphs the new moon occurs at synodic decimal zero; the first quarter at decimal twenty-five; the full moon at decimal fifty; and, the last quarter at decimal seventy-five.

Graph "H" shows a cyclical fluctuation in rainfall greater than 20 percent amplitude.

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14 Humphreys, W. J., Physics of the air, McGraw-Hill Book Co. Inc., New York, 1939.

15 Brier, G. W., Bradley, D. A., The lunar synodical period and precipitation in the United States, Washington, U.S. Weather Bureau manuscript, 1964, 20 p.

16 Jennings, A. H., Maximum 24-hour precipitation in the United States, U.S. Weather Bureau Technical Paper No. 16, Government Printing Office, Washington, 1952.

To illustrate how the sun's variations may influence the lunar effect, Graph "I" shows that the 14.765-day wave accounts for 65 percent of the variance of the curve during years of less than median solar activity, while the same wave accounts for only 14 percent of the variance in the curve during years of more than median solar activity during the 50-year period 1900-1949.

Graph "J" shows similar lunar-effect curves for the four cities, Boston, Toronto, New York, and Washington. The four cities were combined to produce the lower curve.

Graph "K" is a summary of normalized[17] precipitation data for the 63-year period 1900-1962 expressed in inches of rainfall. One fact stands out on this and all other lunar-effect curves on Figure 7: the average amount of rainfall is about 10 percent higher a few days after the full moon than a few days before.

CONCLUSIONS

Because proof of an inverse temperature-precipitation relationship has been repeatedly offered and widely accepted, discovery of a means of accurately forecasting global temperature trends could also result in a means of forecasting precipitation trends. For the present, however, probability forecasts based on statistical analyses of weather data seems to be the best we can do. Attempted extrapolation of past weather cycles into the future has an inherent failure factor: the unpredictability of future volcanic eruptions which could envelope the earth with dust to reflect away the sun's energy. Sunspot cycles have been predictable enough, but their relationship to drought has never been universally accepted nor thoroughly understood. No one has ever been able to effectively demonstrate what effect volcanic eruptions have had in the past on the amount of heat the earth received during periods of high solar activity. In other words, we have not been able to subtract out the effect volcanic eruptions had on insolation and there is reason to doubt that we can do so in the future.

Our best hope for accurate drought forecasting in the future could very well be tied directly to our ability to program and use high-speed electronic data-processing equipment. Using such equipment, suspected causal factors can be run down and proved or discarded in an amazingly short period of time. The same power-spectrum approach used to prove correlation between the "Lunar Synodical Period and Precipitation in the United States," and the "Biennial Oscillation," was also used in a time-series analysis to cast serious doubt on claims that a 10-year cycle in weather is a persistent feature of the climate in the Great Plains. Precipitation records for St. Louis for the 126-year period 1838-1963 were used in that analysis. Hand-processing such a great volume of data is a time-consuming if not impossible task. To mention but three possibilities, future efforts to electronically process climatic records spanning long periods of time might be profitably directed toward: (1) analyzing the possibility of climatic variations over a period of 80 or 90 years, corresponding to similar periods of variation in solar activity; (2) examining a popular theory about climatic variations being tied to atmosphere-ocean

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[17] The frequency distribution of daily precipitation data was found to be highly skewed and was normalized by means of the cube-root transformation.

interactions; and (3) looking into the matter of world temperature trends and the inverse relationship known to exist between world-wide temperature and precipitation trends.

Perhaps after eliminating some of the false leads which are bound to crop up, the remaining possibilities can receive the full benefit of our scientific effort. A result might very well be as the noted Climatologist Ivan Ray Tannehill prophetically pointed out:

> "In the future, farmers will not have to gaze despairingly into a clear sky, wondering if a few clear days will continue into a disastrous drought."

PREDICTING DROUGHTS[a]

Discussion by Keith R. Marmion

KEITH R. MARMION,[1] M. ASCE.--Mr. Carr has presented what might be termed "the state of the art" of drought prediction. He has outlined three major starting points from which most attempts at drought prediction have been made. In this discussion I will examine some of these premises and suggest some pitfalls which should be avoided, as well as some possible new avenues of approach which we might try. In our search for a useful means of peering into the future to predict our available water supplies, we must guard against making either of two fundamental mistakes. On the one hand, we must avoid the introduction of error through our method of analysis, thereby seeming to develop techniques which enable us to predict weather phenomena, when in fact, our method of prediction influences to a considerable extent that which will be predicted. On the other hand, we must not require too much of our methods of prediction before we are willing to recognize them as basically valid.

Mr. Carr has mentioned the search by many people for a cyclic effect in the weather. It is a great temptation for us to think that the weather will repeat itself in some fashion, and men through history have succumbed to the thought that periods of drought and periods of adequate rainfall must follow one another with some sort of a rhythmic pattern which, if we could only discover the nature of the rhythm, would enable us to forecast future patterns of rainfall. Unfortunately, most of the investigators into the reality of cycles in hydrologic data have used some technique designed to smooth out the erratic and extreme variations from one data point to the next. Of course, this has been done with the hope that any underlying periodic relationship would be exposed. Two methods have been used by a number of investigators. The first utilizes a moving average of successive data points, and the second utilizes deviations from the mean. The use of either of these methods will insure that the transformed data will have a cyclic nature. Both Friedman[2] and Crippen[3] have shown that a truly random set of numbers may be selected and treated as though they represent precipitation values and that the use of moving averages or cumulative departures from the mean will cause these purely random numbers to take on the appearance of a cyclic variation.

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[a] By John T. Carr, Jr.

[1] Chairman, Department of Civil Engineering, Texas Technological College, Lubbock, Texas.

[2] Friedman, Don G., The Prediction of Long Continuing Drought in South and Southwest Texas, The Travelers Weather Research Center, Occasional Papers in Meteorology, No. 1, 1957.

[3] Crippen, J. R., Cycles in Hydrologic Data, Civil Engineering, Vol 35, No. 1, 1965, p. 70.

How can we examine the periodic nature of data? We must use methods of investigation which will not themselves alter in any way the periodic nature of the data if we wish to examine the hypothesis that cycles are indeed present in the data. Secondly, when some tendency toward cycles is detected, we must determine whether or not the amount of cyclic behavior observed is more than we might find in a group of random numbers. To illustrate this approach, the writer has fitted a sine curve to the annual precipitation totals for each of four cities in Texas. Because a sine curve of very short period would give a "best" fit, since it could pass through each of the points and yet have no meaning from the standpoint of weather cycles, it was decided to select 5 years as a lower limit for the cycle period and to examine sine curves of varying amplitude and period up to 25 years in length for the cities studied. The work was done with the aid of an electronic digital computer and the method of least squares was employed. Of course, a sine curve of "best" fit, with period between 5 and 25 years, exists for each set of data. The question, which must be answered is, does this sine curve fit the data significantly better than a straight line drawn through the mean of the data? This question may be answered statistically. To get an indication of the answer, the writer has assumed that the ratio of the variances of the data about each of the lines--that is, the straight line and the sine curve--would be distributed according to the F distribution. This is not strictly true because the data are not normally distributed, but the error introduced in our test by making this assumption is small. The results of these tests for significance are shown in Table 1. It is concluded that we do not have sufficient evidence in the data to warrant an assumption that annual precipitation in these cities follows a cyclic pattern.

We immediately raise the question as to the power of our test to detect a difference in the two variances if a small one exists. Is it not possible the weather really does display regular periodic variations, yet we insist on too much evidence before we will admit the existence of these cycles? As time goes on, we can expect to have at our disposal more sophisticated statistical techniques which will give us a better chance of uncovering cyclic variations if they do exist. One such technique, which is at this time in its infancy but shows promise for the future, utilizes the device of increasing the number of sample points by introducing artificial sample points which have the same statistical distribution as real data. The terms, hydrologic data synthesis and stochastic generation of data, have been applied to this technique. It will be argued, of course, that we cannot possibly get more real information from our data than is contained in that data. But, it must also be recognized that traditional statistical techniques may not take advantage of all information which is contained in the data.

In connection with this idea of cycles in weather, it should be noted that the biennial oscillation of the wind and temperatures in high altitudes mentioned by Mr. Carr has been accepted as reality. Is there not then a real possibility that other weather producing factors may display some cyclical variation? It may well be that a careful study of the cyclic and interrelated nature of such individual weather factors as temperature, wind patterns, etc., over the entire earth, which combine to produce the more complex phenomena of weather, might yield information which could be combined to predict variations in weather over longer periods of time. It should be noted in passing that several cycles of various amplitudes and periods can be combined in such a way as to produce a curve which is essentially a straight line but which, from time to time, deviates markedly from that line.

TABLE 1

Hypothesis:

Our hypothesis is that the variance of our data about the "best sine curve would be equal to the variance about the straight line through the mean if our record of precipitation was infinitely long. (In other words, we hypothesize that the data do not follow any regular cyclical pattern.)

Test:

We test our hypothesis by the use of the F statistic, which is defined as the ratio of the variance about the sine curve to the variance about the straight line.

We will reject our hypothesis with 90% confidence if this ratio is greater than 1.40

City	Length of Continuous Record (years)	Period Length for "Best" Fit Sine Curve	F Statistic
Amarillo	66	20	1.27
Corpus Christi	66	6	1.08
Dallas	66	20	1.15
Houston	66	22	1.17

Result: We accept the stated hypothesis for each of the cities and conclude that the data do not follow a cyclic pattern.

Note: We insisted on retaining the hypothesis unless we could be 90% sure that it is wrong. This is not the same as saying that we are 90% sure that it is correct.

In summary, the writer agrees that past attempts to find cyclic variations in rainfall data have produced little, if any, useful information. It is the writer's belief, however, that we should not abandon all efforts at detecting periodic variations in weather factors. At the same time, let us not pursue this approach to the extent that we neglect more immediately useful techniques of drought prediction.

In view of our present inability to find anything other than a random pattern in precipitation records, statistical analyses of the type made by Dr. Friedman and described by Mr. Carr appear to hold the most promise of producing something useful for present day planning of water supply systems. Dr. Friedman has estimated the probability of occurrence of various amounts of total annual precipitation throughout the State of Texas. These estimates are based on the assumption that the annual rainfall series is a random series drawn from a population which has a distribution described by an incomplete gamma function.

From this mathematical model Dr. Friedman determined the theoretical probability of occurrence of the amounts of rainfall at several points in the State, and developed the set of maps with overprinted isograms to which Mr. Carr has made reference.

A procedure somewhat similar to that employed by Dr. Friedman can be used to predict the probability that a period of drought will be of a specified length. The same technique may also be employed to determine the probability that a period of non-drought will be of a specified length. The writer has made a very simple analysis of this sort for periods of drought and periods of non-drought for the State of Texas using information presented by Lowry[4]. The period of record was 69 years and the number each of droughts and non-droughts vary from 8 to 10 in each of the four areas into which Lowry[4] divided the State of Texas.

A plot of the data was made for each of the areas and a curve of the form

$$Y = Ae^{-BX}$$

was drawn through the data. This curve was fitted to the data by eye. An equation of this form was chosen as the mathematical model because of its having a finite value of Y for small values of X which decreases asymptotically to 0 as X increases. Values of A and B were determined for each of the four areas of Texas, but it was believed that the small number of data points in each of the plots and the method of fitting the curve did not warrant the use of different equations for each of the areas in this paper. Therefore, simple arithmetic averages of A and B were determined from the four values of each and the equations presented in Figures 1 and 2 resulted. These equations apply approximately to the whole State of Texas, but it is not the intent of the writer to imply a high degree of confidence in either of them. Rather, it is his desire to present the idea and to suggest that refinements, especially as the length of our records increase, may provide useful information. The tables shown with Figures 1 and 2 were developed from the equations shown. The tabled value is the probability that any particular period of drought (or non-drought) will be of a given length or longer. Thus we see that the probability of a drought being of 3 years duration or longer is 0.46 and the probability of its duration being 4 years or greater is 0.31. It may be seen, then, that the probability of the drought lasting more than 3 but less than 4 years is the difference of these two values or 0.15.

Hoyt[5] concluded that in the humid and semi-arid areas, drought conditions exist when there is an annual deficiency in precipitation of 15 percent or more. This definition was used by Lowry[4], and has been followed here with the exception that a drought was considered to continue through 1 year of rainfall in excess of 85 percent of average if that year was preceded and followed by years each of which had a total precipitation of less than 85 percent of normal. Using this criterion, it follows that a period of non-drought must be at least 2 years in length.

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4 Lowry, R. L., Jr., A Study of Droughts in Texas, Texas Board of Water Engineers, Austin, Texas, Bull. 5914, 76 p.

5 Hoyt, J. C., U.S. Geological Survey Water-Supply Paper 820, p. 2.

It is not the writer's intent to suggest the adoption of these modified definitions of drought and non-drought periods, but simply an attempt on his part to take into account those two important dimensions of a drought--namely magnitude and duration. Certainly further refinements in the determination of probabilities for duration of wet and dry periods is in order. It is hoped that the material presented here may suggest a tool which will prove useful in man's attempt to plan and provide for periods of inadequate precipitation.

The average of the four drought distribution curves obtained from the four areas of Texas shown on the inset map at left is shown below with the data from the Mid-East (shaded) area.

The equation of the curve shown below is

$$Y = 5.2\ e^{-0.39X}$$

Values of P in the table below is the fractional part of the total area under the curve of that area to the right of X-0.5.

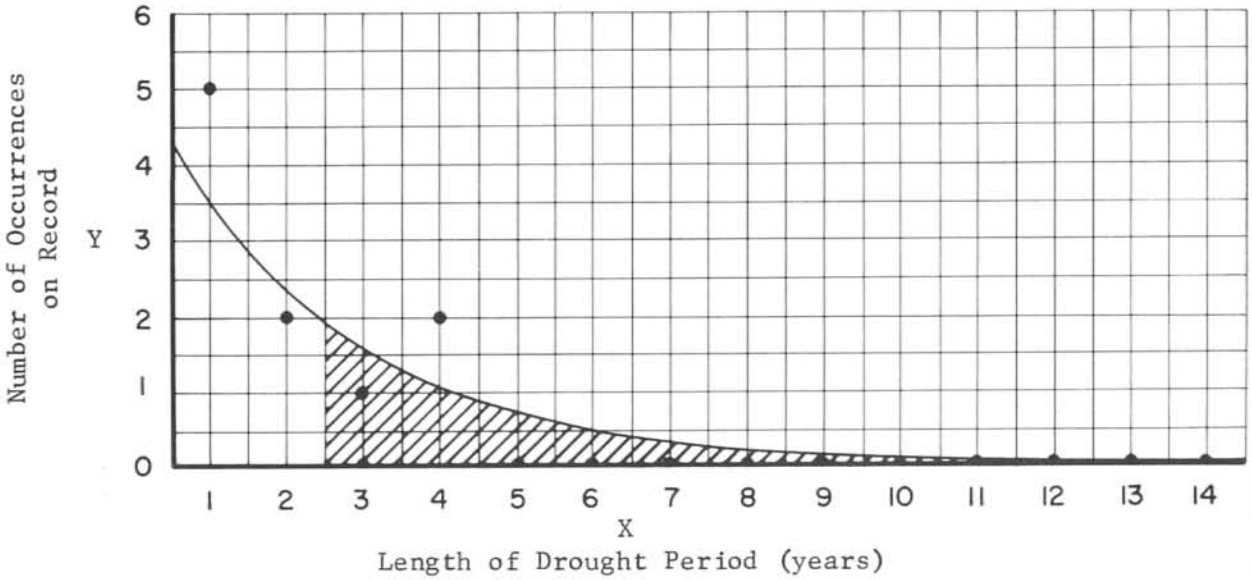

TABLE OF PROBABILITIES

X	1	2	3	4	5	6	7	8	9	10	11	12
P	1.00	.68	.46	.31	.21	.14	.10	.066	.044	.030	.020	.014

P is the probability that a period of drought will equal or exceed X years in duration.

Figure 1

Determination of Drought Duration Probability

The average of the four drought distribution curves obtained from the four areas of Texas shown on the inset map at left is shown below with the data from the Mid-East (shaded) area.

The equation of the curve shown below is

$$Y = 6.35\ e^{-0.33X}$$

Values of P in the table below is the fractional part of the total area under the curve of that area to the right of X-0.5.

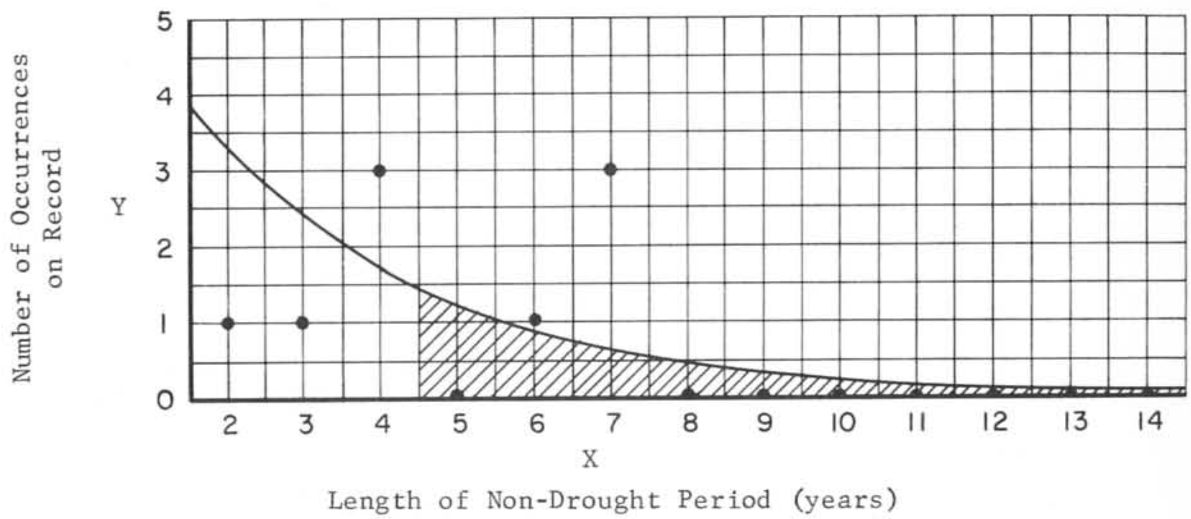

TABLE OF PROBABILITIES

X	2	3	4	5	6	7	8	9	10	11	12
P	1.00	.72	.52	.37	.27	.19	.14	.10	.071	.052	.037

P is the probability that a period of non-drought will equal or exceed X years in duration.

Figure 2

Determination of Non-Drought Duration Probability

DATA COLLECTION PROGRAMS DURING DROUGHTS

DATA COLLECTION PROGRAMS DURING DROUGHTS[a]

By Clarence R. Gilbert,[1] M. ASCE

INTRODUCTION

The sustained spring and/or natural base flow of streams is evidence that the quantity of water stored in the associated ground-water reservoir is sufficient to provide perennial flow to the stream without surface storage. The quantity of sustained flow will fluctuate with numerous hydrologic factors. To evaluate the quantity and quality of such natural sources it is necessary to conduct basic-data studies in a systematic manner. Therefore, the collection of such data under drought conditions should be planned and conducted on a continuing basis to define the hydrologic regimen for low flows throughout the drought cycle.

In recent years, the U.S. Geological Survey with financial assistance from the Texas Water Commission, water districts, cities, and Federal agencies has expanded the scope of hydrologic data-collection programs for drought conditions. The resulting data, when properly analyzed, will be of tremendous aid to the water managers during any future drought.

Hydrologic events are best analyzed and presented in the form of curves on which the extremes represent the drought events. Definition of the curves to very low values prior to the beginning of a drought is certainly desirable to the water manager, because he can then, with reasonable accuracy, extrapolate to values expected during droughts. The following discussion of a few of the Geological Survey data-collection programs is based on data obtained from water investigations that are primarily concerned with data collected outside the actual drought period. In this paper, however, are presented only those data-collection programs which are felt pertinent to the drought theme of this meeting, or those which are not to be discussed in greater detail later in the program.

PROGRAMS AIDING THE WATER USER WITHOUT STORAGE

Where little or no storage by the water user is necessary or economically feasible, data on minimum sustained base flows during droughts are required. In recent years, with wider use of the electronic computer, the Geological Survey has developed a computer program that yields data from which the flow-duration and low-flow-frequency curves are readily prepared. These curves are invaluable in analyzing the low-flow characteristics of a stream. The print-out

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[a] As approved for publication by Director, U.S. Geological Survey.

[1] Hydraulic Engineer, U.S. Geological Survey, Austin, Texas.

sheets from the computer showing the data used are presented as Figures 1 and 2. At the present time, Texas has 129 stream-gaging stations with 5 or more years of daily streamflow records that have been processed through the computer. Most all the qualifying stations (5 or more years of daily streamflow record) in the Red, Sabine, Neches, Trinity, and San Jacinto River basins have records processed as do many selected long-term stations in the other river basins in Texas. As funds become available the processing of records for all stream-gaging stations is expected. The print-out sheets will be made available, probably by river basins, as the processed data become available.

It is impractical and uneconomical in both funds and manpower to attempt to collect daily streamflow records for every stream. Better areal coverage can be attained by the application of computers and statistical methods, to a properly planned sampling field data-collection program. For example, flow-duration curves prepared from data collected at strategic hydrologic points on a continuous basis often can be extrapolated to areas which have only limited field data. A proper data-collection program utilizing a simple correlation technique has increased our hydrologic data coverage. The correlation technique yields data which are much more accurate than estimates based on runoff per square mile of nearby gaged areas, because estimates made in this manner are seldom reliable unless the ground-water hydrology of the two areas is known to be the same.

The data-collection program consists of making a series of base-flow discharge measurements at ungaged sites at or near preselected percentiles of flow duration for the nearby gaged sites. For example, if discharge measurements were made at the ungaged sites for streamflow at the 50, 75, and 98 percentiles of the flow-duration curve for the gaged site, 3 points for definition of the flow-duration curve would be available. At least 3 points for each percentile, or 9 points overall, are desirable. The lower portion of the flow-duration curve for the ungaged site can then be estimated within acceptable design criteria. An example of the flow-duration curve for an ungaged site (Bayou Castor) estimated from discharge measurements is shown on Figure 3. This site is about 3 miles east of the Louisiana-Texas border at the Sabine River.

At the present time in Texas the Survey has 106 low-flow partial-record gaging stations where periodic (2 to 10 per year) base-flow discharge measurements are obtained. The Survey expects that the lower portion of flow-duration curves for most of the partial-record sites will be defined in the near future. Because three-fourths of the runoff occurs in the eastern fourth of the State, the above described partial-record data-collection program obviously has the greatest application in that area of sustained base flows; however, considerable use can also be made of the program in the remainder of Texas. Except in those areas with substantial artesian spring flow, in the more arid regions of the State the low end of the duration curve would approach zero at a much faster rate and at a smaller percentage of daily flow than in the more humid regions.

The major uses of flow-duration curves are: (1) In analyzing the effect of geology on low flows; (2) In water-supply and water-power studies; and (3) In stream-pollution studies. Flow-duration curves have been criticized because they give no indication of the chronological sequence of flows. The lack of data on sequences of flows is critical in some water utilization problems.

In those problems where flow-duration curves fail to provide the necessary solution, low-flow-frequency curves generally can be used. The low-flow-frequency curve is one of the most useful of all low-flow analyses because

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION

Sabine River at Logansport, La. STATION NUMBER 08-0225.00

NUMBER OF DAYS IN CLASS

YEAR \ CLASS	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	CFS-DAYS
1904							12	10	6	24	50	56	57	33	22	22	31	22	6	15																441606.0
1905						4	25	53	4	4	10	9	15	9	7	14	21	7	10	22	56	56	16	20	3											2318618.0
1906										13	13		14	35	46	18	45	32	30	54	25	26	13	1												1573533.0
1907						3	20	20	13	15	21	4	29	39	33	20	29	14	19	16	55	15														1068536.0
1908							8	18	6	32	18	9	20	11	29	24	26	16	10	49	58	14	12	5	1											1597892.0
1909				8	18	36	19	3	14	59	15	19	54	34	35	21	13	5	5	7																289057.0
1910			9	19	4	25	47	25	8	22	14	12	44	32	25	24	15	10	9	19	2															391395.0
1911			31	22	19	37	33	18	29	42	27	13	33	13	5	3	12	8	9	11																246428.0
1912			2	4	7	27	8	34	19	26	17	17	37	18	18	15	13	8	15	26	37	17	1													920360.0
1913						1	66	34	11	32	20	10	20	20	32	26	29	8	9	21	21	5														641490.0
1914								21	6	26	22	7	20	14	23	25	21	12	40	35	49	25	10	5	4											1739841.0
1915									3	41	9	15	15	18	29	24	35	35	12	27	60	21	7	7	4	3										1836052.0
1916								5	9	40	17	2	34	36	52	44	40	9	19	18	24	17														913724.0
1917							3	23	6	23	26	28	46	56	77	46	16	9	4	2																374723.0
1918							12	42	41	78	56	34	27	16	19	12	2	2	3	9	12															315877.0
1919								6	16	7	6	4	3	16	25	41	69	47	43	65	14	3														1171925.0
1920												1	5	21	20	44	39	23	44	77	32	22	18	18	2											2269989.0
1921								15	6	14	16	8	12	35	46	17	46	13	35	42	39	13	2	2	3	1										1398127.0
1922							14	31	33	23	15	12	34	25	20	21	24	17		4	42	28	10	10	2											1474510.0
1923						12	31	32	8	16	22	22	25	31	10	18	27	24	22	28	20	17														883706.0
1924					7	23	16	14	16	35	20	10	11	15	11	13	16	16	13	38	70	22														1296518.0
1925				23	15	26	33	59	17	37	39	23	30	30	8	7	15	3																		155111.0
1926				1	1	13	2	12	6	12	5	10	31	47	28	15	43	16	24	34	26	31	5	3												1324930.0
1927						6	25	20	8	22	11	9	14	16	30	20	34	27	24	31	27	32	7	2												1358678.0
1928					1	11	21	9	8	21	20	15	24	47	53	29	23	26	30	18	10															669997.0
1929					5	12	26	19	10	15	9	8	21	17	17	8	29	33	15	41	65	15														1313786.0
1930						4	53	44	10	26	11	20	20	16	32	16	15	3	4	33	37	7	4	5	5											1125645.0
1931						8	13	12	14	37	16	8	45	35	39	26	27	27	14	38	4	2														670126.0
1932				16	13	9	30	24	10	32	20	13	6	15	26	21	14	6	1	6	21	26	21	31	4	1										1983093.0
1933						18	25	22	22	28	16	14	8	18	11	6	6	19	26	47	65	10	1	3												1289197.0
1934			19	41	6	7	4	18	21	40	14	7	23	21	17	15	16	17	10	16	30	18	5													900089.0
1935				24	18	10		12	19	24	17	2	10	14	24	19	28	25	36	25	28	14	6	7	3											1342405.0
1936			9	10	17	15	4	16	11	23	27	14	19	51	78	22	17	11	11	4	7															424222.0
1937			4	1		2	34	33	22	43	25	13	16	13	19	20	22	11	17	21	38	11														851886.0
1938						30	19	16	13	19	26	18	21	18	15	16	11	11	3	12	61	34	16	6												1590694.0
1939		15	19	27	16	21	9	8	11	36	18	12	18	18	23	26	22	13	6	7	31	9														668332.0
1940		22	19	1	1	2	2	16	40	15	17	4	24	25	30	24	34	33	22	21	14															656884.0
1941							6	13	6	6	16	9	12	8	19	26	23	9	24	31	58	67	18	11	3											2458419.0
1942								2	10	9	8	3	17	23	29	39	39	27	25	37	46	15	26	10												1924523.0
1943							37	13	11	5	9	22	35	62	35	28	39	16	14	23	2	2	4	5	3											865496.0
1944							3	29	13	46	11	29	15	13	17	3	14	20	14	9	54	42	7	19	8											2114028.0
1945								27	16	26	5	11	21	18	16	6	26	21	11	33	24	39	28	20	7	1	4	5								3022978.0
1946										18	24	11	16	11	19	25	33	20	22	24	23	63	40	10	6											2589902.0
1947								24	13	18	13	10	25	18	20	9	32	14	16	40	82	19	6	6												1673608.0
1948							26	21	29	14	17	23	16	9	13	11	24	13	12	45	52	41														1422030.0
1949						6	11	28	3	20	19	13	43	32	22	21	25	17	13	56	36															948944.0
1950										4	10	9	18	26	39	22	34	39	17	40	25	54	12	16												2130276.0
1951						11	19	15	11	16	22	52	41	28	43	30	21	25	2	23	6															520860.0
1952				15	15	19	21	14	28	27	15	7	21	20	32	10	15	22	3	28	38	16														914822.0
1953				31	10	6	5	2	18	31	21	7	14	17	23	22	56	23	18	8	6	15	14	12	4	2										1457620.0
1954		8	32	13	7	16	26	20	14	11	9	2	14	33	47	21	48	8	17	10	4	5														510556.0
1955			3	9	4	3	7	11	18	20	23	23	27	33	45	14	27	17	21	28	24	8														833646.0
1956		4	35	27	8	11	32	29	42	34	22	5	19	23	13	12	10	10	10	10	3	7														378673.0
1957		4	21	3	5	2	24	45	34	23	19	15	8	21	13	11	16	4	7	10	24	15	18	9	5	3	6									1795066.0
1958										4	29	14	19	14	13	6	51	38	43	47	40	17	15	4	4	4	3									2137559.0

CLASS	CFS	TOTAL	ACCUM	PERCT	CLASS	CFS	TOTAL	ACCUM	PERCT	CLASS	CFS	TOTAL	ACCUM	PERCT	CLASS	CFS	TOTAL	ACCUM	PERCT
	.0		20089	100.0	09	200.0	1334	16275	81.0	18	4000	889	5585	27.8	27	70000	5	5	.0
1	15.0	53	20089	100.0	10	300.0	997	14941	74.4	19	5000	1441	4696	23.4	28				.0
2	20.0	203	20036	99.7	11	400.0	747	13944	69.4	20	7000	1627	3255	16.2	29				.0
3	30.0	295	19833	98.7	12	500.0	1266	13197	65.7	21	10000	935	1628	8.1	30				.0
4	40.0	197	19538	97.3	13	700.0	1337	11931	59.4	22	15000	342	693	3.4	31				.0
5	50.0	436	19341	96.3	14	1000.0	1492	10594	52.7	23	20000	247	351	1.7	32				.0
6	70.0	831	18905	94.1	15	1500.0	1098	9102	45.3	24	30000	71	104	.5	33				.0
7	100.0	1037	18074	90.0	16	2000.0	1458	8004	39.8	25	40000	15	33	.2	34				.0
8	150.0	762	17037	84.8	17	3000.0	961	6546	32.6	26	50000	13	18	.1	35				

Figure 1

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WATER RESOURCES DIVISION

Sabine River at Logansport, La. STATION NUMBER 08-0225.00

LOWEST MEAN DISCHARGE FOR FOLLOWING NUMBER OF CONSECUTIVE DAYS

YEAR	1	3	7	15	30	60	90	120	150	183	274
1904	65.0	65.0	67.9	80.9	90.1	105.0	112.0	130.0	186.0	311.0	1150.0
1905	239.0	243.0	266.0	297.0	315.0	385.0	836.0	1370.0	2770.0	4150.0	5570.0
1906	251.0	255.0	275.0	317.0	430.0	808.0	915.0	942.0	1180.0	1220.0	2260.0
1907	65.0	66.7	69.3	72.9	83.1	106.0	121.0	281.0	548.0	1780.0	3090.0
1908	192.0	192.0	200.0	214.0	248.0	387.0	532.0	551.0	536.0	584.0	917.0
1909	30.0	31.0	31.3	33.0	38.3	48.0	53.9	70.9	76.8	110.0	373.0
1910	20.0	23.3	23.7	24.8	27.3	30.5	36.9	43.9	50.7	97.3	210.0
1911	22.0	24.7	27.3	30.1	45.2	70.9	70.8	88.2	175.0	257.0	617.0
1912	81.0	81.0	81.0	82.6	90.2	91.9	111.0	166.0	309.0	643.0	1020.0
1913	60.0	73.3	74.3	79.5	99.3	575.0	1180.0	1250.0	1310.0	1880.0	2840.0
1914	119.0	125.0	131.0	136.0	152.0	236.0	338.0	395.0	382.0	571.0	2430.0
1915	390.0	406.0	446.0	590.0	670.0	1100.0	1410.0	1520.0	2380.0	2770.0	3190.0
1916	81.0	87.3	98.0	109.0	118.0	166.0	200.0	229.0	286.0	372.0	760.0
1917	81.0	85.0	89.1	96.9	132.0	177.0	193.0	253.0	290.0	313.0	457.0
1918	102.0	107.0	112.0	116.0	129.0	174.0	220.0	218.0	267.0	435.0	1430.0
1919	743.0	758.0	866.0	1350.0	1550.0	1850.0	2550.0	3040.0	2890.0	3060.0	5880.0
1920	488.0	549.0	606.0	800.0	800.0	993.0	1190.0	1390.0	1320.0	1410.0	2330.0
1921	94.0	94.0	94.0	94.5	108.0	135.0	168.0	190.0	268.0	394.0	1140.0
1922	75.0	75.0	76.7	83.7	90.8	134.0	204.0	316.0	382.0	406.0	1420.0
1923	55.0	55.0	55.7	61.7	81.7	167.0	426.0	433.0	451.0	827.0	2290.0
1924	32.0	32.0	32.6	34.9	46.2	95.6	126.0	121.0	129.0	148.0	304.0
1925	33.0	34.3	36.9	39.6	46.9	61.3	69.5	90.5	145.0	417.0	1000.0
1926	60.0	60.0	62.9	71.5	97.7	202.0	306.0	340.0	867.0	1060.0	2230.0
1927	81.0	87.0	87.0	92.1	97.5	280.0	656.0	650.0	715.0	743.0	1070.0
1928	47.0	51.7	57.0	63.7	75.1	114.0	186.0	459.0	682.0	1030.0	2030.0
1929	47.0	47.0	48.1	52.6	65.9	155.0	174.0	201.0	286.0	379.0	1970.0
1930	88.0	88.0	88.0	88.0	89.2	95.7	135.0	216.0	245.0	664.0	1460.0
1931	34.0	34.0	35.7	36.4	40.0	87.5	127.0	152.0	201.0	299.0	1700.0
1932	58.0	59.7	63.7	69.3	79.7	89.4	106.0	110.0	131.0	195.0	679.0
1933	120.0	120.0	125.0	155.0	227.0	245.0	269.0	344.0	478.0	1230.0	2150.0
1934	23.0	23.0	23.6	24.8	28.0	31.5	33.9	37.9	59.3	154.0	892.0
1935	139.0	139.0	145.0	166.0	187.0	216.0	237.0	465.0	818.0	1280.0	1440.0
1936	24.0	24.0	25.4	27.3	33.8	45.6	217.0	243.0	424.0	450.0	780.0
1937	55.0	56.0	57.1	69.2	77.5	110.0	119.0	133.0	166.0	212.0	1110.0
1938	33.0	33.7	34.4	35.7	40.7	52.4	108.0	189.0	262.0	294.0	1060.0
1939	16.0	16.0	16.9	17.1	17.5	19.5	23.6	33.9	62.1	97.4	503.0
1940	94.0	94.0	95.0	106.0	164.0	395.0	616.0	710.0	1130.0	1600.0	4090.0
1941	244.0	253.0	282.0	379.0	726.0	811.0	1150.0	1790.0	2320.0	2650.0	3370.0
1942	144.0	147.0	153.0	173.0	244.0	704.0	741.0	1150.0	1280.0	1290.0	1670.0
1943	70.0	70.7	72.3	76.9	81.9	102.0	162.0	393.0	402.0	577.0	2320.0
1944	99.0	102.0	107.0	121.0	130.0	163.0	214.0	215.0	274.0	767.0	3640.0
1945	180.0	185.0	193.0	209.0	277.0	430.0	1850.0	1870.0	2190.0	2950.0	4300.0
1946	228.0	228.0	237.0	252.0	318.0	611.0	574.0	629.0	1770.0	3380.0	4520.0
1947	106.0	109.0	112.0	120.0	138.0	212.0	312.0	316.0	489.0	696.0	2380.0
1948	66.0	67.0	68.1	70.0	79.9	90.9	101.0	139.0	203.0	256.0	1420.0
1949	230.0	239.0	269.0	366.0	450.0	756.0	1350.0	1360.0	1610.0	2100.0	2560.0
1950	280.0	283.0	302.0	348.0	400.0	473.0	487.0	654.0	672.0	892.0	1660.0
1951	59.0	59.7	61.9	68.6	77.2	136.0	129.0	158.0	218.0	330.0	685.0
1952	36.0	36.0	36.6	36.8	37.0	38.5	43.9	66.7	98.7	373.0	1260.0
1953	79.0	79.3	79.9	83.4	95.3	153.0	280.0	334.0	534.0	614.0	1260.0
1954	18.0	18.0	19.1	19.3	22.1	25.9	32.9	49.5	192.0	536.0	1180.0
1955	77.0	77.7	78.6	81.4	88.1	127.0	161.0	208.0	263.0	424.0	827.0
1956	18.0	18.0	19.3	21.0	21.5	24.1	27.1	31.9	48.1	70.9	242.0
1957	90.0	94.7	108.0	126.0	158.0	233.0	351.0	1080.0	2560.0	3520.0	3990.0

Figure 2

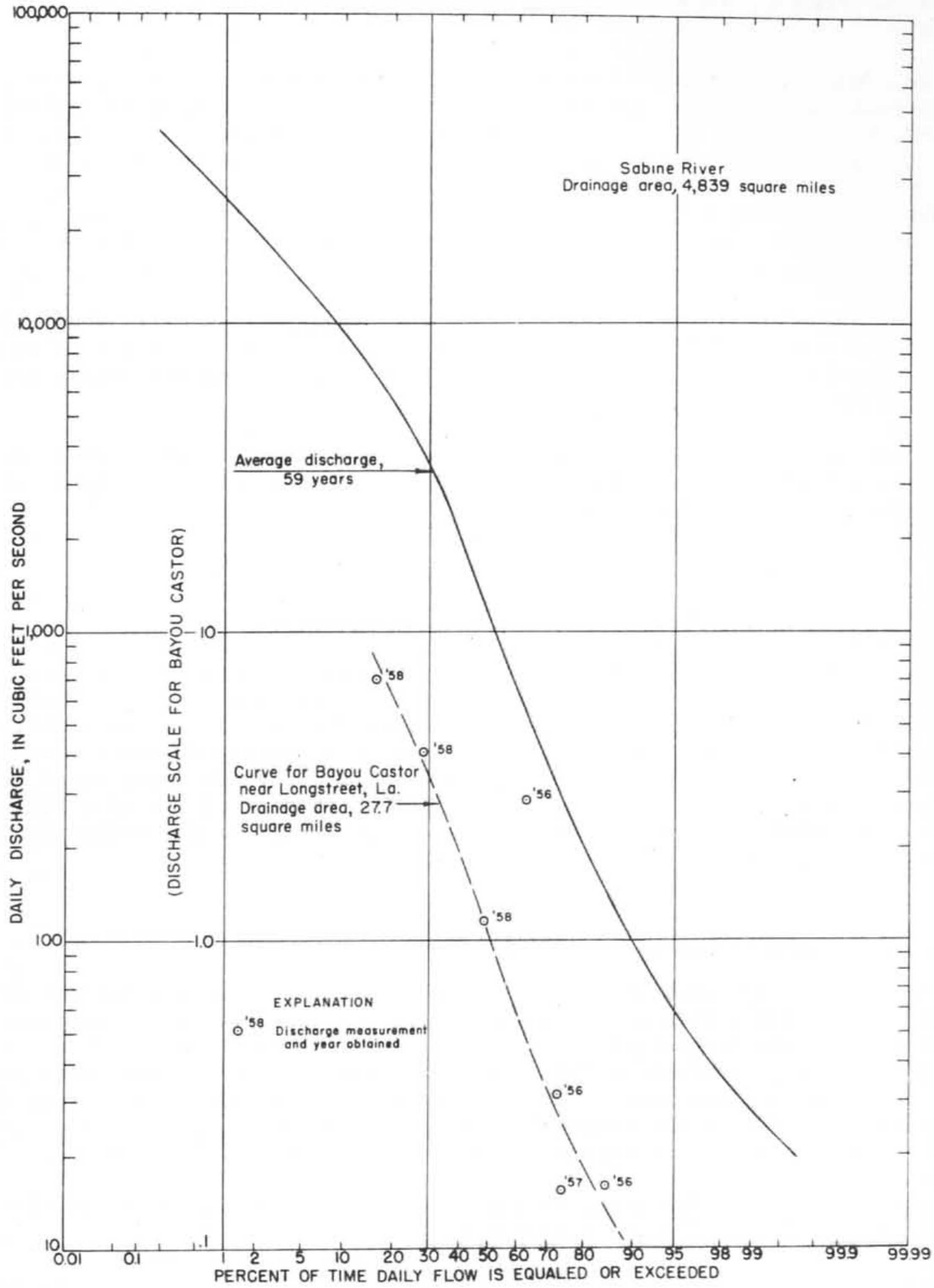

Figure 3

Duration of daily flow, Sabine River at Logansport, La., water years 1904-58. (Estimated curve for Bayou Castor near Longstreet, La.

average flow for a consecutive period is combined with a treatment of probability of recurrence. An example of a low-flow-frequency curve is shown on Figure 4.

In addition to quantitative low-flow data, chemical quality of base flow in the streams is obtained. Useful data on the chemical constituents present in the base flow must be assured from a systematic data-collection program for both the continuous-record and partial-record stations. At the present time in Texas there are 62 streamflow and 2 reservoir sites where surface water chemical quality data are collected by the Geological Survey on a continuous basis. During 1965 samples will also be obtained at approximately 150 other sites on a periodic or reconnaissance basis.

A dissolved-solids-duration curve can be prepared from daily chemical quality data in much the same manner as flow-duration curves. Figure 5 is an example of dissolved-solids-duration curves for two stations on the Neches and Trinity Rivers.

These data-collection programs have been most widely used by small municipalities, industrial users, and "run of the river" hydroelectric plants where appreciable storage is not feasible.

PROGRAMS AIDING THE WATER USER WITH STORAGE

Data-collection programs which aid the large water user during droughts are also necessarily large in scope and magnitude. In most of Texas, surface storage is generally a prerequisite to the use of large quantities of water. Programs for the collection of data that define the results or ramifications of storing and dispensing large quantities of water during droughts are being carried on by the Geological Survey in cooperation with the Texas Water Commission and others. Some of these programs involve studies of the base flow and delivery of water in long reaches of large streams, and of the sedimentation and chemical stratification in reservoirs.

Base-Flow and Water-Delivery Investigations

Data-collection programs involving extensive base-flow studies are carried out in river reaches with potential dam sites. The object of the studies is to define the changes in quantity and quality of base flow in the reach and identify the causes or sources of these changes. The studies are made when the base flow is near a constant rate. For best results, the studies should include both investigations made in the summer when evapotranspiration is high, and in the winter when this factor is insignificant. Investigations made both in the summer and winter should also afford results indicative of different contiguous ground-water levels. The drought condition of base flow is important both for design and operation of major reservoirs.

Actual data collection in the field for the base-flow study is customarily accomplished in the following manner:

1. A reach of river, generally between two stream-gaging stations, is selected for the study.

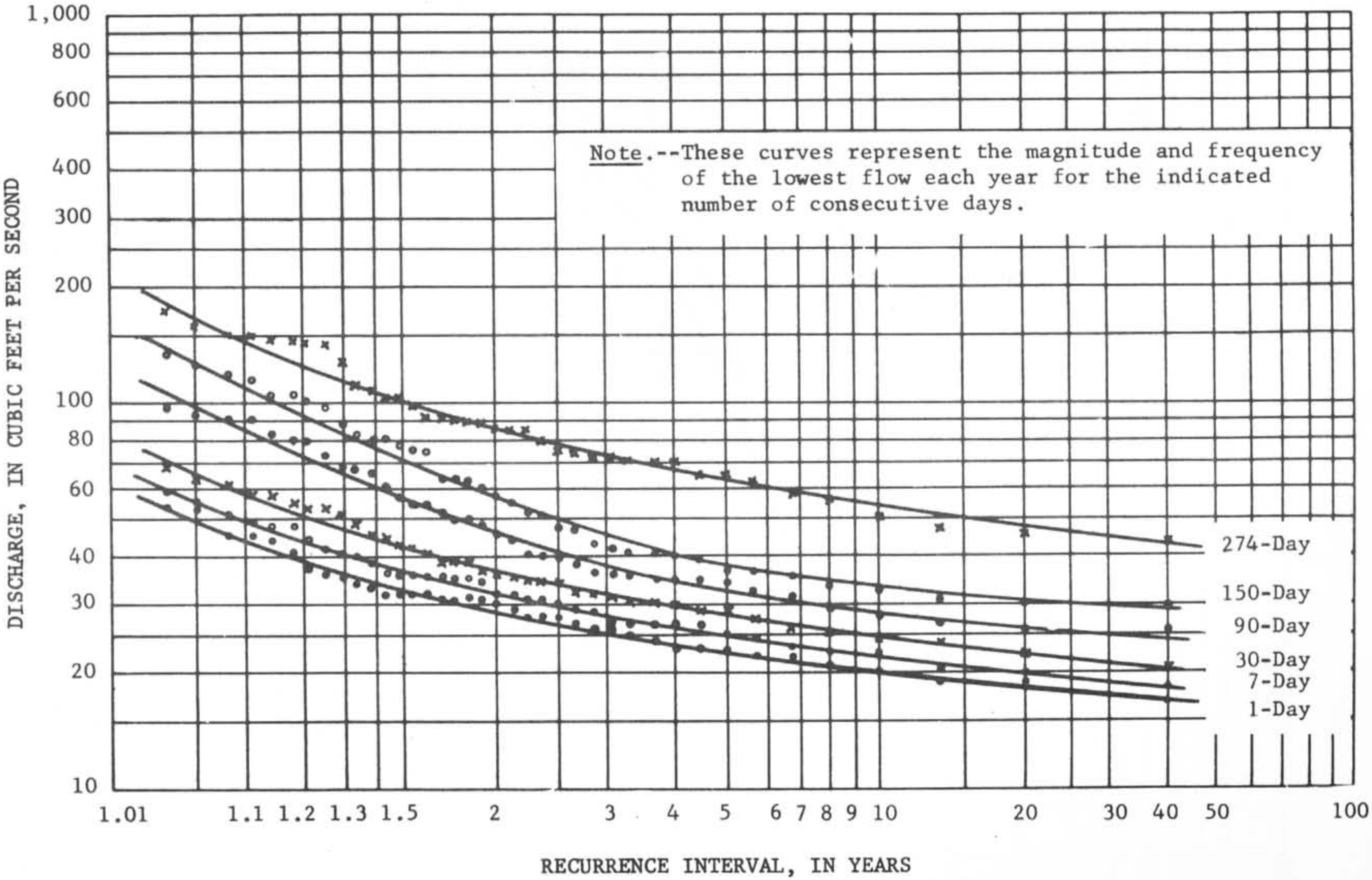

Figure 4

Example of low-flow frequency curves.

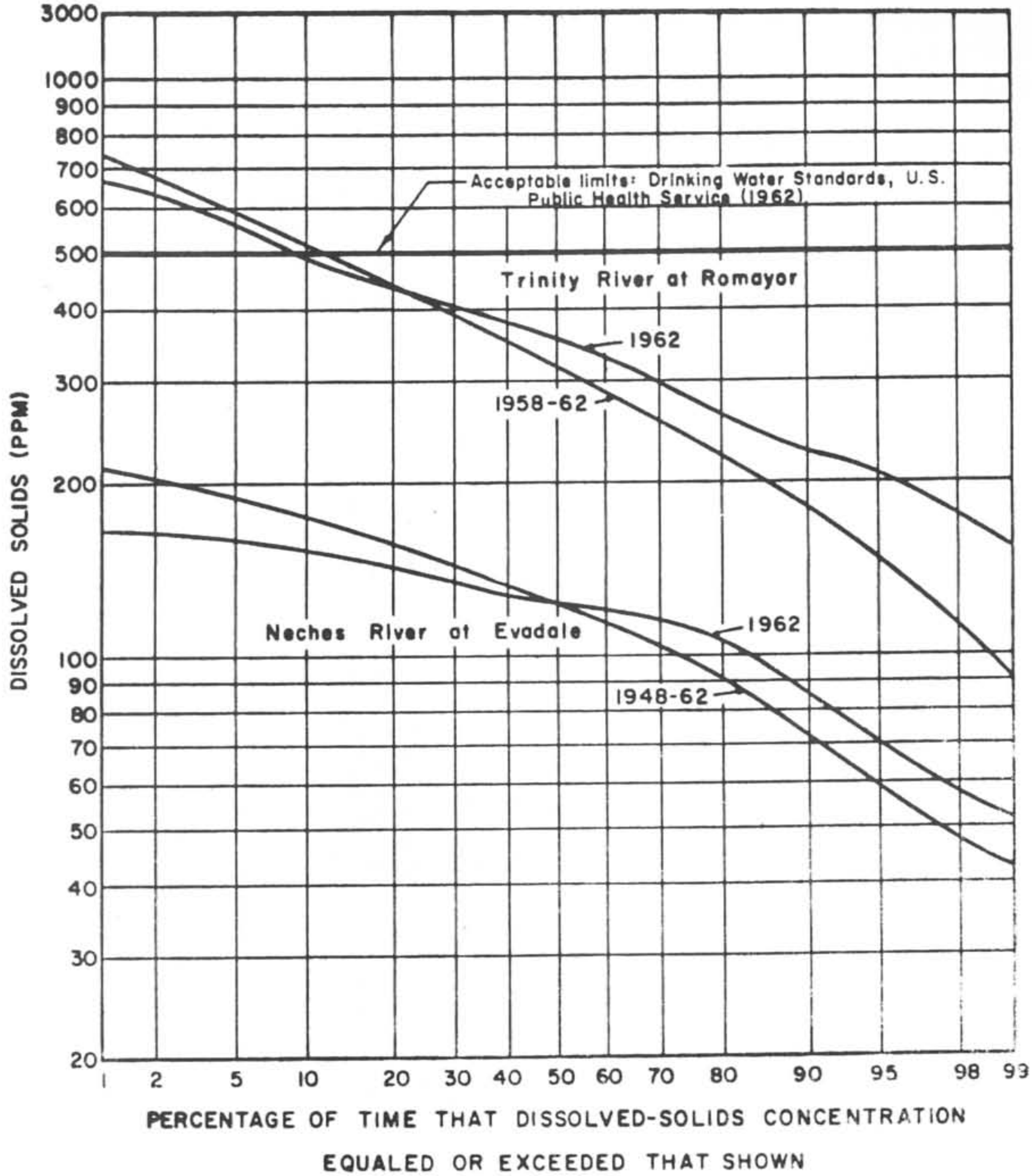

Figure 5

Duration of dissolved-solids concentration at two selected gaging stations.

2. Sites are selected along the reach for the measurement of discharge and collection of water samples for chemical analysis. Site selection is based on the known changes in geology, phreatophytic growth, tributary inflow, and diversions or return water in the reach of river involved. If suitable topographic and geologic maps are available, selection of sites may be made at the office and only minor changes will be expected in the field. In the absence of suitable maps, a field reconnaissance prior to the investigation is often necessary.

3. Actual field measurements of discharge are made at sections that have little or no underflow. If sufficient road crossings are available at the stream, accessibility to discharge-measurement sites presents no problem; however, if the river reach must be traversed by boat, then locating the sites is a slower process. Samples for quality of water analyses are collected at such intervals along the reaches that all evidence of pollution is defined. Conductivity meters are used to trace and isolate pollution. Copious notes are taken on geology and physiography to aid in isolating causes of the changes in quantity and quality.

4. All tributary inflow, return flow, and/or diversions are measured and sampled.

5. A continuous record of stage and discharge during the investigation is obtained at one or more points in the reach. These data are taken from existing stream-gaging stations if possible; if not, temporary recording gages are installed to provide the relevant data.

6. Changes in the ground-water level adjacent to the stream should be obtained for correlation with quantitative base-flow changes in the reach. The slope of the contiguous water table is extremely important for water-delivery studies.

The Geological Survey has made nine base-flow investigations on streams in Texas since 1962. More are anticipated in the future. Reports on these investigations have been prepared and published, or will be published in the near future, in the Texas Water Commission Bulletin series of reports.

Water-delivery investigations are made in those river reaches downstream from existing reservoirs or in long reaches of diversion canals or stream channels used as canals. These investigations are made in almost the identical manner as base-flow investigations and have almost identical objectives. Operation during droughts is of vital concern to both the reservoir owner and the downstream water user. The ideal time and rate of release are important for conservation of water. Water-delivery studies yield results which form the basis for efficient reservoir operation. Comprehensive investigations have been made on the Nueces and Pecos Rivers within the past two years. Reports on these investigations will also be published in the Texas Water Commission Bulletin series of reports.

Reservoir Sedimentation and Stratification Investigations

Sedimentation data on reservoirs with impoundment principally for domestic and industrial supplies are especially vital during droughts. Obviously, knowing that a reservoir contains 300,000 acre-feet of water and 50,000 acre-feet of sediment at the beginning of a drought--rather than thinking you have 350,000 acre-feet of water--is of primary importance. A sediment study of Lake

Dallas in 1952, at the beginning of a severe Texas drought, showed a 157,000 acre-foot capacity at spillway level instead of the 194,000 acre-feet of 1946. The Texas Water Commission now stipulates in each permit for reservoirs of about 15,000 acre-feet or more that the permittee accurately determine the sediment accumulation at 10-year intervals, or as advisable.

Studies of sedimentation in reservoirs should be augmented by periodic chemical analyses of the water, because the chemical character of the water affects the flocculating characteristics of the suspended sediment.

Periodic surveys of stored water in reservoirs should be made to determine any significant stratification of waters with respect to temperature and to dissolved oxygen, chloride, manganese and iron, and other constituents. Sustained low inflow to the reservoir, as well as other factors, can cause stratification. Data from the surveys provide information for setting up reservoir-operating procedures to offset the detrimental effects and take advantage of the favorable aspects of stratification. The Geological Survey has made surveys for the determination of chloride stratification at Possum Kingdom, Belton, Whitney, Proctor, and Hubbard Creek reservoirs in the past four years. The Hubbard Creek Reservoir surveys in particular, are used to compute the total chloride yield of the drainage basin.

Dissolved-oxygen surveys have been made at Possum Kingdom and Hubbard Creek reservoirs in the past two years. The depletion of dissolved oxygen in reservoirs during drought periods is expected to increase in future years as stream pollution increases. The Geological Survey believes that the collection of dissolved-oxygen data must expand considerably in Texas in the next few years to meet water-management needs.

SMALL WATERSHED YIELD DURING DROUGHTS

Since 1951 the Geological Survey, with financial assistance from the Texas Water Commission, city of Dallas, San Antonio River Authority, Tarrant County Water Control and Improvement District No. 1, and Soil Conservation Service, has made investigations of the effects of floodwater-retarding structures on the yield at downstream points. To determine these effects, data are presently being collected in 11 watersheds in the Trinity River, Brazos River, Colorado River, Guadalupe River, and San Antonio River basins.

Analyses of data collected at four of these watersheds show that during drought years the drainage upstream from the floodwater-retarding structures is essentially noncontributing. Although the data thus far do not define the effects any farther downstream than the structures, data-collection programs aimed toward this objective are presently underway. Data on the drought-year yield of these developed watersheds are necessary to downstream planning.

DATA COLLECTION AT MISCELLANEOUS SITES

The last data-collection program I would mention here today is perhaps the simplest, yet one of the most important in the Geological Survey. The program is one of measurement of flow, or usually observation of no flow, at hundreds of different stream sites during droughts. This program is added proof of the importance of a negative answer. The knowledge of those streams which had no flow during extremely dry periods is needed for water-use planning.

CONCLUSIONS

Emphasis should be given to the importance of continuing data-collection programs which are aimed principally at the drought phase of the climatic cycle. The timing of the investigation should be such that sufficient data are collected prior to the actual beginning of the drought to define all but the extreme drought event. This procedure will give the project planner enough data to insure reasonable extrapolation down to the drought event or condition.

A recent comprehensive publication in the field of hydrologic-data collection is "Criteria for Hydrologic Data Collection, Arkansas-White-Red Basins." Many competent hydrologists, working as a subcommittee of the Arkansas-White-Red Basins Inter-Agency Committee, devoted much time and effort to the preparation of this report. The report warrants the attention of all who are involved in hydrologic data-collection problems.

THE EFFECT OF DROUGHTS ON EVAPORATION RATES

THE EFFECT OF DROUGHTS ON EVAPORATION RATES[a]

By Gordon E. Koberg[1]

ABSTRACT

Meteorological parameters that affect evaporation from open water surfaces indicate that droughts will increase annual lake evaporation rates. Also, observations of annual pan evaporation indicate that droughts will increase annual lake evaporation rates. Generally, the potential increase in annual evaporation rates by droughts should be higher in the humid areas of the eastern United States than in the arid areas of the Western States. However, there are very few evaporation measurements of reservoirs by the energy-budget or mass-transfer methods for long periods to support the conclusions.

INTRODUCTION

During periods of droughts or periods of deficient precipitation, reservoirs are one source of water to supply the needs of the users. The supply of water in the reservoirs is limited and as the supply diminishes, most of the users become increasingly aware of the drought situation. Evaporation reduces stored water and has no concern about the diminishing supply during periods of drought. At the present time, methods to control evaporation losses are in the experimental stage and are not in widespread use. The purpose of this paper is to examine annual evaporation rates from lakes and reservoirs which are estimated by the energy-budget or mass-transfer methods and to determine whether periods of drought will change the independent functions or parameters in either of the two methods and thereby increase the rates over those that normally occur. An examination will also be made of observed evaporation from pans to determine the effects of droughts.

EVAPORATION THEORY

In the phenomenon of evaporation, water molecules move from below the surface into the surface layer of molecules that constitute the surface and out into the air just above the surface. The same molecules can return into the surface layer and below the surface if they are not lost by diffusion to the atmosphere. The number of molecules lost to the atmosphere in a given period of time is the evaporation rate.

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[a] As approved for publication by Director, U.S. Geological Survey.
[1] Hydraulic Engineer, U.S. Geological Survey, Denver, Colo.

Energy-Budget Method

The energy-budget method is an accounting of all energy for a reservoir over a period of time except that energy which is needed to move the water molecules from below the water surface to the air above and only for those molecules which are lost to the atmosphere. The energy needed to balance the accounting is the energy required to convert the molecules from the liquid to the vapor state. The amount of energy required to change the state of a given number of molecules has been determined by laboratory experiments and is known as the latent heat of evaporation. With the latent heat of evaporation known, the total rate of evaporation can be determined from the reservoir.

The basic energy budget for a reservoir may be expressed as follows:

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_e - Q_h - Q_w = Q_u$$

in which Q_s = solar radiation incident to the water surface;

Q_r = reflected solar radiation;

Q_a = incoming long-wave radiation from the atmosphere;

Q_{ar} = reflected long-wave radiation;

Q_{bs} = long-wave radiation emitted by the body of water;

Q_e = energy utilized by evaporation;

Q_h = energy conducted from the body of water as sensible heat;

Q_v = net advected energy into the body of water;

Q_w = energy advected by the evaporated water;

Q_u = increase in energy stored in the body of water.

If a drought is considered as an atmospheric phenomenon, then in the energy budget Q_s, Q_r, Q_a, and Q_{ar} are also atmospheric phenomena. The parameters Q_e, Q_h, Q_w, and Q_v are dependent both on atmospheric phenomena and energy balances in the reservoir whereas Q_{bs}, and Q_u are dependent only on balances of energy in the reservoir. Of the eight items affected by atmospheric phenomena, Q_s, Q_a, Q_h, and Q_e are considered to be the most significant. The parameter Q_e is the energy utilized by evaporation and any changes in it will be dependent on changes in Q_s, Q_a, and Q_h.

In Figure 1, a graph of average annual measured solar radiation and computed long-wave or atmospheric radiation for Fort Worth, Texas is shown for the period 1950 to 1963. The atmospheric radiation was computed using the method described by Koberg[2]. If the mean annual solar radiation is determined for this period, the graph indicates that the first 7 years of the period was above

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[2] Koberg, G. E., Methods to compute long-wave radiation from the atmosphere and reflected solar radiation from a water surface, U.S. Geological Survey Prof. Paper 272-F, 1964, pp. 107-136, 4 figs.

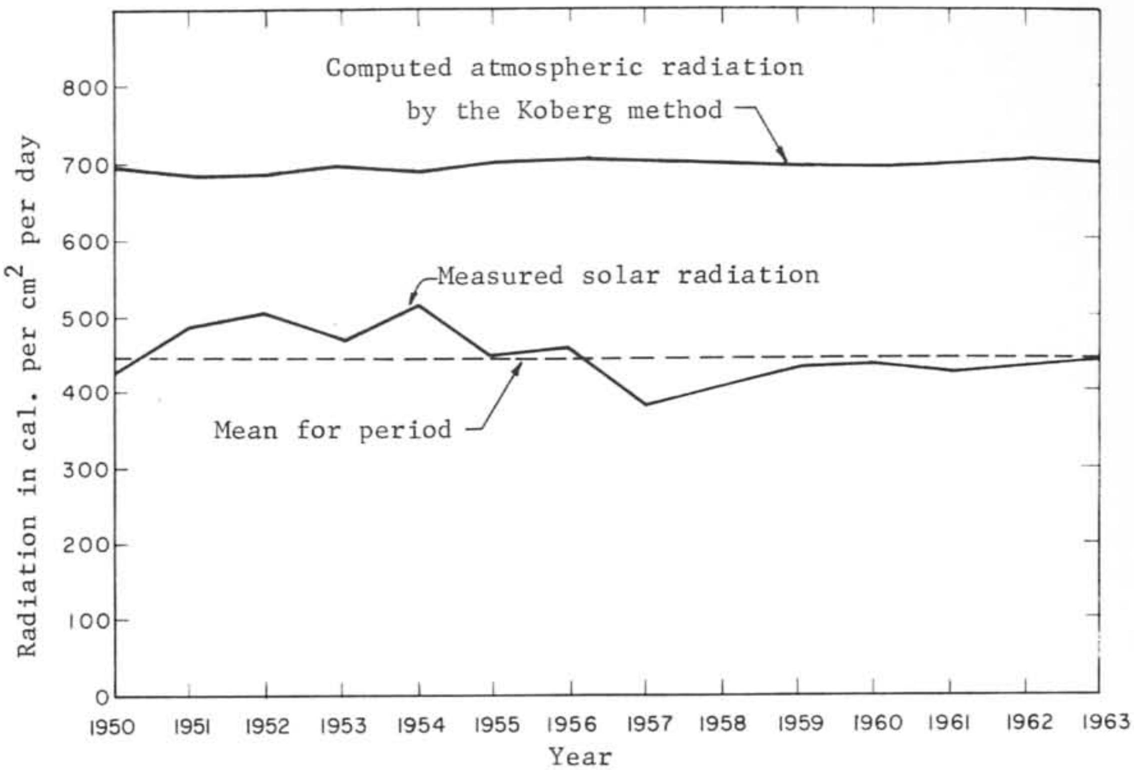

Figure 1

Average Annual Solar and Atmospheric Radiation at
Fort Worth, Texas, for the Period 1950 to 1963
(Data from U.S. Weather Bureau)

the mean whereas the last 7 years was below. During part or all of the first 7 years of the period, it is known that most of Texas was in a period of drought. As data are not shown prior to 1950, the first 7 years of the 14-year period will be considered a drought for this analysis.

Figure 1 shows that during a drought period solar radiation is as much as 13 percent greater than the mean whereas the computed atmospheric radiation remains almost constant throughout the 14-year period. The increased solar radiation provides additional energy for increasing annual evaporation. It is not known at this time if all of the increase in solar radiation is utilized in evaporation. If records of temperature of a water surface were available for a reservoir near Fort Worth during this period, better estimates could be made of the increase in the evaporation caused by the increase in solar radiation.

Q_h or the heat conducted to the air is dependent on wind velocity and the difference in temperature between the water surface and air. Figure 2 shows a graph of the average annual air temperature and wind velocity at Fort Worth, Texas for the period 1950 to 1963. During the drought period, annual temperatures were as much as 2°F higher than the mean for the period. The graph of the effect of wind during the period of drought is not as well defined as the air temperature or solar radiation graphs but it seems to indicate winds are higher during drought periods. However, a definite conclusion should be based on a longer record of wind. The increase in air temperature and wind velocity during the drought period will increase the evaporation rate. The amount of increase in the evaporation rate will depend on the temperature of the water surface, for which no records are available.

Mass Transfer

The mass-transfer method of estimating evaporation determines the rate of diffusion of water molecules above the water surface into the atmosphere. The rate of diffusion is generally proportioned to the wind velocity and the difference between the air at the water surface and the ambient air. Reliable mass-transfer methods to estimate evaporation rates have been established by laboratory experiments and field studies such as the Lake Hefner study.[3] The mass-transfer method can be expressed in its simplest form as

$$E = N u^b (e_o - e_a)$$

where E = evaporation in inches per day;

N = a coefficient;

u = wind velocity in miles per hour;

b = a coefficient;

e_o = saturation vapor pressure corresponding to temperatures of the water surface in millibars;

e_a = vapor pressure of the air in millibars.

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[3] U.S. Geological Survey, Water-loss investigations--Lake Hefner studies, technical report: U.S. Geological Survey Prof. Paper 269, 1954, 158 p., 101 figs.

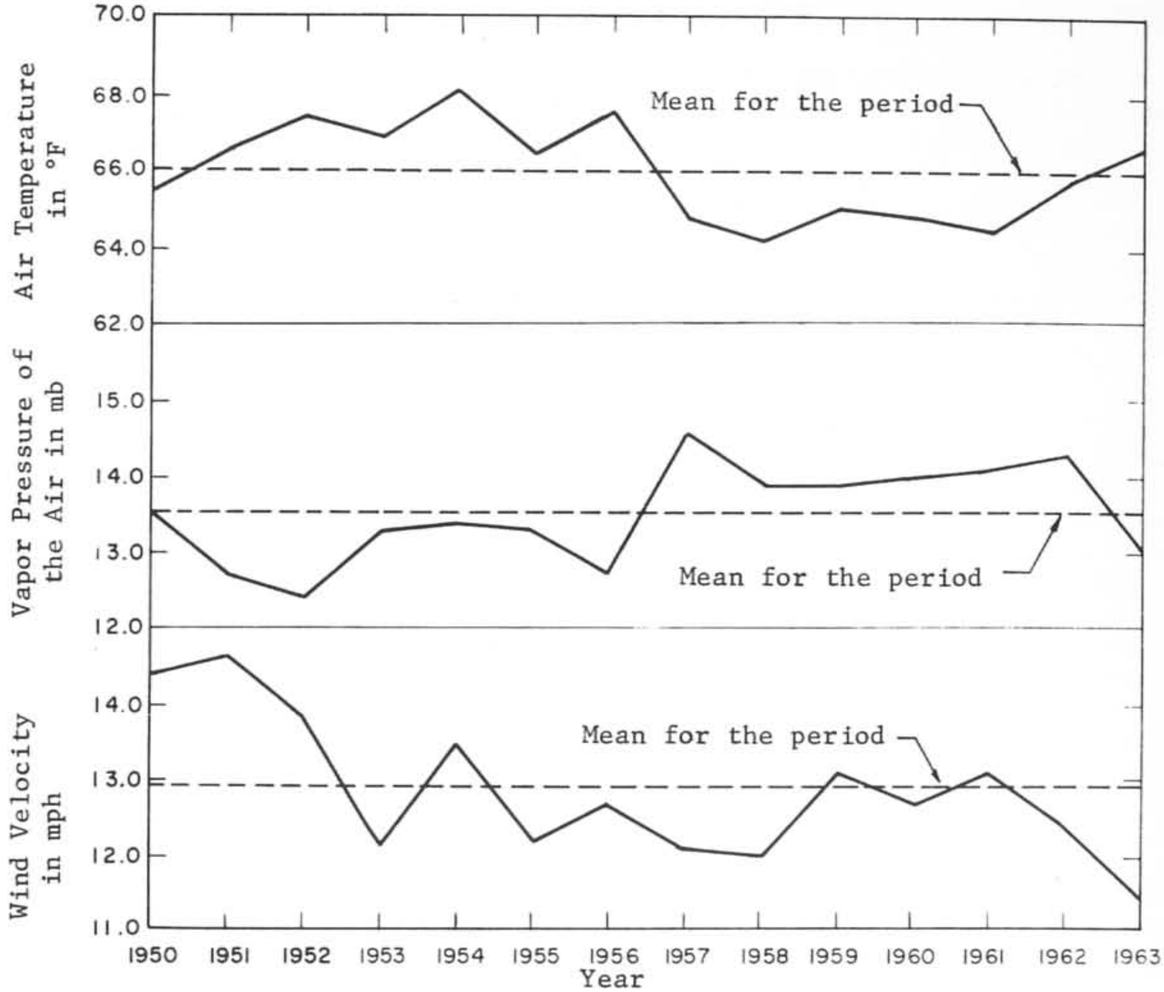

Figure 2

Average Annual Air Temperature, Vapor Pressure, and Wind Velocity of the Air at Fort Worth, Texas, for the Period 1950 to 1963
(Data from U.S. Weather Bureau)

In the mass-transfer equation, wind velocity and vapor pressure of the air are atmospheric phenomena. The saturation vapor pressure of the air at the water surface is dependent on the temperature of the water surface and, in turn, is dependent on the balances of energy in the reservoir.

Figure 2 shows a graph of the vapor pressure at Fort Worth, Texas for the period 1950 to 1963. During the period of drought, the vapor pressure of the air is below the mean for the period of record. From the previous discussion of the wind velocity in the energy analysis, it was concluded that wind velocities were slightly higher during periods of drought. The decrease in vapor pressure of the air and the increase in wind velocity during a drought will increase the annual lake evaporation rate. The amount of increase will be dependent on the temperature of the water surface of which no records are available.

PAN EVAPORATION

The preceding analysis of the energy-budget and mass-transfer methods of estimating evaporation has shown that evaporation rates will be increased during periods of drought. Further confirmation of the previous analyses can be made by examining the evaporation from a class A pan for the period 1950 to 1963. For this period a graph of annual pan evaporation at Denison Dam, Texas is shown in Figure 3. During the period of drought, pan evaporation was higher than the mean for the period of record and confirms our previous conclusions. The amount of increase in the rate of annual pan evaporation is not necessarily the same for a reservoir mainly because the temperature of the water surface for a reservoir is dependent on the functions of energy storage and advected energy which has no similarity to a pan.

In Figure 3 the annual precipitation as observed at Fort Worth, Texas is also given. It shows annual precipitation during the period of drought was below the mean for the period of record. However, the effect of drought on pan evaporation and the corresponding deficiency in precipitation are not considered to be quantitatively related.

ANNUAL EVAPORATION RATES

For other parts of Texas, the effect of drought on annual evaporation rates may not be the same as for Fort Worth, Texas. Before this analysis is made, an examination of the range in annual lake evaporation for a particular latitude and the reason for the different rates will be helpful. In Figure 4, a graph of the annual lake evaporation for the latitude of 35 degrees is shown for the continental United States. Data for this graph were taken from the evaporation map for the United States which was prepared by Kohler and others.[4] If the land surface was of constant altitude and atmosphere was of equal moisture composition for this latitude, the evaporation would be nearly constant. However, Figure 4 shows that the annual lake evaporation rate ranges from 35 to 82 inches. The main reason for the large range in annual rates is the variation in moisture of the atmosphere.

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[4] Kohler, M. A., Nordenson, T. J., and Baker, D. R., Evaporation maps for the United States, U.S. Weather Bureau Technical Paper No. 37, 1959, 13 p., 6 figs., 2 pls.

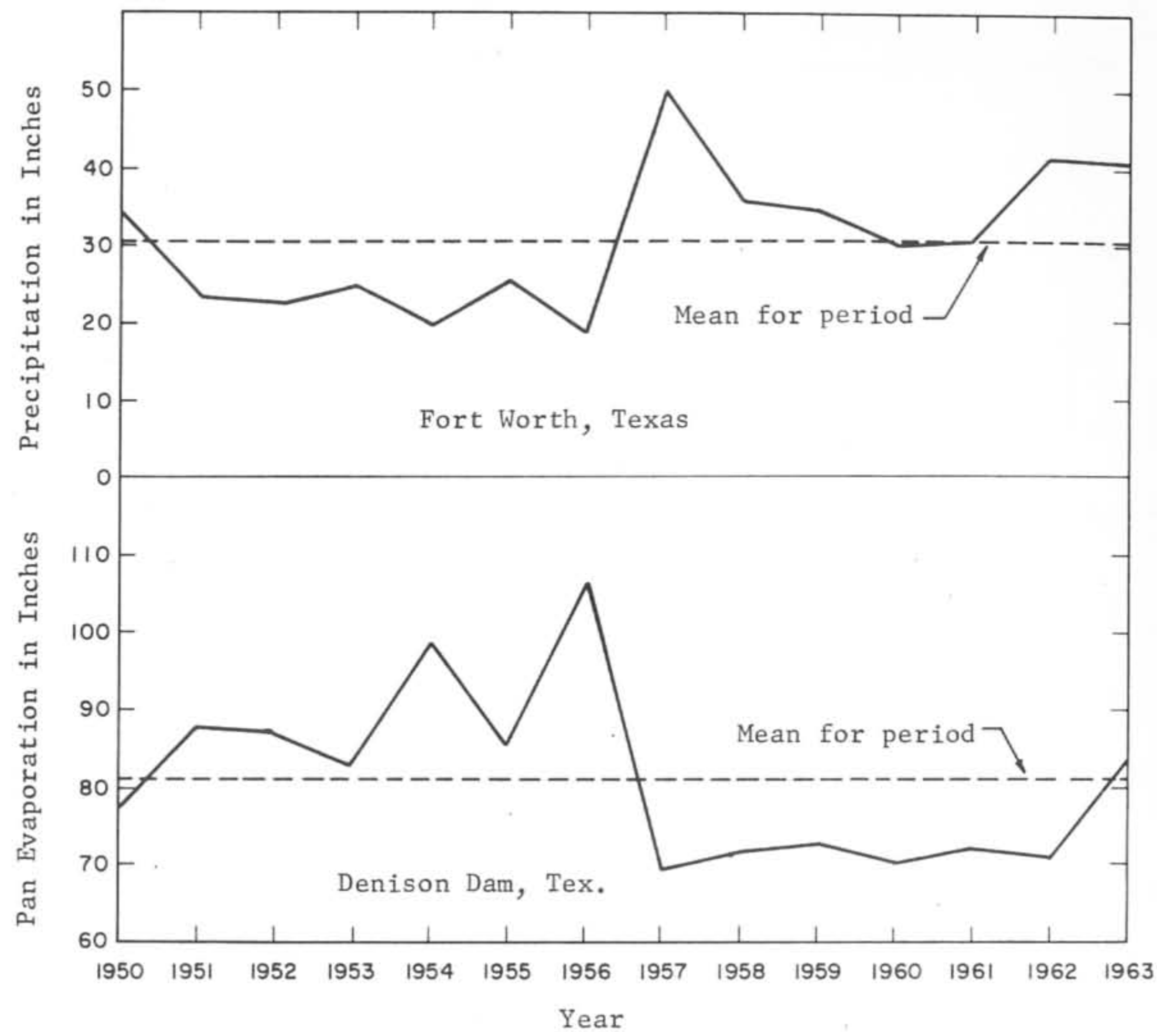

Figure 3

Annual Precipitation as Observed at Fort Worth, Texas, and Annual Pan Evaporation as Observed at Denison Dam, Texas for the Period 1950 to 1963 (Data from U.S. Weather Bureau)

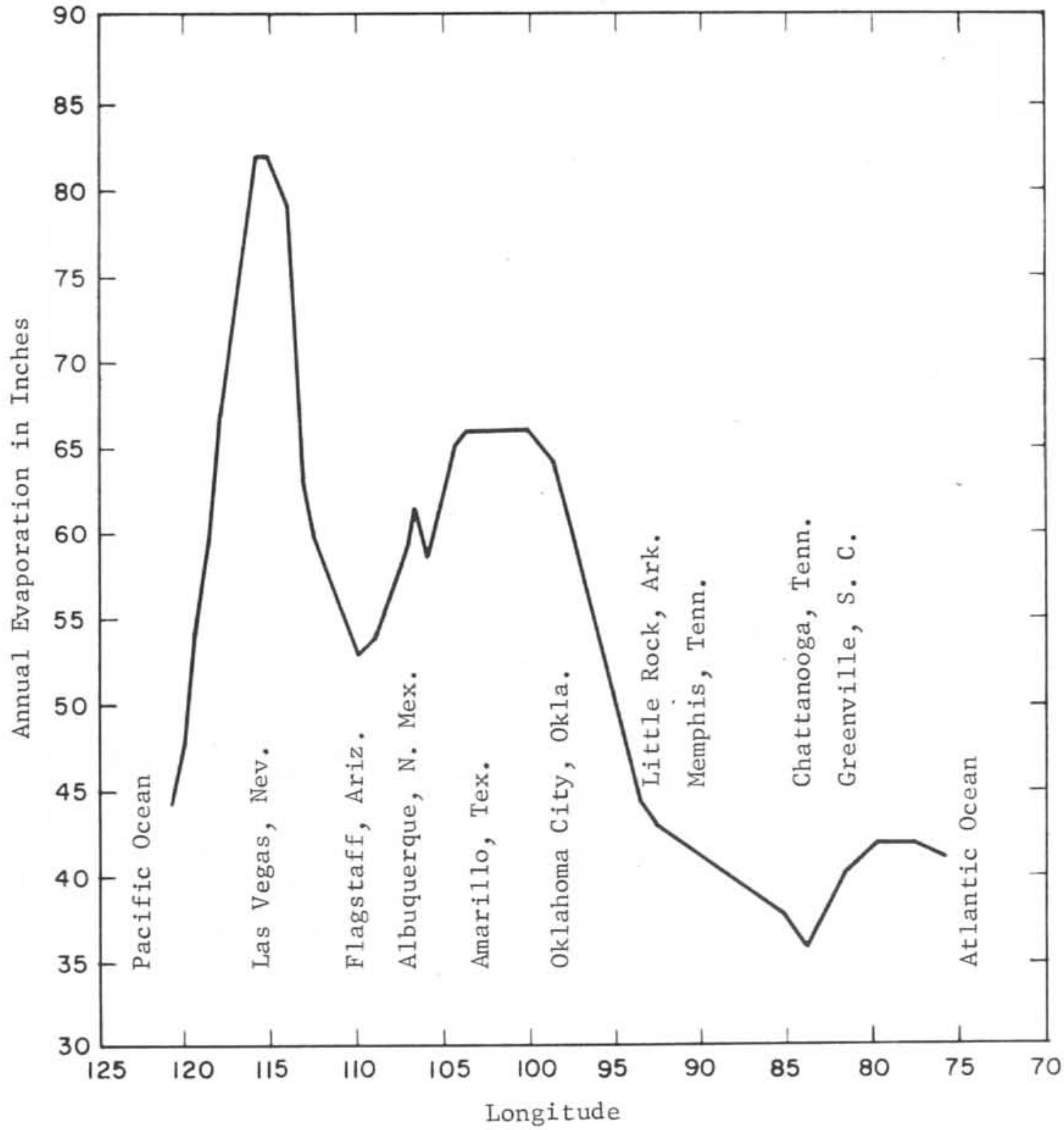

Figure 4

Annual Lake Evaporation across United States at Latitude of 35°. Data Taken from Weather Bureau Research Paper No. 37.

Further analysis of the graph in Figure 4 shows that maximum annual lake evaporation rates for the latitude of 35 degrees occur in the area near Las Vegas, Nevada. In this area the solar radiation is 86 percent of the possible clear sky radiation and the average annual vapor pressure of the ambient air is only 6 millibars above the absolute minimum of 0. A change in the vapor pressure of the ambient air from 6 to 0 millibars and a corresponding change in the solar radiation from 86 to 100 percent will increase the annual rate approximately 50 percent. An increase of this magnitude will result in an annual evaporation rate of approximately 125 inches which should be approximately the maximum for this latitude.

The minimum annual lake evaporation rate for the latitude of 35 degrees occurs in the area east of Chattanooga, Tennessee as shown in Figure 4. In this area the solar radiation is 64 percent of the possible clear sky radiation and the average annual vapor pressure of the ambient air is 12 millibars. If the vapor pressure of the air is reduced to 0 and the solar radiation increased to 100 percent, the annual evaporation rate would equal the maximum rate for the latitude of 35 degrees or an increase of approximately 300 percent.

CONCLUSIONS

For the latitude of 35 degrees, Figure 4 shows that annual lake evaporation rates generally decrease in an easterly direction from the maximum rate at Las Vegas, Nevada to the minimum rate near Chattanooga, Tennessee. A general statement for the effect of droughts would be that annual evaporation rates will be increased by droughts and the eastern part of the United States will have a higher potential increase in rates than the western part.

Annual lake evaporation rates, according to the evaporation map, range from 50 inches at the eastern border of Texas to 80 inches at the southwestern border of Texas. The effect of droughts in Texas would be to increase annual evaporation rates with the largest potential increase in the eastern part of the State.

Additional verification of the conclusions reached in the previous analyses could be made if estimates of annual lake evaporation by either the energy-budget or the mass-transfer methods were available of reservoirs in Texas for the period 1950 to 1963. The only known estimate of annual lake evaporation by one of these methods on a continuing basis for the State of Texas is for a small stock tank near Laredo, Texas. The annual evaporation rate is shown in Figure 5 for the period 1960 to 1964. In addition, Figure 5 shows the annual evaporation rate for Lake Mead for the period 1953 to 1963. The graph of annual evaporation for Lake Mead shows a range of 80 to 89 inches whereas the graph of the stock tank shows a range of 49 to 76 inches.

The small range in annual evaporation rates for Lake Mead shows that annual evaporation rates are nearly constant in the arid areas and therefore the effect of droughts in this area may not be as critical as in the humid areas. The range in annual evaporation for the stock tank is 3 times that of Lake Mead and the period shown in Figure 5 is not considered a drought period. The effect of droughts will increase the annual evaporation rate for the stock tank but in this area which borders on the high humid area of the Gulf and the dry area of the West, it may be difficult to define periods of drought.

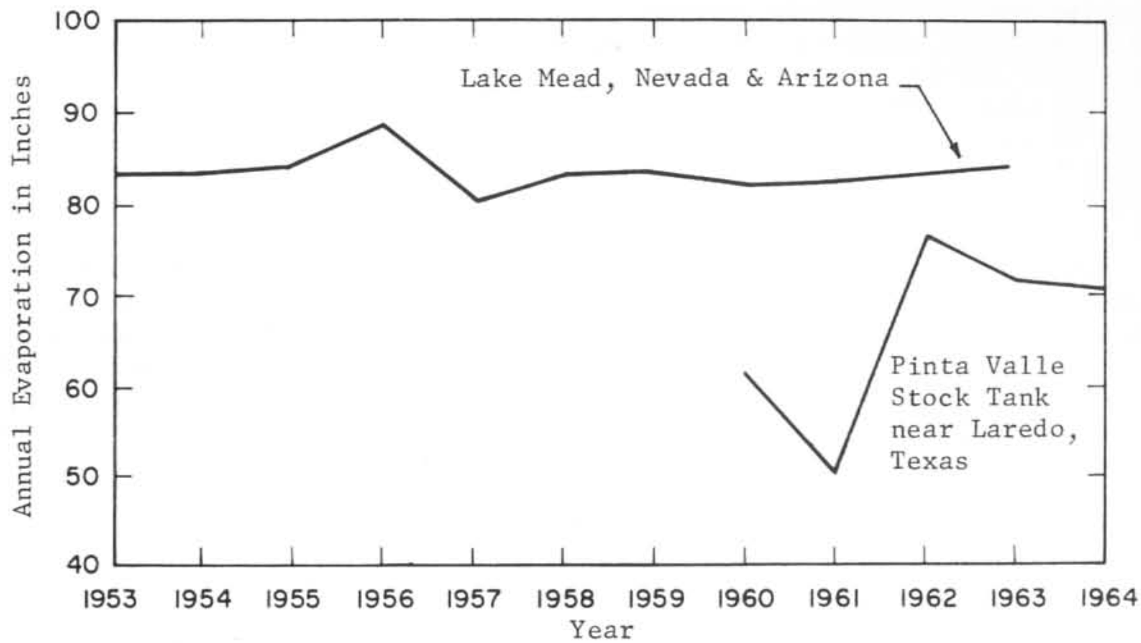

Figure 5

Annual Evaporation from Lake Mead for the Period 1953 to 1963 and Annual Evaporation from a Stock Tank near Laredo, Texas, for the Period 1960 to 1964

THE EFFECT OF DROUGHTS ON EVAPORATION RATES[a]

Discussion by Louis L. McDaniels

LOUIS L. McDANIELS.[1]--Mr. Koberg has ably discussed the evaporation phenomenon, its theory, and the energy-budget and mass-transfer methods of estimating rates of natural evaporation from open water. He has adequately explained and shown that evaporation rates will be increased during droughts.

His analysis of the difference in evaporation rates in relation to the difference in magnitude of some of the influencing climatic factors in evidence along the latitude of 35 degrees at Chattanooga, Tennessee and Las Vegas, Nevada is intriguing. This analysis is particularly substantive that evaporation rates increase during droughts when climatic conditions at Las Vegas are considered as drought in relation to climatic conditions at Chattanooga.

The writer will discuss and illustrate other facets of drought closely associated with potential evaporation which can collectively produce more severe effect on water supplies stored in surface reservoirs than is caused by increased evaporation rates per se.

The net effect of an increase in the rate of natural evaporation from open water surfaces during drought in any particular part of Texas on an annual basis is directly associated with and dependent on the amount of rainfall.

Mr. Koberg described the range in annual lake evaporation rates from the eastern to the southwestern borders of Texas in accordance with the U.S. Weather Bureau evaporation map for the continental United States. He pointed to the lack of lake evaporation data on a continuing basis as estimated by the energy-budget or the mass-transfer methods.

In search of methods which might be better than or as good as other methods in use, be more flexible in application, have a climatic potential for extrapolation backward in time, and have desirable economic features that could be used reliably for estimating evaporation and evapotranspiration losses as used in water resources planning and development studies, the Texas Water Commission used the U.S. Weather Bureau procedures described in Research Paper 38[2] and Technical Paper 37[3] for computing estimates of lake evaporation from standard

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[a] By Gordon E. Koberg.

[1] Coordinator, Planning Division Research Program, Texas Water Commission, Austin, Texas.

[2] Kohler, M. A., Nordenson, T. J., and Fox, W. E., Evaporation from Pans and Lakes, Research Paper 38, U.S. Weather Bureau, Washington, D. C., 1955.

[3] Kohler, M. A., Nordenson, T. J., and Baker, D. R., Evaporation Maps for the United States, Technical Paper 37, U.S. Weather Bureau, Washington, D. C., 1959.

climatological data. The numbers computed are called climatic-index numbers by the Commission instead of lake evaporation rates or depths because of suspected low values resulting for the state west of about longitude of 99 degrees, and because of the desire to establish adjustments for lag involved with differences in energy storage in surface reservoirs as may be related to size, depth-area relationship, surface configuration, and geographic location and orientation. Monthly climatic-indexes were computed and tabulated on a statewide basis for the 61-year period 1903-1963 and stored in IBM cards by quadrangles of 1-degree latitude and 1-degree longitude. In addition to use as evaporation indexes, these climatic-indexes are used for estimating consumptive use of water by agricultural crops and consumptive waste of water by nonbeneficial vegetation in past years by the Commission method[4] for use in planning studies.

The climatic-indexes are consistent relationships derived from air temperature, dew point temperature, wind movement, and solar radiation data. Charts for selected years and the longtime average annual climatic-indexes are used herein to illustrate the potential effect of increased evaporation rates during drought and the net effect as associated with rainfall on water supplies contained in conservation storage reservoirs in Texas.

Figure 1 contains statewide charts showing climatic-index isograms of the 61-year average annual depths during the period 1903-1963, and the total depths for each of the years 1941, 1956, and 1957. The years 1941 and 1957 were wet, and the year 1956 was dry in Texas. It is assumed for convenience of illustration that these climatic-indexes are potential evaporation depths and therefore represent the relative differences in gross lake evaporation rates or depths across the State during these periods.

The differences between potential gross lake evaporation depths during some wet years and dry years at any selected point in Texas as indicated by the isograms on the charts in Figure 1 are not large enough to be alarming. At selected points in quadrangles marked A, B, C, and D, represented by the cities of Beaumont, Fort Worth, San Angelo, and Amarillo, respectively, comparable data are as follows:

Quadrangle	Gross Lake Evaporation Depths, In Inches			
(Point)	1903-1963	1941	1956	1957
A (Beaumont)	51	49	54	49
B (Fort Worth)	57	50	64	48
C (San Angelo)	61	61	67	54
D (Amarillo)	58	45	72	56

The direct net effect of drought on the contents of conservation storage reservoirs as related to evaporation is indicated by the annual net lake evaporation depths--potential gross lake evaporation depths minus rainfall. Figure 2 contains charts showing isograms of differences in annual net evaporation across Texas for two wet years, 1941 and 1957, compared with a dry year, 1956.

[4] McDaniels, L. L., Consumptive Use of Water by Major Crops in Texas, Bulletin 6019, Texas Board of Water Engineers, Austin, Texas, 1960.

These differences in amounts are for 1956 minus 1941, and for 1956 minus 1957. For comparison at the same points in quadrangles marked A, B, C, and D, these differences are as follows:

Quadrangle (Point)	Net Lake Evaporation Depths, In Inches		
	1956	1956 minus 1941	1956 minus 1957
A (Beaumont)	15	38	28
B (Fort Worth)	43	42	60
C (San Angelo)	58	33	28
D (Amarillo)	62	55	29

These net lake evaporation depths and the differences represent some of the extremes in the balance between annual gross lake evaporation and rainfall depths.

The difference in potential gross lake evaporation at Fort Worth in 1956 and 1957 is shown as 16 inches, and the difference in net lake evaporation for the same years is shown as 60 inches. This may appear improbable, but the amount results from rainfall in 1956 being 45 inches less than the gross lake evaporation depth, and rainfall in 1957 being 15 inches more than the gross lake evaporation depth. Similar conditions occurred in the Beaumont area in 1941 and 1956.

The balance between potential gross lake evaporation and rainfall generally appears significant when analyses of annual data are made for drought years. However, increases in evaporation rates may be more serious than indicated during hot and dry summer months when inflows to reservoirs are inadequate for needs and the demands for water are highest.

Loss of water from reservoirs in many areas of Texas by evaporation are significant portions of the water stored. The present methods of estimating evaporation losses provide a range of answers, none with any degree of exactness. This need for a more accurate method of estimating evaporation losses from conservation storage reservoirs calls for continuing investigation to determine losses more accurately, development of the most efficient reservoir sites for water supply conservation, continuing improvement of water management and use, and pursuit of measure to salvage losses from reservoirs and distribution systems.

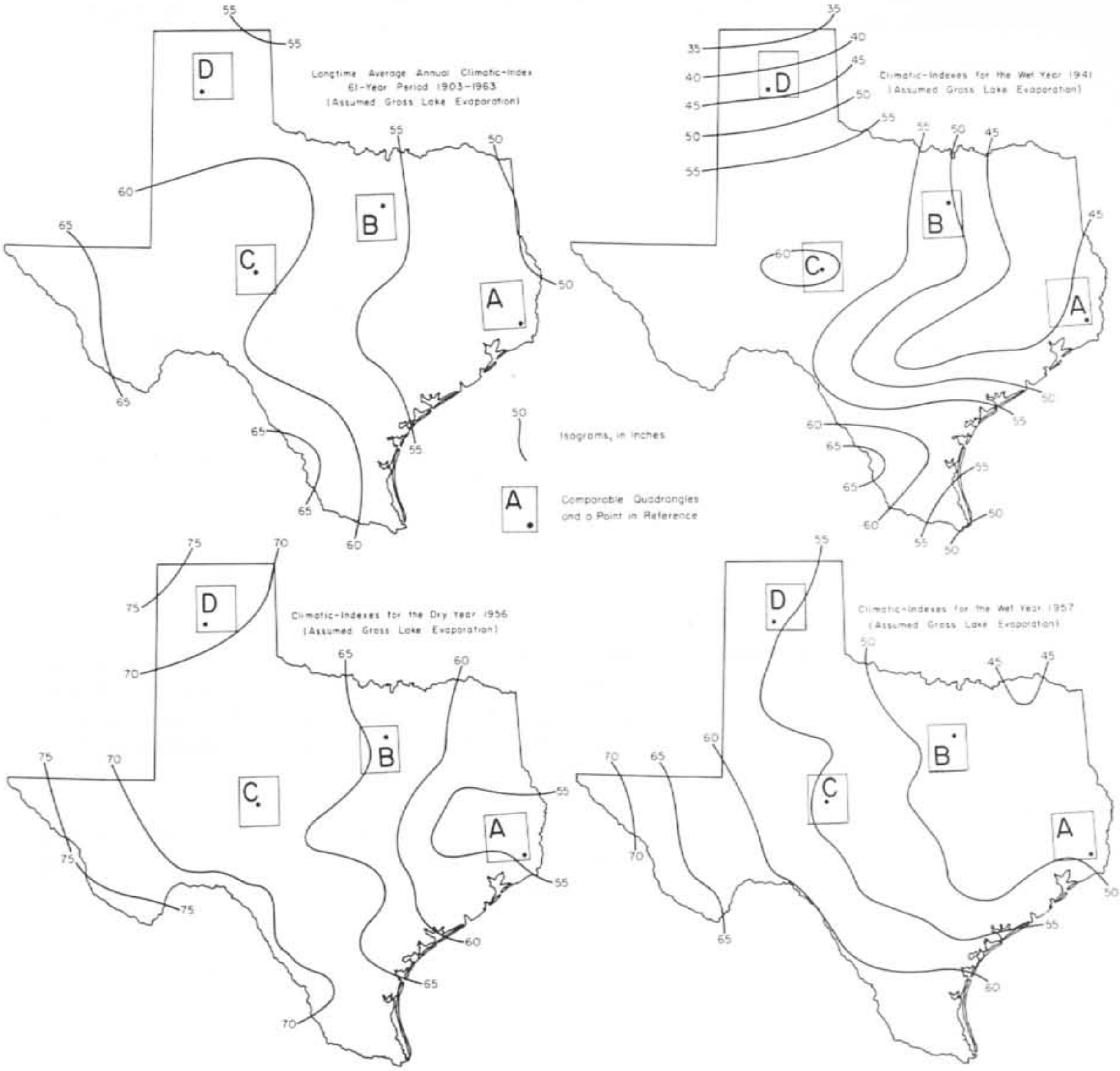

Figure 1
Assumed Potential Gross Lake Evaporation

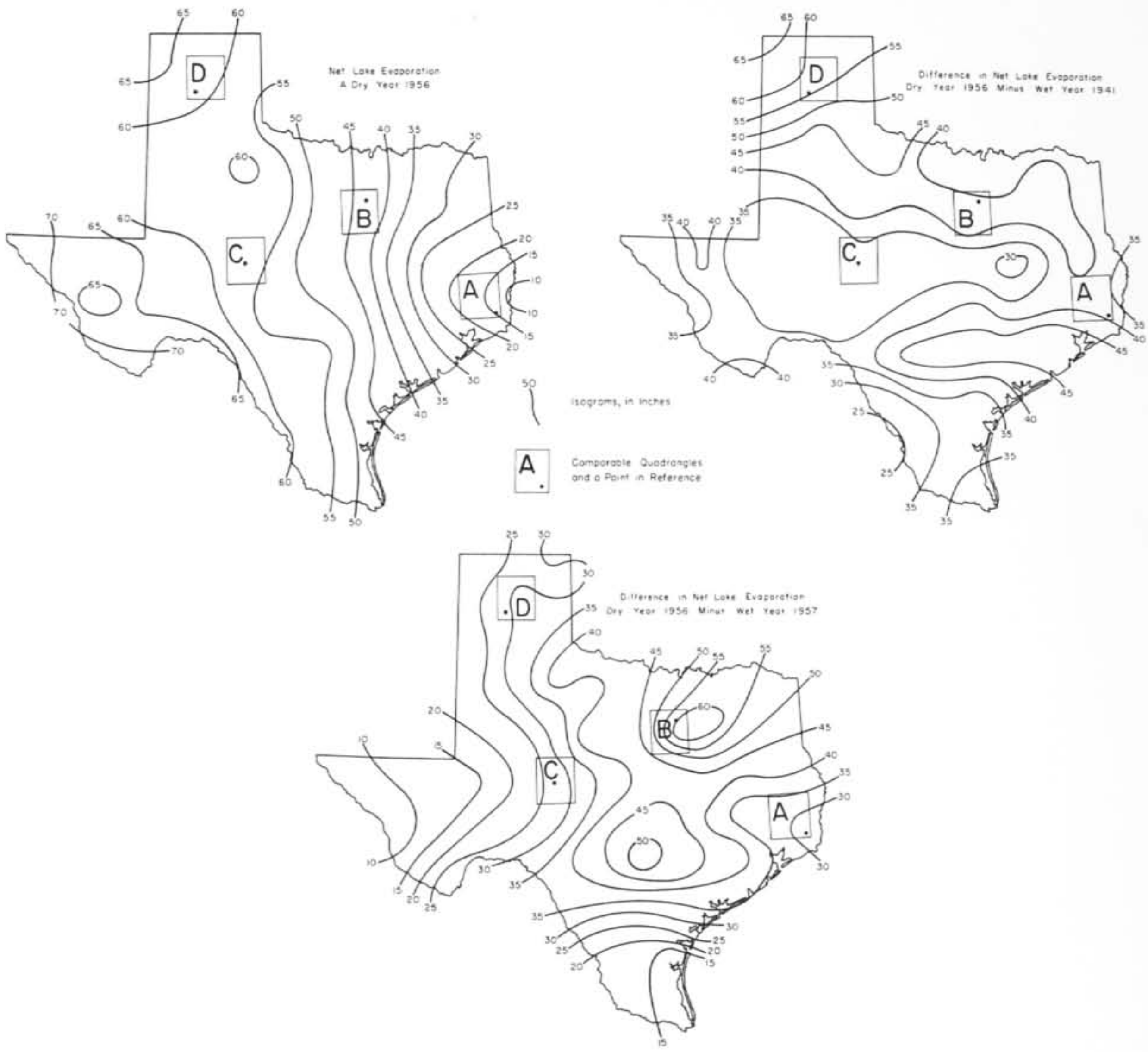

Figure 2

Differences in Net Lake Evaporation During Wet and Dry Years in Texas

TOLERABLE WATER SHORTAGES DURING DROUGHTS FOR VARIOUS USES

TOLERABLE WATER SHORTAGES DURING DROUGHTS FOR VARIOUS USES

By B. J. Claborn,[1] AM. ASCE

ABSTRACT

Tolerable water shortage is interpreted in economic terms. A method is suggested for determining the incremented value of water to the residential user.

INTRODUCTION

People will accept--and tolerate--water supplies less than optimum. Just how much less than optimum is the subject of this paper. In other words, a usable definition for the minimum amount of water made available to, and tolerated by, the citizenry is sought. How shall one judge when the citizenry no longer tolerates the current supply? Is there a single amount, common to all uses, below which the water supply will not be tolerated? Or, is the minimum tolerable supply different for each use? These are not idle questions; answers will shape the selection of a minimum acceptable water supply.

A water supply for a particular use is assumed to be acceptable (tolerated) until the user performs some overt act to change the status quo. This "overt" act may take the form of entering an agreement with the supplier for a larger quantity; of moving to a locale where more water is available; or in the case of an industrial plant, of installing reuse facilities. Talking is excluded from consideration as an "overt" act; if the supply is really inadequate by the user's standards he will initiate action.

A system has reached an intolerable water shortage whenever any of the water users performs some overt action to increase his water supply. However, other users may find the supply adequate. Apparently there is no specific water shortage which can be tolerated by all persons and businesses concerned. "Tolerable water shortage" must be considered to be a relative economic concept. With more than one user in any particular system, it will represent some pre-assigned but arbitrarily chosen amount of "overt" action on the part of the system as a whole. When the cost of additional water exceeds the value of the water supplied, the existing supply will be termed a "tolerable water shortage."

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[1] Asst. Professor, Dept. of Civil Engineering, Texas Technological College, Lubbock, Texas.

This paper suggests methods to ascertain the economic losses sustained at different levels of supply less than optimum. These losses will depend on the use of the water. The uses considered here are (1) power generation, (2) irrigation, (3) municipal supplies, (4) sewage effluent dilution. Several things are common to all of these, and some basic ideas will be set forth before undertaking the study of the individual uses.

The economic aspects of a commodity may be described in terms of its marginal use and marginal value. Marginal value is the value of the last unit produced; marginal use is the use to which the last unit purchased is applied. Figure 1 shows a graph of unit price (marginal value) versus demand (marginal use) for an individual. The demand increases as the unit price or marginal value of the commodity (in this case, water) decreases. At very low unit cost, extremely large quantities of the commodity may be used. It is probable the individual consumer will apply the first increment of water purchased (the unit with the highest marginal value) to purposes of sustenance of the human body. Variations will exist in use of the next increment. Some will use it for bathing, others for home sanitation, perhaps some for maintenance of lawn, flowers, etc. But the point is, not all uses have equal marginal value to the individual. This is true whether use is considered from the individual point of view as in Figure 1, or considered from the point of view of irrigation as Figure 2 illustrates. The curves in the two figures are, of course, the same general shape. The unit price of water versus the demand for the water by some individual farmer is plotted.

POWER

The subject of firm water supply, low water flow, storage consideration, and all of the aspects of water supply in relation to power and power generation have been studied extensively by electric utility companies. A repetition of those studies is not appropriate in this paper. However, all of the principles which are developed here in regard to other uses are also applicable to the use of water in the generation of power. No further consideration will be given to this particular use.

IRRIGATION

The use of water for irrigation ranges all the way from total crop water supply by irrigation in some portions of the extremely arid west (the Central Valley of California, for example) to occasional brief applications of supplementary water in some of the southeastern states. In the planning stage, each of these projects face the same decision; how much water should be provided? The question may take the form of how large a reservoir to build, or how many wells to drill.

In the planning stage of an irrigation project embracing a storage reservoir, there exists the possibility of providing a quite wide range of firm water supplies to the user, even though the irrigation interests are entitled to a limited portion of the mean flow. This firming up of the water supply is done with the storage reservoir and its storage capacity. A reservoir could be built so large that it would rarely, if ever, fill. Such a reservoir would utilize all of the unallocated water available for irrigation. However, such a reservoir would be extremely expensive to build, and these costs would be passed along to the user in the form of higher cost per unit of water. If the

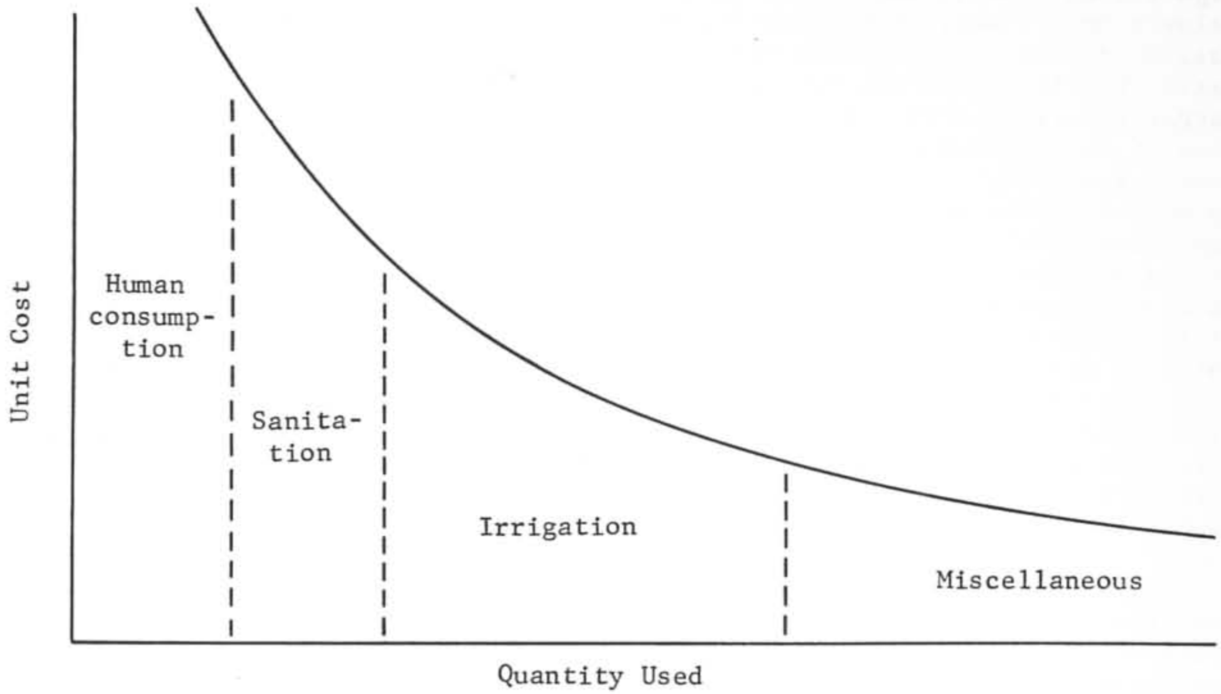

Figure 1

Marginal Value Versus Marginal Use Relation - Individual

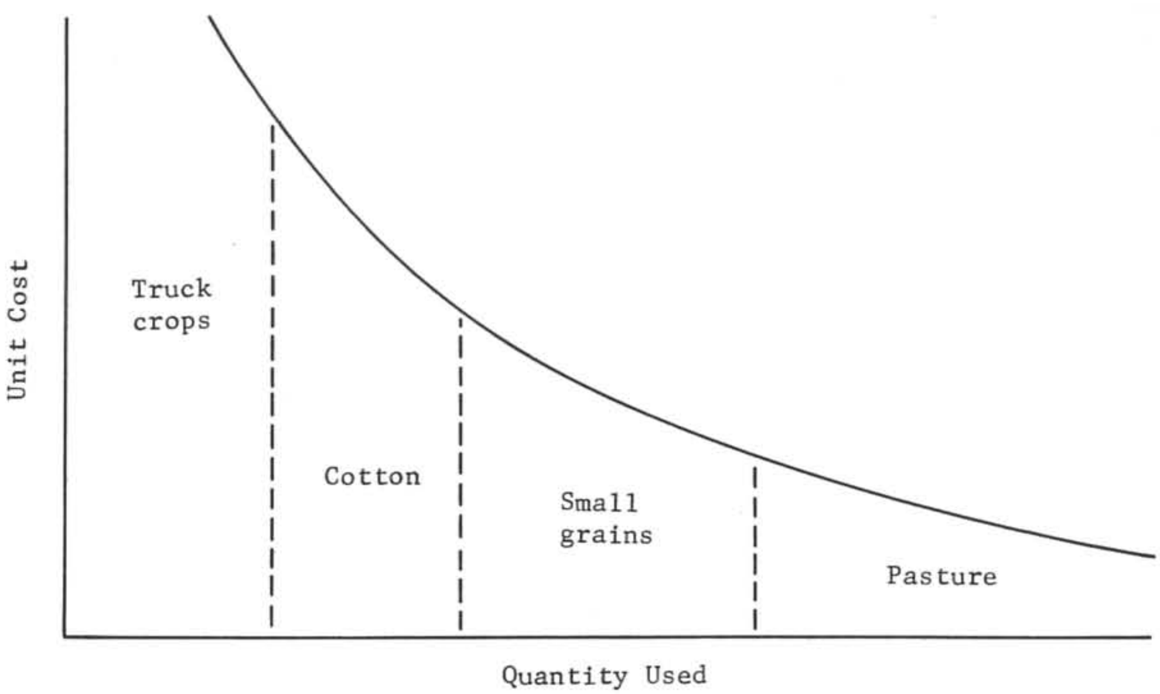

Figure 2

Marginal Value Versus Marginal Use Relation - Irrigation reservoir is made smaller, some water will flow over the spillway in years of high stream flows. There will be less water available from storage in years of below normal flows. Consequently, the firm supply of the smaller reservoir is less than that of the larger one. However, the cost of the reservoir is also less. The irrigator can use the water on less profitable crops than with the larger reservoir. The system designer seeks to maximize some parameter indicative of this relationship between amount of reservoir storage and profits to the user. Typically, the benefit-cost ratio is chosen as the parameter. In order to maximize this parameter, the planner will consider various amounts of storage water which will be available each season throughout the longest recorded period of sub-normal river flows. This water will be distributed on whatever basis may seem practical to the planner among the various irrigation operators. It is assumed that each operator will use the water on the most profitable crop which he can grow. If additional water is available beyond the needs of this crop, the next most profitable crop will receive the water. With these assumptions, the total benefits to the users may be evaluated for the water supply for each year of record. The present worth of these benefits at an equitable rate of interest must be compared to the present worth of the cost of the reservoir and system.

The present worth calculations put a premium on time of occurrence of the low flows. To illustrate, suppose 30 years of records are available. In 5 of these years, the flow is below normal, requiring the use of a great deal of storage water. Assume that the benefits for each of the "normal" years is \$1.00, and due to insufficient storage, the benefits are only \$.50 during each of the 5 below normal years. The present worth of all the benefits is \$15.67 if the 5 below normal years are the first 5 of record, and \$16.46 if the drought years are the last 5 of the 30 year period. This problem may be eliminated by the use of probability concepts. Without additional information, the 5 years are assumed to have a recurrence interval of 5 out of 30 events. The probability of any 1 year having benefits of \$1.00 is therefore 25/30. The present worth of 30 years of such benefits is

$$\begin{aligned} \text{P.W.} &= (17.29203)\,\frac{25}{30}\,(\$1.00) \\ &= \$14.41 \end{aligned}$$

The present worth of 30 years of \$.50 benefits with only 5/30 probability is

$$\begin{aligned} \text{P.W.} &= (17.29203)\,\frac{5}{30}\,(\$0.50) \\ &= \$1.44 \end{aligned}$$

The total present worth of the benefits is the sum of the two, or \$15.85.

The frequency and duration of the drought is the major consideration in this type of study, and the planner faces the same problems of frequency analysis that spillway designers face in flood control projects. That is, economic values must be assigned to events which do not occur every year during the life of the project. The frequency of occurrence of the drought therefore plays a major role in the present value of the losses sustained for any given amount of storage.

The procedure described here contains no new thoughts--it is the procedure utilized in the planning offices of the Bureau of Reclamation and in the offices of most consulting engineering firms. This procedure, judiciously applied, leads to a firm water supply equal to the tolerable minimum supply for irrigation during periods of drought. It results in "planned" water shortages.

One example of the concept of a tolerable water shortage in irrigation use is found on the High Plains of Texas. In this region there is a continuing decline in the water table from which the irrigation water is obtained. Farmers know current water production is on a mining basis and eventually there must be some curtailment of agricultural activities in the area due to the lack of water. Land values have been affected to some extent by this situation. In one case in particular, the reason cited for selling the land was the inadequacy of the water supply. This man had reached his minimum tolerable water supply and, seeing no feasible way to gain additional supply, sold the land. On the other hand, the man who bought the farm, certainly not ignorant of the declining water table, gave evidence that he had not yet reached the minimum tolerable level of water supply by his investment in plant and equipment. This illustrates very forcefully the idea that water supply--a tolerable level of water supply--is a very individual matter and can be decided for a group of individuals only on the basis of some average value or some aggregate action by the group.

MUNICIPAL AND INDUSTRIAL WATER USES

If the problems encountered in dealing with irrigation supplies are manifold and difficult to evaluate, the picture becomes even more cloudy and more complex as one studies municipal and industrial supplies. The irrigator is dependent on his water supply to provide a livelihood for himself and his family and consequently can be expected to give a reasonable economic value to the water in terms of increased income from irrigation farming. However, the bulk of municipal water in most Texas cities goes to the private consumer. There is no single use with an easily described value attached to it, but rather differing values depending upon personal preference and financial status. Immediately one is engrossed with problems of both economics and sociology. These problems influence the thinking when one is seeking an acceptable water shortage. For example, at a meeting of the American Water Works Association, the subject for a panel discussion was "What is Good Service and Who Should Pay For It?" The nearly unanimous opinion offered by the panel was that water should be made available to all customers in any quantity demanded, where and when demanded. This is immediately foreign to the ideas of planned shortages advanced in terms of irrigation supply and leaves one wondering if this might not be asking too much. On the other hand, when one begins to talk to people concerned with city growth (for example, Chambers of Commerce) there is immediate concern that adequate water be made available. These people generally feel that adequate water is a prime attraction for new industry for the city. There is little gained by relocating a large water use plant in an arid region; indeed, company management is not likely to allow this to happen.

There are many varying factors to attempt to evaluate in determining the economic losses from a particular amount of water shortage. To simplify the problem, consider a stable population--that is, one not changing with time. Divide the consumers into three groups:

(1) Fire Protection

(2) Industrial

(3) Residential.

Fire Protection: The cost of fire protection associated with reduced water supply may be measured in terms of the increase in fire insurance rates. Currently in the State of Texas, a firm supply of 130 gallons per capita per day is considered adequate, and each deviation of 5 percent below this results in an increase in fire insurance rates of approximately \$0.01 per \$100.00 evaluation.

Industrial: The direct losses to industrial users are relatively well defined, although difficult to assemble. If the industry is one in which the quality of the product is dependent on the water supply, the loss will be measured in terms of a decreased return on investment due to the poorer quality product. Where the quantity of production is limited by the water supply, the fixed costs of the units actually produced will be higher than normal, and again loss can be measured in terms of reduced return on investment.

The question of secondary losses will certainly need to be considered here. Reduced production is certain to mean a reduced labor force. If the water supplier is a private water concern, even the losses of the industrialists is not pertinent. However, when the supplier is the municipal water department, the loss of income has an effect on the income of the city, of which the water department is but a part. Opinions of economists on the extent to which this loss should be recognized vary from a loss of the total payroll to only the revenue loss by the water department as customers leave town. In the stable population model postulated, the minimum amount to be included is the amount of welfare expenditures incurred on behalf of this group, plus any loss of tax revenue.

Residential: Economic losses have been reasonably well defined for the uses considered to this point because the value of the units produced was determined by a "market place." Water supplied to the residential user is "retail" water; the purchaser uses it to satisfy personal wants. Since these wants are not, in general, commodities subject to exchange, no market place exists in which to determine the value of want satisfaction.

The residential user is somewhat like the irrigator in two respects: (1) He is apt to be very verbal about any "shortage." (2) His uses are diversified. The irrigator usually irrigates several crops and is much more willing to forego water on one crop than another. Likewise, the residential user has many uses for water--drinking, cooking, cooling, cleaning, sanitation, irrigation, and many others. These uses--or want satisfactions--do not all rank equally with any user. As stated earlier, water for drinking will rank first and consequently should be assigned the largest economic value. But what value? On the Mojave Desert of California, the price is \$1.60 per gallon when purchased by the glass in a restaurant. For each user, some sort of value-use relation exists similar to that shown in Figure 1. If the supply to the user is curtailed, either by shortage or pricing, he will refrain from those uses having the smallest want satisfaction. If the use is restricted from a normal use of B to A (Figure 4), economic loss to the user is the area under the curve between A and B. The price which the user is willing to pay for water for the satisfaction of a particular want must represent the economic value of the satisfaction of that want to that particular user at that particular moment.

(The inequities of water rationing in the usual manner--that is, by restricting lawn irrigation to alternate sides of the street on alternate days--is apparent when diagrams similar to Figure 1 for a large number of people are considered. Many people place a greater value on a beautiful lawn than on

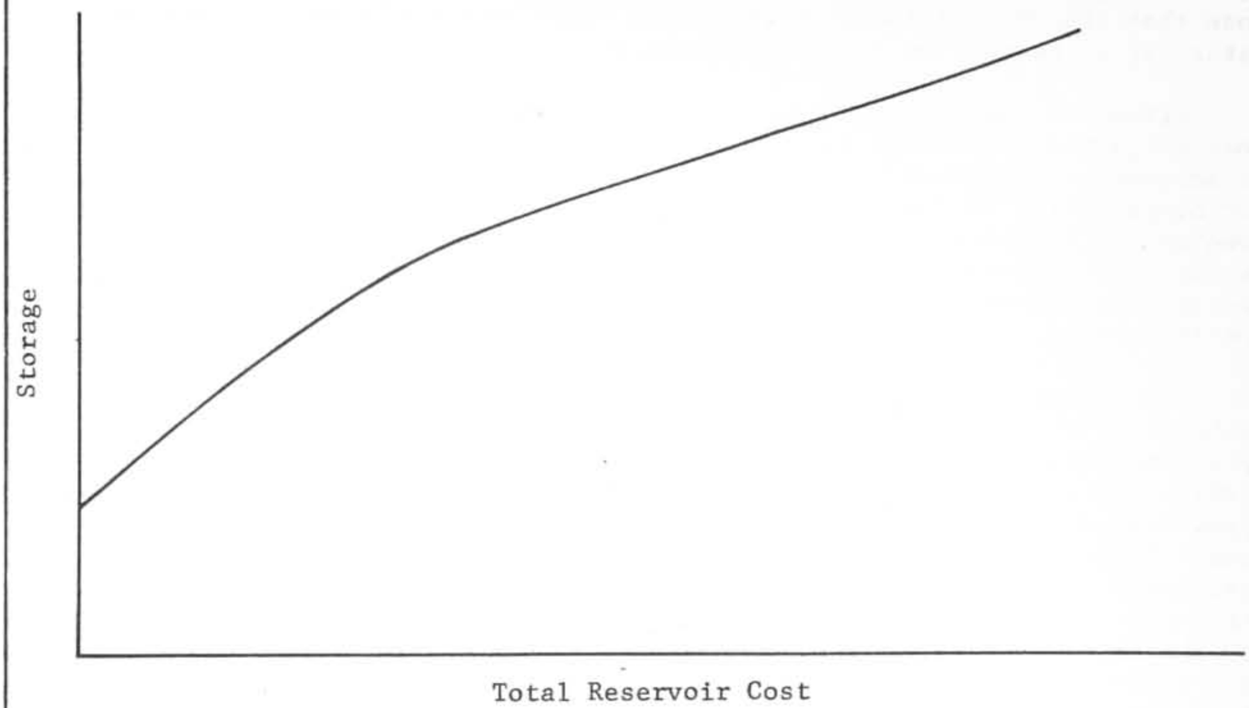

Figure 3

Typical Reservoir Cost-Storage Relation

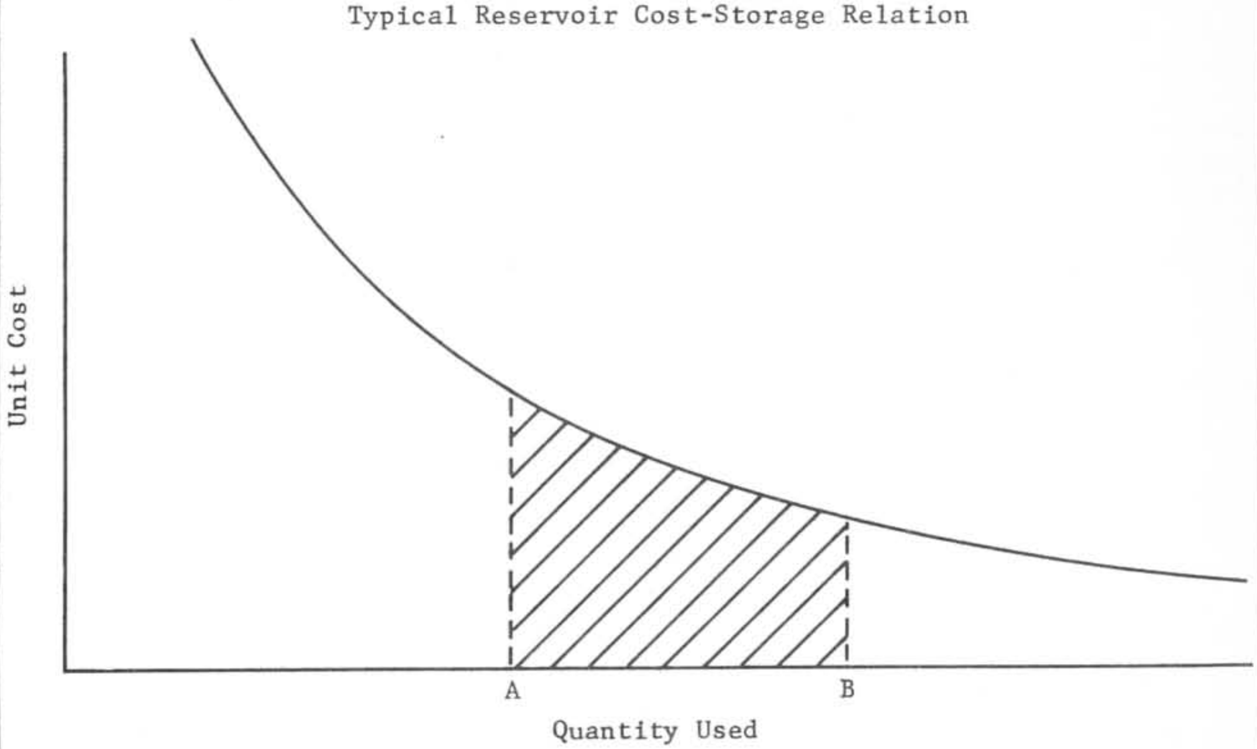

Figure 4

Loss Due to Restricted Supply

other things. Water rationing forces these users to suffer greater economic loss than the user pictured in Figure 1. Such inequities are avoided when water use is restricted by price increases.)

Without a curve similar to Figure 1 applicable for the entire city, there does not appear to be any logical way for determining a tolerable water supply in advance of the actual shortage. This is true because the planner must wait for overt action by the users to express an unsatisfactory supply situation. However, with a curve of use versus value, the losses sustained from a smaller supply can be balanced against the savings in construction and operation cost for the smaller supply. These calculations are identical to those discussed for irrigation.

An attempt has been made by the author to derive such a curve from data gathered by the American Water Works Association in a survey of water work operating data in 1955. This survey contains a great deal of information concerning the operation of water supply systems in all areas of the United States. Approximately 120 cities located between the Mississippi River and the Continental Divide were selected for analysis (Figure 5). Only cities for which inadequate data was reported were omitted. The derivation of a composite value-use curve is based on the assumption that people are statistically alike; that is, the different use factors (measured in gallons per capita per day) for the same price in two different cities is the result of different environment, not difference in people. The environmental causes are subject to analysis, and a relationship may be derived to express use as a function of value for some standard environment. The environmental factors selected were summer rainfall and high temperature. The amount of summer rainfall received in a particular locale will affect the amount of water used for lawn irrigation. The relationship between use and rainfall was assumed linear. Total rainfall for the 4 months, May through August, was used. Temperature was used as an index of water used for air conditioning. A base temperature of 70° was selected, and degree months above the base for the entire year were used as the value. Again a linear relation was assumed.

Mathematical models tested were of the form

$$Y = A_o + A_1X_1 + A_2X_2 + A_3X_3$$

where Y is the average use in gallons per capita per day,

A_o, A_1, A_2, and A_3 are regression constants found by the method of least squares,

X_1 is the functional relation assumed for the rate,

X_2 is the sum of the rainfall, May through August,

X_3 is the sum of the mean monthly temperatures above 70° F.

Logarithmic, hyperbolic, linear, exponential, parabolic, and cubic functional relationships were tested for X_1. All gave about the same standard error of estimate. For the hyperbolic relation, the resulting equation is:

$$\text{Use} = 90.70 + \frac{465.2}{\text{Rate}} - 2.32\ (\text{Rainfall}) + 0.35\ (\text{Temperature}).$$

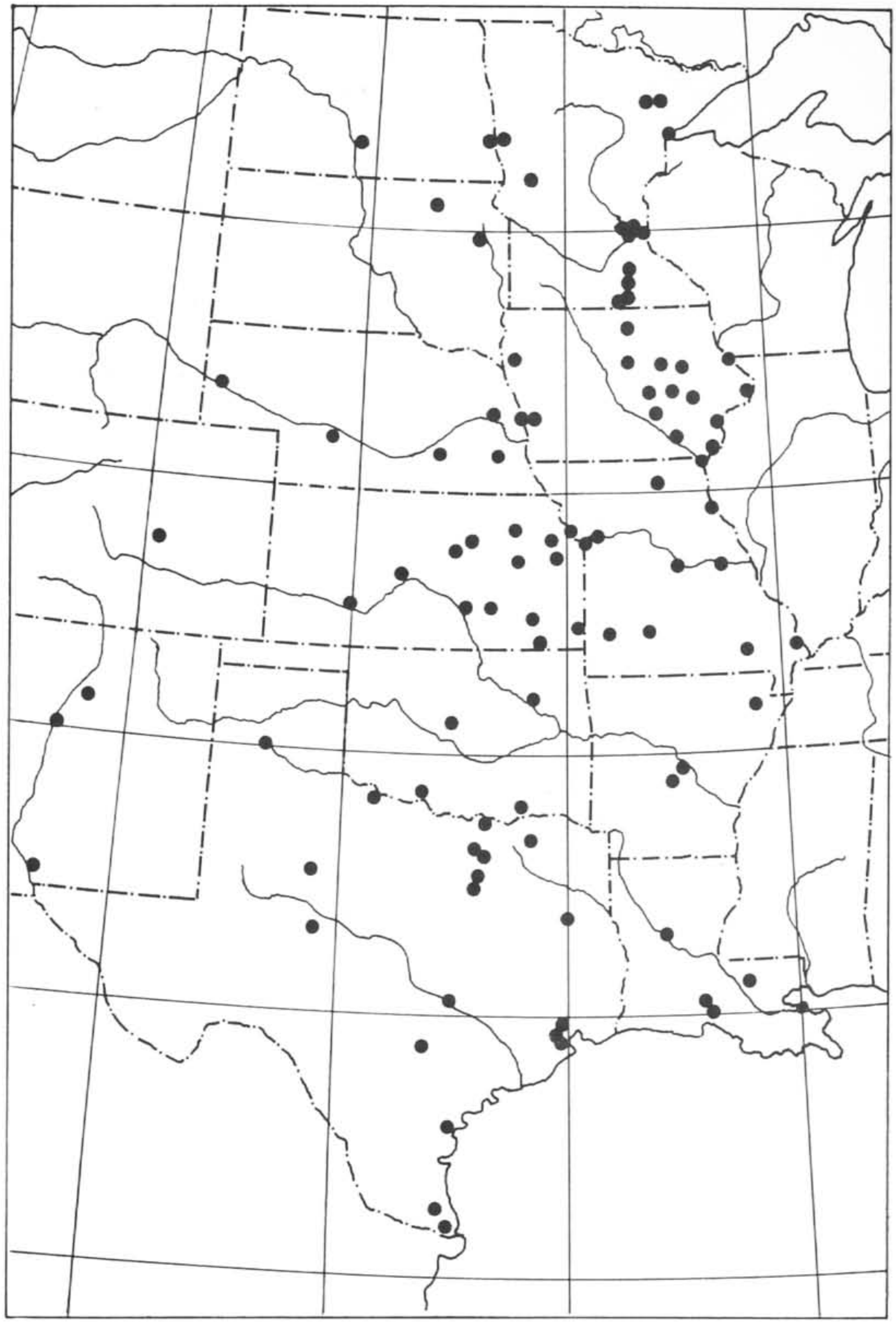

Figure 5

Location of Cities Used in Correlation

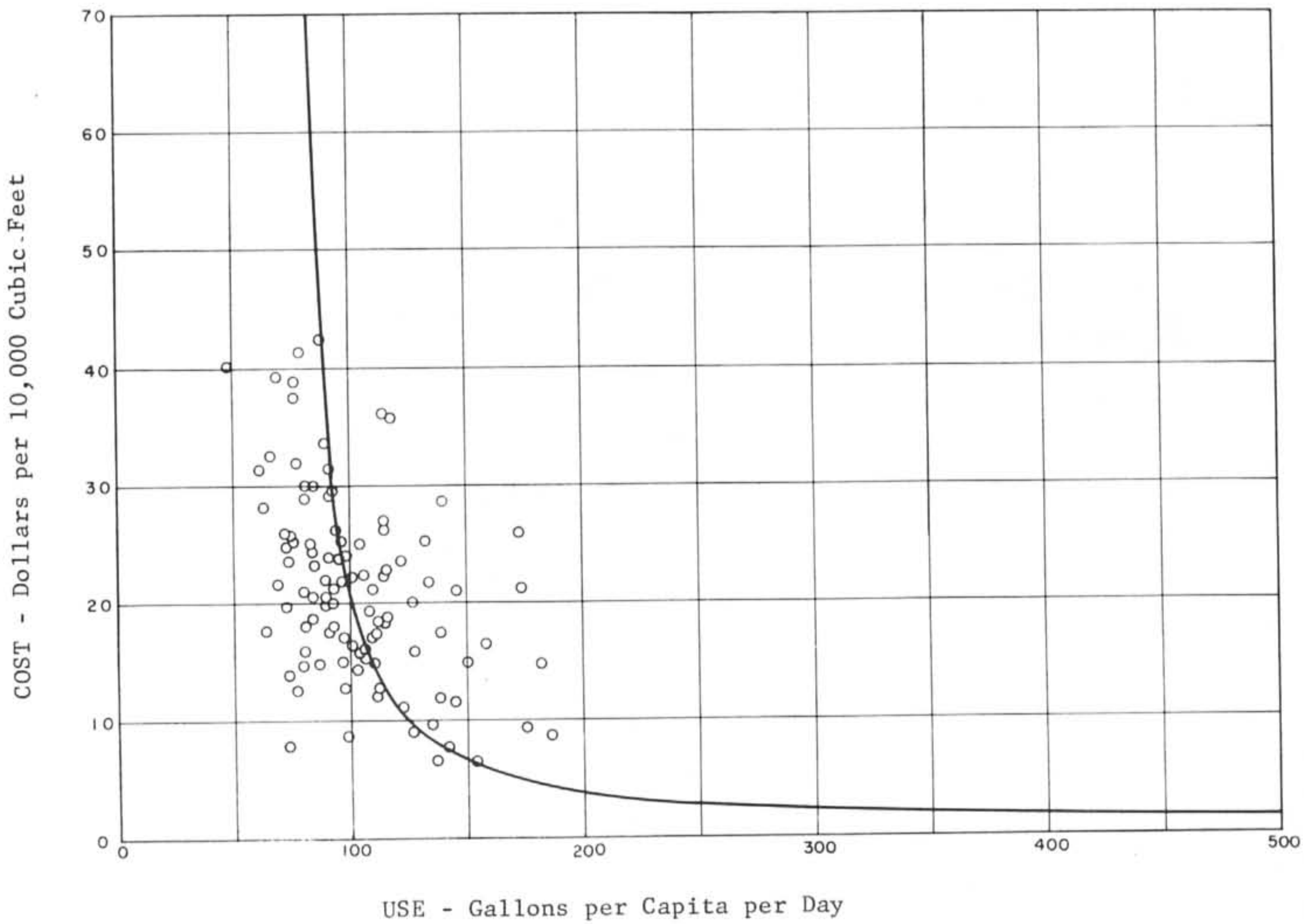

Figure 6

Residential Use-Cost Relation for Midwestern
United States Cities - 1955 Data

If the water cost is unrelated to the rate, the equation indicates infinite use. While the use is high under these conditions as shown in Table 1, they certainly are not infinite. On the other end of the scale, as the rate becomes very large, the use will be about 70 gallons per capita per day, an unreasonable figure if the conclusion of the highest marginal benefit from drinking water is true. Fortunately the planner is not likely to be interested in either of these extremes. The values predicted on the basis of the equation have a standard error of estimate of 25.9, or two-thirds of the measured values fall within plus or minus 25.9 gallons per capita per day of the predicted value. Figure 6 shows the equation plotted for mean rainfall and temperature conditions, with deviations from the line indicated.

TABLE 1.--WATER USE IN VARIOUS CITIES WITH FLAT-RATE PRICE STRUCTURES

City	Use gal/capita/day
Bellingham, Wash.	250
Berlin, N. H.	157
Burlington, Iowa	136
Burlington, N. J.	134
Denver, Colo.	145
Fort Collins, Colo.	240
Missoula, Ala.	397
Modesto, Calif.	280
Reno, Nevada	392
Sacramento, Calif.	239
Salisbury, Md.	170
Tulare, Calif.	322

The amount of variation of the use explained by the independent variables is only about 30 percent. Examination of the basic data does not suggest what other variable might be used to improve the relationship. Some improvement would probably result from considering the water requirements for lawn irrigation using the Lowry-Johnson method, or the Blaney-Criddle method for estimating consumption use.

The entire analysis is complicated by the grouping together of commercial, industrial, and residential uses in the report and by the many ways in which water pricing is done. The curve needed by the planner is one reflecting the marginal value to the residential and commercial user. Some variation in use in the basic data is attributable to industrial use; however, no data are available to allow exclusion of this water. The effect of the second complication is also serious. Most billing is done on a minimum charge basis, and the amount allowed without additional charge varies from zero to 1067 cubic feet per month for the 103 cities studied. Certainly the effect of water cost is not the same when 1067 cubic feet are supplied "free" as when a charge is made for each unit.

The relation described here is a rather poor substitute for an actual value-use relationship for a particular city or for better mathematical models which may be derived with more detailed data. The equation represents people whose wants may be changed by the environment. (The model assumes wants independent of environment.) The definite change in the value-use relationship with time has been completely ignored. These changes are continually occurring as evidenced by the increase in per capita consumption reported each year in spite of the rising water prices.

A more direct method of obtaining the value-use relationship for a particular city would involve deliberate manipulation of the price and concurrent observation of the use. Any such change in the price would require some period of time to allow the use to adjust to stable values. The change in the use-value relationship with time noted above would have to be removed from the observed values.

Data of this type could be obtained for the summer months by cities with chronic summer water shortages. Over several summers water price might be set at different levels dependent on the availability of water. Use would be curtailed in compliance with the particular value-use curve applicable to that city. In addition to the securing of data, and to the more equitable rationing procedure as mentioned earlier, this method has the advantage of avoiding the use of such terms as "water shortage" and "drought" with the resulting poor industrial image of the city. Thus, water is unlimited in supply--at a price. The additional income would not be unwelcome in most water utilities.

SEWAGE DILUTION

The problem of a tolerable water shortage when the water is being used for sewage effluent dilution will be dependent on the degree of treatment afforded before release. In extremely short periods of low flows, it may be possible to store the effluent until flows suitable for dilution are restored. Streams subject to chronic low flow periods are particularly unsuited for use in diluting sewage effluent. With more emphasis being placed on water pollution control and on water reuse, the occasion of use of streams for dilution is decreasing rapidly.

SUMMARY

The problem of defining a minimum water supply for various uses has been expressed as a problem in the economic evaluation of alternates. The position has been taken that the water supply tolerated is that supply where the marginal cost exceeds the marginal value attached to the next unit by the user. Economic analysis can be made in a straightforward manner for irrigation and industrial uses. However, residential uses are "retail" in nature, and little is known about the marginal value of water to this group. An attempt has been made to draw an inference of this value from the water works data of the cities of the midwest.

TABLE 2.--BASIC DATA

1	2	3	4	5	6
City	Population Served--thousands	Use--gal/capita/day	Rate--$/10,000 cf	Rainfall--inches	Temperature--degree-months
Aberdeen, S. D.	23	61	19.68	11.80	8.7
Albert Lea, Minn.	16	70	25.00	14.30	14.4
Albuquerque, N. M.	170	125	17.55	2.97	22.7
Alexandria, La.	54	59	31.50	25.05	35.3
Amarillo, Tex.	130	136	20.25	9.03	16.2
Ames, Iowa	23	60	39.40	11.89	15.5
Austin, Minn.	24	102	12.05	10.85	10.6
Austin, Tex.	193	149	17.45	11.04	63.5
Baton Rouge, La.	171	74	30.00	17.55	48.7
Bellaire, Tex.	22	100	22.75	21.99	60.8
Bismarck, N. D.	23	84	33.66	8.91	6.0
Brownsville, Tex.	50	100	13.96	5.48	75.1
Cape Giradeau, Mo.	24	58	32.00	18.39	28.4
Carthage, Mo.	12	60	32.50	12.50	27.8
Cedar Falls, Iowa	17	74	21.00	10.78	14.8
Cedar Rapids, Iowa	80	96	22.00	8.63	16.6
Cleburne, Tex.	20	84	22.05	14.90	42.3
Clinton, Iowa	28	74	29.22	11.12	17.3
Coffeyville, Kan.	22	114	23.60	14.08	31.2
Colorado Springs, Colo.	75	149	16.70	10.11	3.1
Corpus Christi, Tex.	180	199	21.20	4.17	61.6
Council Bluffs, Iowa	50	87	26.20	11.54	17.9
Dallas, Tex.	585	125	18.30	11.06	70.7
Denison, Tex.	21	80	23.20	14.49	43.6
Denton, Tex.	28	77	25.90	13.13	53.2
Des Moines, Iowa	215	97	24.00	10.10	19.1
Dodge City, Kan.	12	141	15.05	12.74	21.7
Dubuque, Iowa	54	63	23.10	12.70	11.9
Duluth, Minn.	105	99	20.00	17.72	0
Durant, Okla.	13	126	21.90	16.87	50.8
El Dorado, Kan.	16	69	37.25	13.74	31.0
Emporia, Kan.	18	86	17.07	13.64	24.1
Fargo, N. D.	45	102	22.50	12.45	7.8
Faribault, Minn.	16	60	8.00	12.49	13.1
Fergus Falls, Minn.	14	80	16.60	15.45	8.8

TABLE 2.--BASIC DATA--Continued

1	2	3	4	5	6
Fort Dodge, Iowa	30	126	11.59	13.14	16.4
Fort Madison, Iowa	15	56	17.75	11.82	19.3
Fremont, Neb.	18	139	7.80	9.58	25.6
Great Bend, Kan.	21	100	14.80	14.44	29.1
Hannibal, Mo.	21	78	8.75	16.40	19.1
Harlingen, Tex.	33	149	16.00	8.68	80.8
Hastings, Neb.	25	179	8.75	11.46	19.6
Hibbing, Minn	21	91	22.00	18.43	1.3
Hot Springs, Ark.	33	70	29.25	20.19	32.7
Houston, Tex	725	81	25.38	21.99	60.8
Independence, Kan.	15	94	17.30	17.38	32.4
Independence, Mo.	69	62	38.93	16.35	31.2
Jefferson City, Mo.	28	48	31.57	14.25	24.6
Jonesboro, Ark.	20	81	17.56	15.18	34.6
Junction City, Kan.	16	74	26.00	10.68	34.8
Kansas City, Mo.	712	102	27.00	16.35	31.2
Kearney, Neb.	13	146	6.61	11.54	21.0
Keokuk, Iowa	16	135	21.05	13.89	22.5
Kirksville, Mo.	12	67	30.00	14.48	15.5
Lafayette, La.	38	69	20.50	19.48	47.6
Las Cruces, N. M.	20	113	22.26	3.89	21.2
Lawrence, Kan.	25	107	36.15	13.39	28.4
Leavenworth, Kan.	24	65	24.77	13.05	24.5
Lincoln,Neb.	126	133	9.60	9.93	24.6
Little Rock, Ark.	201	77	29.32	18.78	40.2
Manhattan, Kan.	21	106	25.00	9.93	29.2
Marshalltown, Iowa	21	81	24.40	9.38	16.6
Mason City, Iowa	32	77	18.00	13.86	12.0
McKinney, Tex.	15	91	42.50	11.43	48.1
Minneapolis, Minn.	564	82	20.00	12.16	14.1
Moorhead, Minn.	20	83	12.80	12.40	7.1
Nacogdoches, Tex.	15	84	14.88	14.10	48.4
New Iberia, La.	60	77	18.60	29.34	44.2
New Orleans, La.	629	96	6.60	31.88	61.7
North Platte, Neb.	16	170	9.40	10.46	16.3
Oklahoma City, Okla.	299	89	22.35	19.03	37.7
Omaha,Neb.	290	178	14.90	10.89	22.7
Oskaloosa, Iowa	12	72	25.05	10.46	18.3
Ottawa, Kan.	11	95	19.43	15.18	27.4
Ottumwa, Iowa	35	97	26.40	16.69	18.6
Owatonna, Minn.	12	115	11.17	10.40	11.8
Paris, Tex.	24	78	14.68	13.42	45.8
Pittsburg, Kan.	21	70	23.92	20.85	26.3
Poplar Bluff, Mo.	17	70	12.61	11.89	24.9
Robbinsdale, Minn.	14	86	15.00	12.16	14.1

TABLE 2.--BASIC DATA--Continued

1	2	3	4	5	6
St. Cloud, Minn.	30	50	23.50	17.21	6.7
St. Louis County, Mo.	553	73	18.73	13.36	18.7
St. Louis Park, Minn.	38	81	20.00	12.16	14.1
St. Paul, Minn.	339	96	15.60	12.16	14.1
Salina, Kan.	34	113	21.10	9.38	31.1
San Angelo, Tex.	65	105	21.25	8.35	48.3
San Antonio, Tex.	465	124	13.86	9.45	65.6
Santa Fe. N. M.	33	91	24.00	5.96	0
Scottsbluff, Neb.	14	119	9.00	10.44	10.8
Shawnee, Okla.	30	54	40.15	9.77	44.5
Sioux City, Iowa	95	107	15.94	7.62	21.2
Snyder, Tex.	17	83	28.19	6.03	56.4
So. St. Paul, Minn.	19	70	16.00	12.16	14.1
Springfield, Mo.	88	66	41.31	14.19	19.1
Texarkana, Tex.	51	62	21.80	15.16	40.9
Topeka, Kan.	122	100	18.26	15.64	27.4
Tulsa, Okla.	267	131	28.85	16.53	45.7
Vernon, Tex.	14	84	20.45	16.61	55.9
Virginia, Minn.	15	144	26.00	18.50	2.1
Waterloo, Iowa	70	96	14.35	10.78	14.8
Watertown, S. D.	14	72	20.48	14.97	7.6
W. University Park, Tex.	18	89	16.00	21.99	60.8
Wichita, Kan.	237	118	35.82	10.36	30.3

TABLE 3.--SUMMARY OF CORRELATION STUDIES

Functional Relation	Std Error of Estimate	A_0	A_1	A_2	A_3
$Rate^{-3}$	26.80	114.6	17,060	−2.56	0.336
$Rate^{-.05}$	25.70	−500.7	714.6	−2.21	.350
Rate	25.85	147.1	−1.528	−2.16	.345
$Rate^{2}$	26.23	130.4	−0.030	−2.20	.342
$Rate^{-2}$	26.37	108.4	2,671	−2.46	.346

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APPENDIX

The data used in the correlation are shown in Table 2. Column 2 is the sum of columns 2 and 3, Table 1, of the AWWA report. Column 3 is the same as column 17, Table 2 of the report in most cases. However, for about 20 percent of the cities, column 13 of that table indicates substantial quantities of water being furnished free. Where such is the case, the figure shown in column 2 of the table is the result of dividing the number from column 12, Table 2 of the AWWA report showing the quantity sold, by the population served as shown in column 2 of Table 2. The data in column 4 were taken from column 15, Table 3, AWWA report, and are the cost per month of 10,000 cubic feet of water. The figures in columns 5 and 6 are taken from the appropriate Annual Summary of Climatic Conditions for the years 1955 and 1956. Records for both years are necessary because some of the cities reported on other than a calendar basis.

Table 3 is a summary of the results obtained with various functional relations assumed between use and rate. The standard error of estimate was calculated by the equation

$$S = \left[\frac{\Sigma(y - y')^2}{n - m}\right]^{\frac{1}{2}}$$

where y is the reported value of use and y' is the calculated value, n is the number of cities used (103), and m is the number of constants calculated in the regression equation (4). The constants A_o, A_1, A_2, and A_3 are the coefficients in the equation

$$Y = A_o + A_1X_1 + A_2X_2 + A_3X_3.$$

TOLERABLE WATER SHORTAGES DURING DROUGHTS FOR VARIOUS USES[a]

Discussion by Melvin George Schwab

MELVIN GEORGE SCHWAB.[1]--Professor Claborn presented a lucid description of the concept of incremental cost versus incremental value. Unfortunately, the application of this concept in determining tolerable water shortages for planning purposes has been limited because of inadequate data on values, changing conditions, and complex relationships. The situation is further complicated in the case of shortages caused by drought by the question of frequency of occurrence. The period of record in Texas is sufficient for only a very crude, inexact determination of the future frequency of occurrence of severe droughts.

Application of the incremental cost and value approach to the design of irrigation projects is not as sophisticated as some readers might infer from the paper. Although shortages of water for irrigation during droughts are accepted in the design of irrigation systems, and have occurred frequently on operating irrigation projects, the economic effect of varying degrees of shortage is not known very accurately. Texas Water Commission Bulletin 6413 "Water-Supply Limitations on Irrigation from the Rio Grande in Starr, Hidalgo, Cameron, and Willacy Counties, Texas" makes a determination of the optimum irrigated acreage for the Lower Rio Grande Valley. The economic portion of this analysis assumes that irrigation water has a constant per acre-foot value in crop production which does not change during years of shortage. The recommended acreage is based partly on judgment, rather than rigid economic analysis. This is not intended as a criticism of the bulletin. It is a good reflection of present-day knowledge and procedures. The Bureau of Reclamation makes similar assumptions in estimating the effect of shortages upon crop production of proposed irrigation projects. Bureau of Reclamation design criteria for irrigation shortages on a proposed project are generally not based upon an incremental benefit-incremental cost analysis for that project. Our irrigation shortage design criteria are more conservative, perhaps because of the margin of uncertainty in estimating future water supply and future use of water per acre, and because of a tendency to consider stability to be one of the desirable attributes of an irrigation project.

The degree of drought period shortage that would be tolerable from the standpoint of not causing abandonment or permanent reduction of irrigated area is much more severe than would be indicated as desirable by the usual design criteria or financial analysis, I believe. The Bexar, Medina, and Atascosa Counties Water Control and Improvement District No. 1 operates on irrigation canal supplied by their Medina Reservoir on the Medina River near San Antonio. This project suffered very severe water shortages during 9 consecutive years,

[a] By B. J. Claborn.

[1] Chief, Hydrology Division, U.S. Bureau of Reclamation, Austin, Texas.

1948-1956 inclusive. Yet since the end of this drought the diversions into the canal have been as large as before the drought. A study of the effect of this severe and prolonged water shortage on this irrigated area might be instructive. During the 7 year period 1951-1957 inclusive, the average diversion by the American Canal at El Paso was only 42 percent of the 1958-1960 average. However, the reduced surface supply was partly offset by extensive pumping of shallow ground water. In effect the area re-used its own return flow.

As Professor Claborn points out, little is known regarding the marginal value of water to city users. I do not know of a better approach than the comparison of per capita use with unit cost presented by Figure 6, yet I do not feel that this is entirely adequate. Figure 6 indicates that there is only a mild reduction of water use with increasing unit cost, within the range of costs prevalent in Texas. This suggests that the value of water to many users exceeds its present cost. To test this thought, I examined my own water bills for 1964. My family's per capita use was 224 gallons per day, and the average price was 30 cents per thousand gallons. My total water bill for the year was $97.00. This is quite a bit of money, but a very small percentage of my annual expenditures. If the water rate were cut in half, I don't believe we would use any more water. If it were increased 50 percent, I don't believe that we would use less. Income is an important factor in determining the use and market value of water.

By overt action, the historic judgment in Texas has been that the minimum tolerable supply for a metropolitan area is some degree of surplus over current use. The drought period water supply shortages that have been experienced by cities in the past have not been intentional or deliberately planned. It appears to me that there are four major reasons for this historic policy. These are (1) lack of knowledge of the true total cost of a city water shortage, (2) the relatively low cost of providing a surplus supply to accomodate and encourage growth, (3) inadequate knowledge of the severity and frequency of occurrence of future droughts, and (4) the rapid expansion of water use in metropolitan areas. Water use may increase by 50 percent during the 10 years that often elapse between a firm plan and the first delivery of water from a new reservoir. Under these conditions, and with all the other uncertainties that exist, the possibility of taking a 10-percent shortage during a drought is not an important factor in planning. Estimated costs of additional water supplies are low enough in eastern and central Texas, and at many locations in west Texas to permit continuation of the policy of fully ample metropolitan water supply.

Implementation of the concept of incremental cost vs. incremental value through city water rates has its difficulties. Rates often reflect the decrease in incremental delivery cost per 1000 gallons that occurs with increased use. However, all users in a city are charged the same rate regardless of whether they are one block or 5 miles away from the nearest water plant, despite resultant large differences in delivery costs. In a similar way, the rate structure of a city is likely to reflect the average cost of raw water from all sources rather than the incremental cost of the latest source added to the system. It would be hard to placate an irate housewife by telling her that, although the water department was operating in the black, water rates were being doubled to implement the concept of incremental cost vs. incremental value.

Water rationing during a drought through sharp temporary rate increases might not result in a prompt enough and great enought reduction of water use. Furthermore, some people might question whether this method of water rationing would be more equitable than the alternate methods now in use.

Figure 3 of the subject paper shows a curve relating reservoir storage to total reservoir cost. For many reservoir sites, the curvature is in the opposite direction; the cost per acre-foot of reservoir capacity decreases as the size of the reservoir is increased.

TOLERABLE WATER SHORTAGES DURING
DROUGHTS FOR VARIOUS USES[a]

Discussion by E. T. Smerdon

E. T. SMERDON,[1] AM. ASCE.--The problem of "tolerable water shortages" which Mr. Claborn has discussed is interesting and important. The key word in the title of Mr. Claborn's paper is "tolerable" and what it means to different individuals. I understand that a water supply situation is tolerable until the water user does something to improve his supply. This is an interesting useful concept, but to really be useful one needs actual economic figures or values to associate with so-called tolerable supplies.

The shape of the curves relating marginal value of an item to marginal use such as in Figure 1 and 2 is well known. A real need is to have such curves for different industries, classified by some appropriate water use level distinction, so that planners dealing with limited water supplies which can feasibly be developed, can consider types of industries which might situate in a given city. I would also suggest that there is no single water supply level which is tolerable for an industry, but rather a supply-cost relation which is acceptable. Highly complex economical analyses are involved if one hopes to thoroughly consider this problem. Often, insufficient data are available to make these analyses. I am sure that Mr. Claborn faced this problem.

In the example in the irrigation section of the paper concerning present worth of benefits, I assume that the project life as well as length of record upon which below normal flow probability is determined, are both 30 years. Also, I believe that the author assumed an interest rate of 4 percent in making the calculations for the present worth example. I think it worthwhile to reiterate the importance of making drought frequency analysis for any determination of present worth of benefits. Also, this drought frequency analysis may be one of the most difficult to make, depending on length of records available and other factors.

In the section of the paper on municipal and industrial water uses, the author presents data and various mathematical models for a marginal value versus marginal use relationship for residential water use. These data have so much scatter that this analysis becomes essentially meaningless. This can be seen by the magnitude of the standard error of estimate in relation to the mean. It would have been helpful if the author would have given some confidence measures resulting from the statistics of the analysis. The author has pointed to the problems encountered when using municipal water use-cost data in analyses of this type.

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[a] By B. J. Claborn.

[1] Director, Water Resources Institute, Texas A&M University, College Station, Texas.

It seems that in the future when an analysis of water use-cost data are attempted, a standard of living factor might be used, in addition to the rainfall and temperature factors. There is almost certainly an interaction with income level and the tendency to have air conditioning and irrigated lawns. A city might be subdivided according to appropriate residential areas for such a study, so differences in standard of living could be related to water use-cost functions.

The author suggests that the municipal water use relationship might be improved if water requirements for lawn irrigation were determined by some method of estimating consumptive use. This could perhaps be checked by making water use calculations for winter instead of summer.

The author suggests that if the water supply-water price relationships are properly established, one can avoid using such terms as water shortage and drought with the resulting poor industrial image of a city. I doubt if very many industries, which use any significant amount of water, fail to thoroughly investigate the total use-price relationship for water prior to locating in a given city. Knowing that potential future water supplies are related to growth potential, they are likely to look quite deeply into water supply conditions.

The author's concept of tolerable water supply is very useful, particularly as supplies become less plentiful. The real need now is to determine for all classes of people and industries, just what their tolerable water supply level may be. This would be of great value to water planners.

A DESIGN DROUGHT CONCEPT FOR RESERVOIR PLANNING

A DESIGN DROUGHT CONCEPT FOR RESERVOIR PLANNING

By Robert S. Gooch,[1] AM. ASCE

SYNOPSIS

It is proposed that estimates of the dependable yields of surface water reservoirs be based on probable minimum runoff and probable maximum net evaporation during drought periods, rather than on the recurrence of specific droughts covered by existing hydrologic records. It is possible to develop from historical records realistic relationships showing probable average runoff and evaporation rates for various drought durations. These relationships constitute design droughts, analogous to design floods for spillway planning.

An algebraic relationship can be used to establish dependable reservoir yields from the design drought criteria. From a number of specific comparisons, the simplified algebraic equation is shown to give results which are in close agreement with those of detailed operation studies.

INTRODUCTION

One of the more important considerations in any plan for surface water development is how much water can be provided and depended upon during times of drought. This question is basic to the adequacy and economic feasibility of a water supply project regardless of size. The answer, of course, hinges primarily on an evaluation of the probable severity of future droughts. The choice of data for a reservoir yield study implies a judgment that the assumed conditions are the worst which need be anticipated during the operating life of the project.

In general, drought data are derived from historical records of streamflow, evaporation and rainfall. Standard mathematical procedures are then used to predict reservoir performance during a recurrence of past hydrologic events. In some cases, adjustments are also made to cover known trends in watershed behavior, such as might decrease the amount of runoff during a repetition of previously-observed weather conditions. Even with this modification, however, the degree of drought severity is basically set by specific sequences of rainfall and related meteorological factors which have occurred since the beginning of official observations.

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[1] Hydraulic Engineer, Freese, Nichols and Endress, Consulting Engineers, Fort Worth, Texas.

Although this approach has been in use for many years, it does have some notable disadvantages. Fundamentally, it accepts the records of the past few decades as the measure of critical droughts in the future. Few streamflow stations in the United States have records longer than 50 years. Most have been in service only since the 1930's or later. It is altogether likely that there will be droughts in years to come which are more severe than any experienced during the period of existing records. This point has been emphasized repeatedly by water shortages in various parts of the nation, arising from drought conditions more stringent than any previously experienced.

A considerable volume of computation is required to prepare data and carry out the usual reservoir operation studies. More often than not, a number of assumptions must be made in applying the historical records to the reservoir site. The inherent uncertainty of these assumptions can lead to appreciable disagreement among two or more independent studies of the same project. It is probably a fair criticism of the customary methods to say that they focus attention unduly on the mechanics of computation, rather than on the overall validity of the results. There is a natural tendency to think of any lengthy mathematical operation as having a degree of exactness which the problem itself may not in fact justify. A more satisfactory approach in this instance might be to deal less in terms of detail and to concentrate instead on more general criteria for the drought conditions and simpler methods for their application.

What is proposed in the following pages is that historical records be used to formulate design drought criteria for use in estimating dependable yields, just as design floods are used to plan spillways. The basic concepts involved are that:

(a) For a given reservoir site, there is a relationship between minimum probable runoff and drought duration, which can be expressed graphically as a smooth curve--that is, a curve of minimum probable runoff for drought periods of 1 year, 2 years, 3 years, etc.

(b) There is a similar relationship between probable maximum net evaporation and drought duration.

(c) There are valid methods by which these relationships can be approximated and used to estimate dependable reservoir yields.

THE DESIGN DROUGHT CONCEPT

Figure 1 is a plot of the minimum average runoff rates observed for periods of from 1 to 12 consecutive years during a total of 60 years of recorded flows at the Neches River gaging station near Rockland, Texas. Table 1 is a listing of the quantities represented in the plot. Together, the table and the graph illustrate certain familiar characteristics of drought runoff. The minimum average flows for short periods of time are substantially lower than those for longer periods. The lowest single year's flow in this instance was less than one-tenth of the average for the full 60 years, whereas the minimum average flow for 12 consecutive years was nearly 80 percent of the overall average. In spite of the well-defined trend toward higher average flows with increasing length of drought period, the observed values are noticeably inconsistent. For instance, the average flow during the driest 5 consecutive years was more than that during the driest 6 consecutive years. The difference between the minimum flow observed in a 12-year period and that observed in an 11-year period is

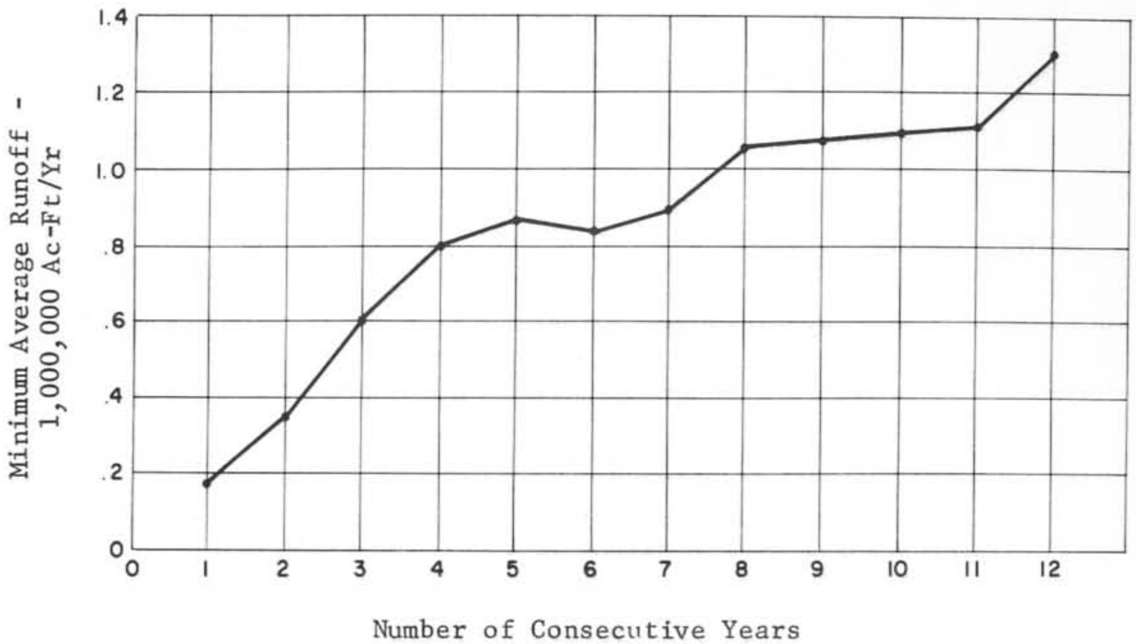

Figure 1

Minimum Recorded Runoff for Various Periods of Consecutive years on the Neches River Near Rockland, Texas: 1903-1963

TABLE 1.--MINIMUM OBSERVED RUNOFF AT THE GAGE ON THE NECHES RIVER NEAR ROCKLAND, TEXAS, FOR VARIOUS LENGTHS OF TIME

- 1903-1963 -

Length of Period in Years	Dates of Period of Minimum Observed Runoff	Minimum Observed Quantities Total Runoff (Acre-Feet)	Average Runoff (Ac-Ft/Yr)
1	10/1924 through 9/1925	164,000	164,000
2	11/1916 through 10/1918	697,900	348,900
3	3/1954 through 2/1957	1,829,400	609,800
4	6/1953 through 5/1957	3,208,000	802,000
5	7/1908 through 6/1913	4,337,600	867,500
6	4/1951 through 3/1957	5,054,100	842,300
7	4/1950 through 3/1957	6,276,600	896,700
8	5/1949 through 4/1957	8,459,500	1,057,400
9	5/1948 through 4/1957	9,629,500	1,069,900
10	1/1909 through 12/1918	10,876,600	1,087,700
11	6/1908 through 5/1919	12,242,400	1,112,900
12	7/1907 through 6/1919	15,548,600	1,295,700

many times more than the corresponding difference in values for 11-year and 10-year periods.

If enough records were available to define the true minimum runoff limits for this gage, it is logical to assume that such irregularities would disappear, and that the data would plot as a smooth curve. For these 60 years, however, there simply have not been any drought periods of certain durations (4 years or 5 years, for example) during which the average flow was even approximately as low as can be expected to occur from time to time in the future.

On the other hand, it is probable that there are a few periods in this set of records during which the average flows were close enough to the limiting minimum values for the watershed so that they might properly serve as design drought criteria. Specifically, the rates for 1 year, 2 years, 7 years and 11 years are evidently closer to the minimum limits than are the other quantities shown in Figure 1. If, as in Figure 2, a smooth curve is drawn through these 4 points, it is seen to lie only a short distance below the points for 6 years and 10 years, as well. A curve drawn in this manner establishes a set of minimum runoff values for various durations of time which are consistent with the least values ever observed at the gage. In effect, it adjusts the observed data wherever available records do not happen to reflect truly severe conditions.

Evaporation data are subject to the same reasoning and procedures. Figure 3 shows the results of a similar analysis of net evaporation in the vicinity of the Rockland gage.[2] In Figure 3, maximum average values of net evaporation for various lengths of time have been plotted and enclosed by an envelope curve of maximum limits for the available data. The curve defines a set of net evaporation rates which are consistent with the most severe conditions indicated by the historical records.

Extension of data collected during previous droughts to produce realistic standards of minimum average runoff and maximum average net evaporation is the essential feature of the design drought concept. The envelope curve method shown here is not necessarily the best way to develop the design drought criteria, although it does have the advantage of a clear relationship to observed data. The important point for present purposes is the form of the criteria and their application, rather than the particular method by which they are derived.

It might be preferable to add a safety factor to the envelope curve criteria by lowering the curve 5 percent or 10 percent below the critical points of the observed records. Interesting possibilities are also raised by the relatively new concepts of parametric hydrology[3], involving use of statistical procedures to develop long sequences of synthetic but valid runoff quantities based on observed watershed characteristics. This latter approach should allow

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[2] Net evaporation data for Figure 3 were taken from Table G-13, Texas Water Commission Bulletin 6006, "Monthly Reservoir Evaporation Rates for Texas, 1940 through 1957," by Robert L. Lowry, May, 1960.

[3] Maas, Arthur, and others, Design of Water-Resource Systems, Cambridge, Mass., Chapter 12, entitled "Mathematical Synthesis of Streamflow Sequences for the Analysis of River Basins by Simulation," written by Harold A. Thomas, Jr., and Myron B. Fiering, 1962.

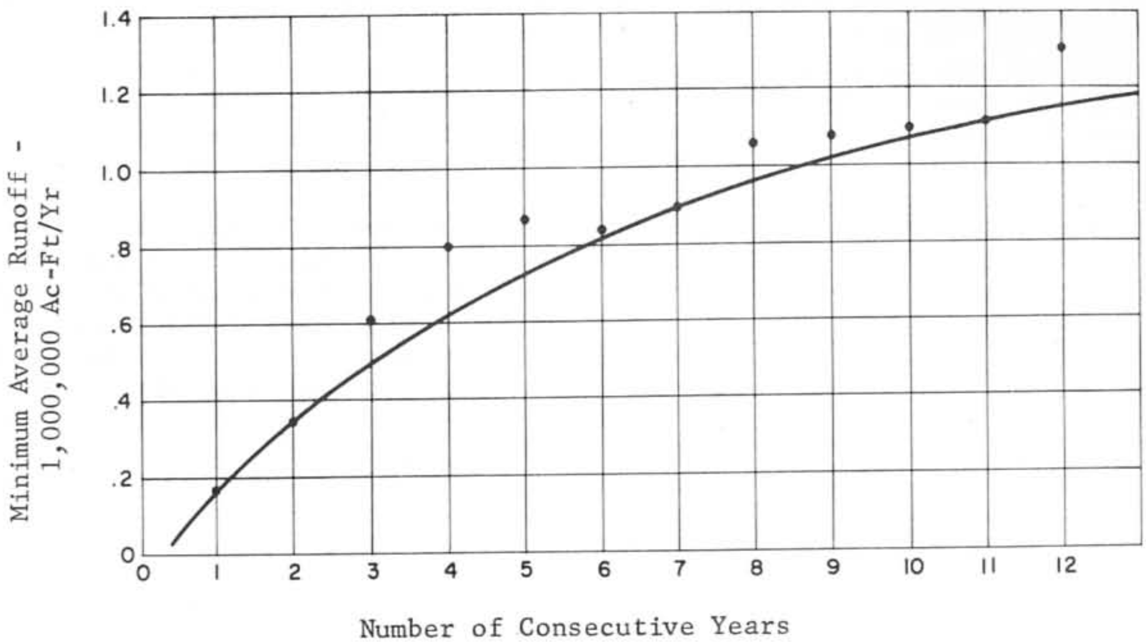

Figure 2

Envelope Curve of Minimum Recorded
Runoff for the Neches River Near
Rockland, Texas: 1903-1963

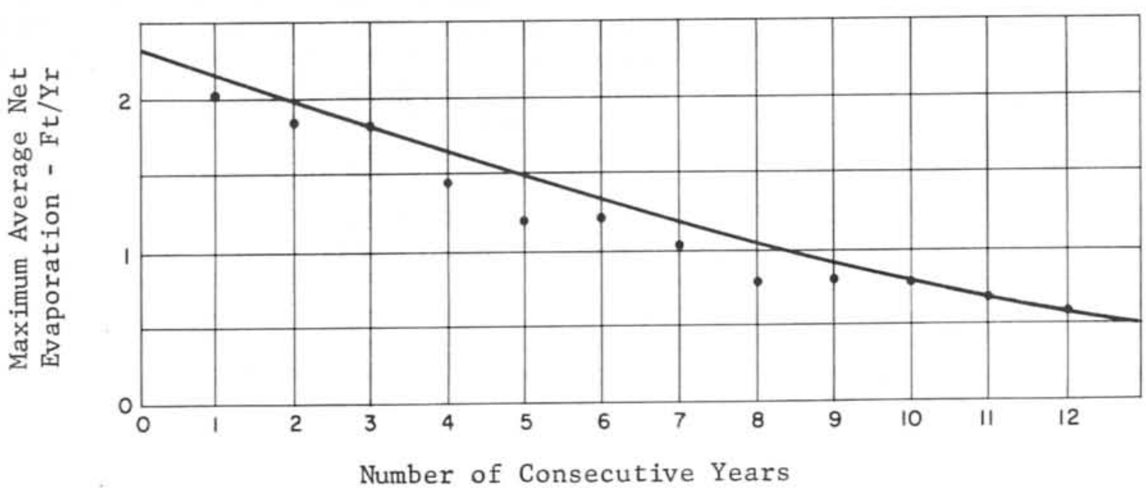

Figure 3

Envelope Curve of Maximum Net Evaporation
for Rockland Reservoir Site and Vicinity

an evaluation of the potential frequency of the design drought conditions, as well as their magnitudes.

APPLICATION OF DESIGN DROUGHT CRITERIA

The design drought concept precludes the customary month-by-month reservoir operation studies, since the criteria for runoff and evaporation are expressed in overall averages for the drought period. The yield must therefore be obtained through use of an algebraic relationship in the following form:

$$Y = \frac{C}{N} + R - ExA \qquad \text{(Equation 1)}$$

where the symbols represent the following quantities:

Y: The yield in acre-feet per year.

C: The portion of the reservoir capacity used during the drought in acre-feet.

N: The length of the critical drought period in years.

R: The average runoff during the critical drought period in acre-feet per year.

E: The average net evaporation during the critical drought period in feet per year.

A: The average of the reservoir areas at the beginning and end of the critical drought in acres.

The capacity and area values will be known for a given site, and the runoff and net evaporation can be read from the design drought curves for any assumed critical drought duration. The length of the critical period and the resulting yield can be determined by trial.

An example of application of design drought criteria to a specific project is shown in Tables 2, 3 and 4. Table 2 is a summary of capacities and areas for an assumed reservoir at the Rockland site on the Neches River. It is also assumed for purposes of the example that the reservoir has available the runoff from the entire watershed above the Rockland gaging station, in which case the design drought criteria might be as shown in Figure 2 and Figure 3 and listed in Table 3.[4]

From Table 2, it is seen that the conservation capacity available for use during the drought would be 2,000,000 acre-feet, and the average area would be 52,300 acres. Table 4 shows three trial yield estimates with critical drought periods of 3, 4, and 5 years, using the area and capacity quantities in Table 2 and the runoff and evaporation criteria from Table 3. The minimum yield

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[4] The example is, of course, hypothetical, and does not represent actual planning for the Rockland project. The assumption that no other major projects are in operation upstream would not be correct for the Rockland site, but is introduced to allow use of the criteria already developed in Figures 2 and 3.

TABLE 2.--AREA AND CAPACITY DATA FOR AN ASSUMED RESERVOIR AT THE ROCKLAND SITE, AS USED IN THE EXAMPLE

	Capacity	Area
Top of Conservation Pool	2,050,000	95,000
Bottom of Conservation Pool	50,000	9,600
C: Net Conservation Storage Used	2,000,000	--
A: Average Area	--	52,300

TABLE 3.--DESIGN DROUGHT CRITERIA BASED ON FIGURE 2 AND FIGURE 3

Length of Critical Drought Period (Years)	Average Runoff (Ac-Ft/Yr)	Average Net Evaporation (Feet)
1	164,000	2.17
2	348,900	2.00
3	500,000	1.83
4	625,000	1.67
5	730,000	1.51
6	820,000	1.35
7	896,700	1.20
8	960,000	1.07
9	1,015,000	.93
10	1,065,000	.80
11	1,112,900	.68
12	1,155,000	.58

TABLE 4.--EXAMPLE OF YIELD ESTIMATE FROM DESIGN DROUGHT CRITERIA

	Trial 1	Trial 2	Trial 3
N: Length of critical drought period (years)	3	4	5
R: Average drought runoff (acre-feet/year)	500,000	625,000	730,000
E: Average net evaporation rate (feet/year)	1.83	1.67	1.51
Y: Yield = $\frac{C}{N}$ - R - ExA (acre-feet/year)	1,071,000	1,038,000	1,051,000

resulting from these trials is 1,038,000 acre-feet per year for a critical drought lasting 4 years.

RELIABILITY OF THE ALGEBRAIC YIELD ESTIMATES

A particularly important factor in relation to the design drought concept is whether yield estimates obtained by means of Equation 1, working with overall averages rather than monthly increments, are sufficiently reliable for practical application. Table 5 lists 24 reservoirs for which detailed yield studies were available and for which algebraic yield estimates were prepared according to Equation 1. They cover a variety of reservoir sizes, minimum storage levels, and other variables, so that the table is considered a good sample of the types of studies normally encountered. (It should be noted that Table 5 does not include examples of the use of design drought criteria, but only compares the results of Equation 1 and detailed operation studies where the same data are used in both methods.)

In none of the cases listed in Table 5 is the difference between the yield obtained from Equation 1 and that resulting from the detailed yield study greater than +7 percent or -4 percent. The average discrepancy between the two methods was +3 percent. Neither the basic data nor the degree of certainty of the final answer should be considered to require closer precision that these comparisons indicate for the algebraic estimates.

CONCLUSION

The design drought method would appear to offer several advantages. It is fast and easy to apply. It greatly simplifies the process of evaluating dependable yields, and it should produce estimates which are more closely in line with what might be expected under severe drought conditions.

The most practical basis for using the design drought concept would undoubtedly be to adopt criteria on a regional scale, so that uniform standards would be generally recognized and followed. If, for example, state and federal agencies would develop and publish design drought curves for the watersheds under their jurisdiction, they would be in a much better position to evaluate the water resources of those areas on a reliable and consistent basis.

One of the major difficulties of water resource planning is the lack of a common language when speaking of dependable yields. The recognition of established design drought criteria would go far toward resolving this problem.

TABLE 5.--COMPARISON OF RESERVOIR YIELDS OBTAINED BY USE OF EQUATION 1 AND BY DETAILED YIELD STUDIES

Reservoir	Yield Estimated by Equation 1 (MGD)	Yield Shown By Detailed Yield Study (MGD)	Percent Difference by Equation 1
Blackburn Crossing	146	140	4%
Brownwood	47	46	2%
Cedar Creek	153	152	1%
Conroe	59	58	2%
Cleveland	66	62	6%
Forney	41	42	- 2%
Ferguson Crossing	211	197	7%
Garza - Little Elm - Aubrey	151	157	- 4%
Grapevine	36	34	6%
Houston	170	172	- 1%
Lampasas	79	80	- 1%
Lavon	74	69	7%
Livingston	937	924	1%
Lower Lake Creek	28	27	4%
McGee Bend	1135	1103	3%
Ponta	356	345	3%
Possum Kingdom	176	171	3%
Richland - Tehuacana	249	240	4%
Rockland	766	735	4%
Somerville	74	71	4%
Tennessee Colony	378	373	1%
Waco	85	80	6%
Weches	325	312	4%
Wesley Seale	174	171	2%
Total	5916	5761	3%

Notes: The above studies cover a range of assumed capacities at the various sites and are not in all cases the definitive yields for the projects. The Rockland Reservoir study listed was not for the same conditions as those used in the example of Tables 2, 3, and 4.

A DESIGN DROUGHT CONCEPT FOR RESERVOIR PLANNING[a]

Discussion by W. L. Meier, Jr.

W. L. MEIER, JR.,[1] AM. ASCE.--The author is to be commended for his clear, concise paper concerning the concept of the design drought and its use in reservoir yield estimation. His statements noting the inadequacy of traditional yield estimation techniques are most appropriate for a meeting of this sort. It is felt that particular importance should be given to his statements concerning the importance that is often placed on detailed computations. Several of his statements which seem to be most appropriate are quoted here:

> "It is probably a fair criticism of the customary methods to say that they focus attention unduly on the mechanics of computation, rather than on the overall validity of the results. There is a natural tendency to think of any lengthy mathematical operation as having a degree of exactness which the problem itself does not in fact justify."

To these statements can be added the fact that even a yield based on a lengthy reservoir operation is an estimate itself.

Detailed reservoir operation computations are usually performed on digital computers because of the speed of computation that these machines afford. The validity of these computations depends on the premise that the historic hydrologic record provides sufficient extreme conditions to be used as a basis for design.

Computer solutions do provide useful yield estimates with a minimum of effort, in a short time, and at reasonable cost. The method proposed by the author while providing a quick, reliable estimate of yield still requires considerable effort in developing the input data. The development of data is a major problem in any hydrologic analysis and could well be the subject of study itself.

The author has proposed a useful, workable method for defining a design drought. In considering the method for establishing the design drought, the author noted that there was a significant inconsistency in the plot of average runoff versus number of consecutive years shown in Figure 1. This inconsistency is caused by the probabilistic variation of streamflow. Such variation gives impetus to the possible use of stochastic methods for defining design droughts. The assumption is made in the paper that the envelope curve defined by the average flows for 1, 2, 7, and 11 years provide a useful design criterion. This

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[a] By Robert S. Gooch.
[1] Planning Hydrology Division, Texas Water Commission, Austin, Texas.

criterion is reasonable and provides a more severe basis for design than would the historic record. The same can be said for the similar analysis with respect to net evaporation rates. It is also reasonable to assume that the maximum reservoir evaporation rate occurs concurrently with the average low flow for a particular duration of time.

It seems, however, that engineers have extracted about all of the information possible from the historic trace of hydrologic data. The author's design drought concept does provide more severe drought inflows and net evaporation rates than the historic record implies. However, no assurance is given in the concept that droughts of greater severity will not occur and no measure of the probability of drought occurrence is provided. If additional numerical data are to be developed in the preparation and support of designs, statistical procedures will have to be utilized for extending streamflow data using the techniques of the newly developing area of stochastic hydrology. A good summary of the theory of this area is given by Chow.[2] Long synthesized records could be used to better define the probabilistic variation of low flows. These data along with correlations between streamflow and net evaporation rates would allow for more precise development of input data for yield estimates. At the present time work is being undertaken to refine these techniques and extend their utility.[3,4] Such procedures would make it possible as the author states to make more reliable estimates of average low flows for various time periods.

In addition to introducing the concept of the design drought, the author proposes a method for estimating the yield of a reservoir. Reservoir yield at a particular site is a function of the inflow, storage capacity available, and evaporation and other losses. According to Equation 1 in the paper, the yield can be estimated using a simple algebraic equation containing time averages of inflow, capacity used during the critical period, and evaporation loss as parameters. It should be noted that to use this equation the "critical period" must be defined as the period of time from full reservoir level until greatest drawdown rather than "spill to spill." The inflow can be developed using the concept proposed in the paper or be a stochastic variable. In order to evaluate the capacity utilized, some type of area-capacity relation must be developed so that area and capacity may be evaluated at least at two points. Then the determination of average area (from the two end areas) and the resulting average evaporation loss can be made.

Two possible variations in the method can be introduced at this point. The two are differentiated by whether an area-capacity relation is or is not available at the site. If an area-capacity relation is available for the proposed reservoir site, it would be more realistic to estimate the average area with the area corresponding to the average reservoir capacity during the drawdown period. This would tend to increase the magnitude of the computed average area and,

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[2] Chow, Ven Te, Handbook of applied hydrology, New York, McGraw-Hill Book Co. Inc., 1964, pp. 8-91 to 8-96.

[3] Beard, Leo R., Use of interrelated records to simulate streamflow, unpublished paper presented at the ASCE Water Resources Engineering Conference in Mobile, Ala., 1965.

[4] Fiering, Myron B., Multivariate technique for synthetic hydrology, Hydr. Div. Jour., ASCE Proc., Vol. 90, No. HY5, 1964, pp. 43-59.

therefore, the evaporation loss quantity. The use of this computational variation might increase the accuracy of the proposed estimating method since as shown in Table 5 the method generally over-estimated the yield quantity.

When an area-capacity relation is unavailable, yield estimates can be evaluated if only a reliable estimate is made of the surface area at top of conservation capacity. Considering the input parameters for Equation 1, the averages of inflow and net evaporation rate are independent of site characteristics. The capacity utilized is dependent only on whether sufficient storage capacity is available at the site and whether the reservoir would fill prior to the drought. The net evaporation loss is dependent on the loss from some average of effective reservoir area during the drought. Many investigators have discussed the possibility of estimating evaporation losses using only the area at the top of conservation storage. Meyers[5] suggested an "effective area ratio" as a means of expressing the average surface area during the period of reservoir drawdown as a percentage of the surface area at full storage capacity. Marks[6] and Kubik[7] stated that the effective area ratio should vary from 0.6 to 0.75 and 0.555 to 0.634, respectively. If an effective area ratio of 0.6 is assumed and yield estimates are made for the proposed Rockland Reservoir at Rockland using the area at full storage, the estimates will differ less than one percent from those made by the author. Therefore, it seems that acceptable estimates of yield may be made using Equation 1 when complete area-capacity information is not available.

One other possibility for using the proposed method is that yield-capacity relations for a particular reservoir site could be developed using the proposed method. As is shown in Table 4 of the paper, the method provides a means for estimating the minimum yield which can be obtained for a particular reservoir capacity.

For those who are interested, other investigators have considered methods for estimating yields in reservoir planning and design. Marks[6] presented a method for estimating yield using curves which represented idealized reservoir shapes. The method proposed by Gooch appears simpler and provides acceptable accuracy. Kubik[7] has proposed a method with which reservoir yields can be estimated using a probabilistic mass curve. The method has the advantage of arranging the low flows which have a particular probability of occurrence in the worst possible sequence. Stall[8] has developed a method similar to that of Kubik and has used it to develop curves with which reservoir yields can be estimated throughout the state of Illinois. Droughts of different durations and probabilities of occurrence can be studied, and allowances for evaporation losses and loss of capacity due to sedimentation are made.

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[5] Meyers, J. Stewert, Evaporation from the 17 western states, Washington D.C., U.S. Geological Survey Prof. Paper 272-D, 1962, p. 77.

[6] Marks, C. R., A simplified method of determining reservoir yield, unpublished paper presented at Texas-Oklahoma ASCE Convention in Dallas, Texas, 1960.

[7] Kubik, Harold E., Probability concept applied to reservoir yields, unpublished paper presented at 1964 winter meeting of Amer. Soc. of Agricultural Engineers in New Orleans, La., 1964.

[8] Stall, John B., Low flows of Illinois streams for impounding reservoir design, Urbana, Ill., Bulletin 51, Illinois State Water Survey, 1964.

SYSTEM OPERATION OF RESERVOIRS TO OBTAIN
OPTIMUM YIELD DURING DROUGHT

SYSTEM OPERATION OF RESERVOIRS TO OBTAIN OPTIMUM YIELD DURING DROUGHT

By C. R. Marks,[a] M. ASCE

SYNOPSIS

An outline procedure is developed for optimizing the yield of a system of reservoirs. The maximum firm yields for system comprised of alternate storage increments and reservoir units are first determined by approximate methods. The system producing optimum water costs or benefits is then selected and a final "proof" analysis of the system is made by more accurate methods. The procedure provides for alternate operating strategies and for consideration of factors commonly found in Texas watershed systems designed primarily to supply water for municipal and industrial use.

THE PROBLEM

Limitations of This Discussion

The problem implied by the title of this paper is large enough to form the subject matter of a good sized book. It will therefore be necessary to limit severely the scope of this discussion.

By the title itself this discussion is limited to the yield during drought; thus it will not include operation of reservoirs for flood control. Neither will it include the additional yield above the firm yield which can be obtained during the times of high inflows, provided a greater rate of withdrawal is permitted when the reservoirs are filled above a predetermined elevation.

Since this is a meeting of the Texas Section, the problem will be further limited to the conditions found in Texas. This substantially eliminates some procedures which have been used in other places, where seasonal operation on an annual cycle is feasible.

I have chosen to further limit the discussion primarily to water supply for municipal and industrial use. Irrigation use will be considered only in connection with existing water rights, or as an incidental feature. The scope of the discussion will be limited to pointing out guide lines in the direction of further study, rather than in trying to develop details of a solution.

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I shall talk only about the reservoirs in a single river basin, but the principles developed could be applied to a system composed of several such basins.

Because of limitations of time in preparation of this talk, I have drawn heavily upon my own previous studies, and upon published literature wherever possible.

FACTORS INVOLVED

Involved in a solution to this problem are a large number of factors, some of the most important of which are discussed below.

Geography of the System

The geography of the system is perhaps the most important factor. A compact system of sequential reservoirs imposes one kind of problem; a compact system of reservoirs in parallel another; and a widely spread out combination of these systems a third. The latter is obviously the most general case. In addition, the geography often controls the type of reservoir, the type of demand, the evaporation, and a number of other factors.

Runoff Characteristics

Included in the runoff characteristics are the average amounts of runoff, its variability, and portion of the runoff which occurs below the last downstream storage point. Also included are factors which may change the historical runoff as applied to present or future times.

Reservoir Characteristics

The principal reservoir characteristics are: the depth-area-capacity relationship; the evaporation rate; the relation of total storage to runoff; the efficiency of the reservoir (which will be described later on); the allowance for sediment; and the use of the reservoir for other purposes than water supply. In this discussion it will not be possible to cover all of these characteristics, and some of those not considered may have a profound effect on the optimization of reservoir yield in some instances.

Characteristics of Demand

Principal demand characteristics are its geographical distribution, its seasonal variation, and the type or types of use. Further characteristics of the demand are that its distribution may be influenced by the amount of supply, and especially by the cost of the supply. Certainly this will be true relative to certain types of use. It is for this reason that the suggested solution proceeds in several steps. The first step is to obtain a rough approximation of the yield. The succeeding steps refine this estimate more and more precisely. This procedure is suggested because the overall optimum watershed yield will depend upon many characteristics of the demand as well as the other factors just mentioned. The amount of return flow and its pattern is also related to the characteristics of the demand.

Conveyance System

The capacity, time-lag, and losses from the conveyance system will also affect the usable system yield in many cases. Consideration of these factors will probably best be done as a refinement or modification of the basic yield, after this has been fairly well established without regard to the conveyance system. This discussion will not consider the conveyance system at all; however, in some cases it may be necessary to introduce the conveyance system as a factor early in the analysis.

Return Flow

Return flow has already been mentioned, but it must be emphasized that it is a most important factor. Its principal characteristics are its amount, its timing, its location, and its quality. Any or all of these may be of prime importance in the analysis.

Quality Problems

The water quality problems involved in various portions of the watershed, and with respect to types of use, may become very important. They are particularly important with respect to return flow. In the present analysis it will be assumed that all of the water is of adequate quality for the uses intended, and that use of the return flows to satisfy a portion of the demand is feasible.

Types of Optimization

The final factor entering into the solution of the problem is the type of optimization desired. It is assumed that the solution may be applied in planning and programming a development system. In such case an optimization can be made with respect to any one of the following criteria:

1. The absolute maximum watershed yield.

2. The maximum watershed yield subject to development of independent supplies for local use in portions of the watershed.

3. The maximum yield with permissible risks of shortages under certain conditions.

4. Optimization with respect to both quantity of water and certain cost factors. This last method will almost inevitably occur as part of the procedure for planning a system, because it may lead to the selection of some projects and the rejection of others. However it appears to me that this type of optimization will usually involve two stages, that is:

a. Analysis of yields and costs for several alternate systems and/or capacities of reservoirs;

b. Selection of the best system on the basis of cost and other pertinent factors.

PREVIOUS SOLUTIONS OF SIMILAR PROBLEMS

Simplified Models

Manzer and Barnett[1F] have developed a digital computer program designed to analyze the operation of a reservoir system. The system which was used consisted of two reservoirs in parallel at the upper end of a watershed, a third reservoir in sequence with these two, and a fourth on a tributary below the third. The system was operated for power production, irrigation and flood control, and the program is designed to compute and print out the benefits from each use for a range of capacities and operating rules. However, the input data must include the desired levels of system outputs, and the printed results merely show any deficiency in supply or the amount remaining in storage. Hence the program does not actually optimize the yield, nor does it even determine what the yield would be without shortages.

The statement is made in this reference that: "No one, however, has yet completed a simulation of a large and complex river basin system on such computers for the purposes of system design."

Specific Applications

Although the above statement was made in 1962 it appears to be still true today. According to Reference 1F, p. 325, The Bureau of Reclamation, The Corps of Engineers, TVA and others have developed computer programs for single watersheds as an aid in operation, but seemingly no one has developed a comprehensive program of general application for planning purposes. (See also: Reference 2, Chapter 25-III and References 3,4,5,6,7,8,and 12.)

Basic Concepts

Some basic concepts for approaching this problem are ably discussed by Mass and Hufschmidt.[1C] On page 252 it is stated, "Never-the-less, there remains the problem of using the computer most effectively. Assuming that significant increments are chosen for each variable in a given river-basin system, the computer need not be asked to examine all possible combinations of variables. The combinations to be simulated can be selected, using a method that justifies confidence that the best result obtained approximates the theoretically best combination."

1F Design of Water Resource Systems, Harvard Univ. Press, 1962, Chapter 9.
1C Design of Water Resource Systems, Harvard Univ. Press, 1962, Chapter 6.

Sampling Process

Hufschmidt[1G] describes one method of optimizing the benefits from a system of reservoirs. It is applied to the same simplified system as was used for the computer program. Presumably it could be adapted to a more complex system, but the time required to reach a solution might well render this approach impracticable for a fairly large number of reservoirs. This method is essentially a systematic sampling of several combinations of reservoir sizes or yield allocations. The sampling process is combined with a method of determining an optimum output by the use of a "response surface" and "steepest ascent procedure." This procedure is fully described in the reference cited.

None Completely Applicable to Texas

Although all of the above methods appear to have possibilities, it does not seem that any of them is susceptible of general application to any river basin or series of river basins. Neither does it appear that any of the methods for which the details were available to the author are applicable to Texas river basins, at least directly. The next section of this discussion will cover the specific requirements of an optimizing procedure as applied to Texas, and subsequent sections will develop a suggested procedure.

Several of the previously developed procedures could apparently be applied to portions of the overall procedure which will be developed in the remainder of this discussion.

SPECIFIC FACTORS IN SOLUTION AS APPLIED TO TEXAS

Review of the available literature as to previous approaches to solution of the optimum yield problem indicates that many of them do not apply to a solution of this problem for the Texas watersheds, or at least not for most of them. Some of the reasons for this are outlined below.

Texas Future Needs Are Primarily For Municipal and Industrial Use

Irrigation uses are of prime importance in the Rio Grande Valley and of a major importance in the Texas Basins Project proposed by the Bureau of Reclamation. Irrigation use would also form the basis for any scheme to pump water successively upstream to the High Plains, as is now being discussed in connection with the Colorado River. However, all of these are highly specialized problems, and the present discussion will not attempt to deal with them.

The principal result of limitation of the study to municipal and industrial use is that frequent or extensive shortages cannot be tolerated. In some instances it may be possible to tolerate the possibility of a partial shortage under conditions having very low probability. This is particularly true where there is a supplementary source of supply, or if the critical design period is

[1G] Design of Water Resource Systems, Harvard Univ. Press, 1962, Chapter 10.

very long. In such case some type of water rationing may be feasible, and may be necessary or desirable during the most severe portions of an extended drought.

High Relative Evaporation Loss

High evaporation rate is characteristic of most portions of the State of Texas, and it is a very important factor in approaching the problem of optimum yield. An illustration of this is found in the example given in the next section of this discussion. The high evaporation rate also causes significant variation in the gross rate of use from a reservoir as compared with the net rate, or demand. For this reason it is often impossible to determine accurately the beginning or ending points of a critical period by reference to a mass curve of runoff.

Need for Maximum Reasonable Development

Texas shares with several other portions of the United States the need for maximum reasonable development of its water supplies in the future--at least for a major part of the State. In some areas this may virtually rule out questions of economy as a factor in optimization.

Chance to Supplement the Firm Yield from Other Sources

There are, in many parts of the State, other sources of water which may be used to supplement the firm yield, especially during the most critical portions of extreme drought. These include: ground water, reuse of return flow, and import from other watersheds.

Effect of Water Rights

Existing water rights will have a major effect upon the determination of optimum yield in many cases. In some cases these water rights may be merely considered to be a portion of the yield. In other cases it may not be possible to predict what portion of these rights will not be satisfied by the use of the runoff originating below the points of impoundment. In such cases a more or less arbitrary rate of release may have to be assigned to a project, in order to provide for these water rights. In still other cases, the release required to satisfy existing rights may be of such a magnitude as to reduce the yield of a certain project to practically zero. It may then be necessary to reach a decision as to whether these existing rights should continue to be honored in the future, or whether some plan should be made to acquire them, in order to make a larger yield available for other purposes. Wherever possible, decisions as to the requirements of existing water rights should precede optimum yield studies.

ILLUSTRATIVE EXAMPLE SHOWING RELATIVE RESERVOIR EFFICIENCY

The author believes there are many places in Texas where yield optimization should include consideration of relative reservoir efficiency. He has previously[9] developed a method for comparing relative reservoir efficiency. In this method there is computed for each reservoir an evaporation factor, defined as:

$$\frac{\text{Total Evaporation Loss for Critical Period}}{\text{Total Conservation Storage Capacity}}$$

To compute this factor all the reservoirs should be operated for firm yield over the same length of period. The relative reservoir efficiencies for a system of reservoirs are in reverse order to the evaporation factors.

The application of relative efficiency is illustrated by the example shown on Figure 1, which shows a simplified example of a 2-reservoir system. The evaporation factors are 1.09 and 0.425 for reservoirs A and B, respectively.

The reservoirs were deliberately chosen to magnify the difference between two types of operation. One of the reservoirs is a flat, shallow one, such as might result from damming off a tidal estuary. The other is a relatively deep reservoir. In Table 1 the system yield is obtained by two alternate operation methods or strategies. In the first method of operation, both reservoirs are drawn down over the entire critical period, and their yields are merely additive. In the second method the least efficient reservoir is drawn down first, by taking almost the entire demand from it. When it becomes empty the entire demand is taken from the other reservoir for the remainder of the critical period. The second method of operation produces a 14 percent larger combined yield than the first method.

The results of this simplified example are confirmed by a statement made by Col. Walter Wells, General Manager of the Brazos River Authority, at the Seminar on Management of River Basins in Austin on April 5, 1965. Col. Wells stated that a system consisting of four tributary reservoirs on the Brazos River below Whitney will produce a yield 10 percent greater than the sum of their individual yields, if they are operated in a coordinated manner.

Relationships similar to the illustrative example will be found between many actual reservoirs. In some cases the relationship will not be the same at all reservoir levels. Thus when reservoirs A and B are both full, A may be the most efficient, but at some lower levels the reverse may be true. Such a situation may be revealed by computing evaporation factors for different ranges of reservoir storage.

OUTLINE OF SUGGESTED RUNOFF AND YIELD PROCEDURES

The full procedure suggested has not actually been applied to any system of reservoirs, and therefore must be considered as tentative. Several of the procedures have been applied, in a limited degree, to an actual watershed study. Based upon this experience it is believed that they can be used as a basis for optimizing system operation along the general lines described below.

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[9] Marks, C. R., A Simplified Method of Determining Reservoir Yield, Paper presented at Texas-Oklahoma Convention in Dallas, Sept. 30, 1960 (See Appendix A).

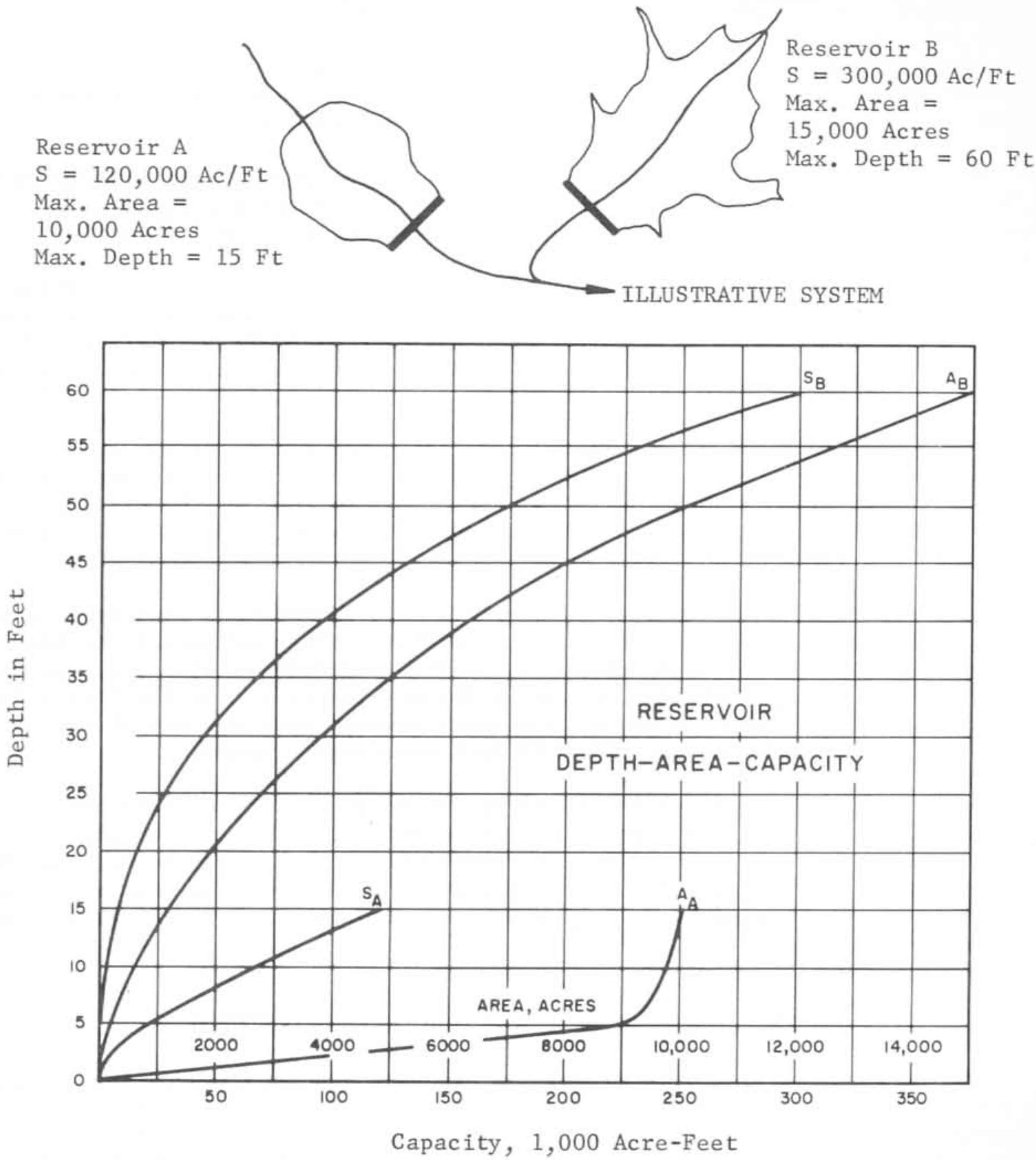

Figure 1

Illustrative Reservoir System

TABLE 1.--YIELDS FOR ILLUSTRATIVE SYSTEM (Figure 1)

Assumptions:

1. Critical period = 4 years
2. Uniform runoff rate

   A = 20,000
   B = 100,000

3. Uniform evaporation = 4 ft/yr
4. Uniform demand

Operating Strategy I - each reservoir operated for independent firm yield over critical period

Operating Strategy II - least efficient reservoir emptied rapidly at beginning of period

	Res. A	Res. B	Total
Strategy I			
Inflow during drought, ac-ft/yr	20,000	100,000	120,000
Average surface area, acres	8,250	8,000	16,250
Evaporation loss, ac-ft/yr	33,000	32,000	65,000
Yield from storage, ac-ft/yr	29,000	75,000	104,000
Net yield, ac-ft/yr	16,000	143,000	159,000
Evaporation Factor	1.09 $\left(\frac{4 \times 33,000}{120,000}\right)$	0.425 $\left(\frac{4 \times 32,000}{300,000}\right)$	
Strategy II (first 0.77 yrs)			
Inflow, ac-ft/yr	20,000	100,000	120,000
Average surface area, acres	8,250	15,000	23,250
Evaporation loss, ac-ft/yr	33,000	60,000	93,000
Yield from storage, ac-ft/yr	154,000	0	154,000
Net yield, ac-ft/yr	141,000	40,000	181,000
(last 3.23 yrs)			
Average surface area, acres	0	8,000	8,000
Evaporation loss, ac-ft/yr	0	32,000	32,000
Yield from storage, ac-ft/yr	0	93,000	93,000
Net yield, ac-ft/yr	20,000	161,000	181,000
Increase in yield, strategy II, ac-ft/yr			22,000 (14%)

Determination of Inflow

The sequence of flows to be used in the study can be derived in several ways. In nearly all instances these will start from streamflow records. Presumably these will be modified, adjusted, extended, and interpolated to apply to the anticipated conditions for the system. Let us assume that eventually a sequence of flows can be developed for each of the present or projected dam sites in the watershed and for the incremental inflow between sites. Let us further assume that this sequence can be extended to a period perhaps as long as 50 years, and preferably longer. Thomas and Flering[1I] have described a method of generating synthetic flow sequences in random fashion from such an actual flow sequence. Maughan and Kawano[10] have another such method. The author[11] has described a method of developing envelope curves for the minimum runoff applicable to low flow periods of varying duration. It is believed that this latter method, either by itself or in conjunction with a synthetic series of flows by one of the methods discussed just above, can serve as a key tool in optimizing watershed yield from a system of reservoirs. Illustrative envelope curves are shown in Figure 2. Plotting points for these envelope curves can be obtained from streamflow sequences by a simple computer program. The curves shown were obtained manually, using annual runoff. Monthly runoff values would produce more reliable curves.

Monthly flows and yields will be used through this discussion.

In detail the runoff to be used would be obtained by the following steps:

1. Using either a real or synthetic sequence of flows, generate the runoff envelope curve at the point of the most downstream impoundment (or a summation of several such points for multiple tributary reservoirs). The curve points used in determining this envelope curve must be identified with actual dates.

2. Plot cumulative average evaporation rates for each reservoir site, for the same periods which determine the runoff envelope (using representative average values between envelope points).

3. Treating all storage as concentrated at the most downstream point, compute the first trial system yield (by the method discussed later) and identify the critical period.

4. Apportion, on a trial basis, the yield to in-basin use and to export; also to subdivisions of the watershed.

5. Estimate the return flow, if any, below each point of storage. Both the amount and pattern of such flow below the last storage point are needed.

6. Using a trial usable downstream inflow, compute trial monthly values of usable downstream inflow for the same period as determined to be critical for

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[1I] Design of Water Resource Systems, Harvard Univ. Press, 1962, Chapter 12, p. 466 et seq.

[10] Maughan, W. D., and Kawano, R. T., Project Yields by a Probability Method, Jour. Hyd. Div. ASCE, May 63, pp. 41-60.

[11] Marks, C. R., Estimating Stream Flow from Point Runoff and Other Data, Paper presented at ASCE National Convention in Houston, Feb. 1962.

the storage. For maximum development of the watershed, this usable inflow is subject to the following equations:

$$Y_{WL} = Y_{SL} + RF + I_{UL} \tag{1}$$

$$I_{UL} = K(Y_{WL}) \tag{2}$$

Y_{WL} = Total Yield in lower watershed (below last storage point)

Y_{SL} = System Yield from storage reservoirs, which is allocated to lower watershed

RF = Return Flow

I_{UL} = Usable Inflow below last storage point

K = Estimated factor, less than unity to account for daily flow in excess of diversion capacity or pondage limits.

7. Iterate Step 6 until the above equations are satisfied.

8. Proportion the envelope curve flows at the last storage point to the other storage points and to intervening areas, obtaining envelope curves for each point.

Determination of Yield for a Single Reservoir

The entire optimization process is necessarily an approximation of limited accuracy, at least when used for planning purposes. If the process is to be applied to an actual operating system, it should include whatever refinements the degree of development and control justifies. Similar refinements may be justified in the advanced stages of planning. Until that point is reached, a simple approximate method of determining reservoir yield is desirable, and may in fact be necessary to reach any practical procedure for optimizing system yield.

For the above reasons it is suggested that reservoir yields used in optimization be determined by the following equation:

$$Y = \bar{I} + \frac{S}{T} - \bar{e}\bar{A} \tag{3}$$

Where Y = firm yield (acre-feet per month)

$\bar{I}$ = average monthly inflow over time T

S = useful storage = Smaximum - Sminimum

T = length of critical period in months

$\bar{e}$ = average monthly evaporation depth for time T

$\bar{A}$ = mean surface area for reservoir operated between Smaximum and Sminimum during time T.

The value of $\bar{I}$ is read directly from the envelope curve.

The value of $\bar{e}$ can be estimated fairly closely if the cumulative average values of $\bar{e}$ are plotted along with the cumulative average inflows used to obtain the envelope curve.

The value of $\bar{A}$ must, of course, be an approximation. Methods of estimating $\bar{A}$ were developed by the author[9] and are included in Appendix A.

To find the firm yield from the runoff envelope curve, the above equation is applied successively to a series of times T. The minimum value so obtained is the firm yield. An illustrative example is shown in Table 2. This is based upon the envelope curve of runoff, for Austin, as shown in Figure 2, in conjunction with illustrative values of S, $\bar{e}$, and $\bar{A}$. The yield obtained by this method will be approximate only to the extent of any error in estimating $\bar{A}$ and $\bar{e}$. It is believed that this approximation will not generally affect the components and operating procedures selected for the optimum system. After these components have been selected, the estimated values can be refined.

Optimum Yield From Combination of Reservoirs

CASE 1--Preliminary Determination.--As discussed in connection with runoff determination, the entire system storage may be considered as concentrated at one point for the first preliminary determination of system yield. In this case the storage volumes and average areas are merely added, and the mean evaporation depth is estimated. Maximum yield is then determined by equation (3) as for a single reservoir, using the runoff envelope curve for the flow at the most downstream point. This procedure is illustrated, in approximate form, by Table 2.

CASE 2--Multiple Reservoir Yield Used Entirely to Supply One Demand With No Other Supply.--This is a simplified case of an actual reservoir system. The yields are additive but the critical period cannot always be readily determined. Also, as shown in the previous illustrative example, a larger yield may be obtainable in some cases by emptying the reservoirs sequentially rather than drawing them down simultaneously.

Thus two basic strategies for optimizing system yield are indicated, namely:

Strategy I - All reservoirs emptied simultaneously.

Strategy II - Reservoirs emptied sequentially, the least efficient ones first.

Obviously there are many other strategies, some of which will be required because of local needs, relation of basin runoff to storage capacity and other factors. However, it is believed that ultimate system yields determined by these two strategies will define limits upon which more detailed strategies can be based.

The system yield by Strategy I can be obtained by merely adding values of Y from equation (3) month by month for all reservoirs in the system. Thus Ysum $= Y_1 + Y_2 + \ldots$ for each trial number of months. The minimum value of Ysum is

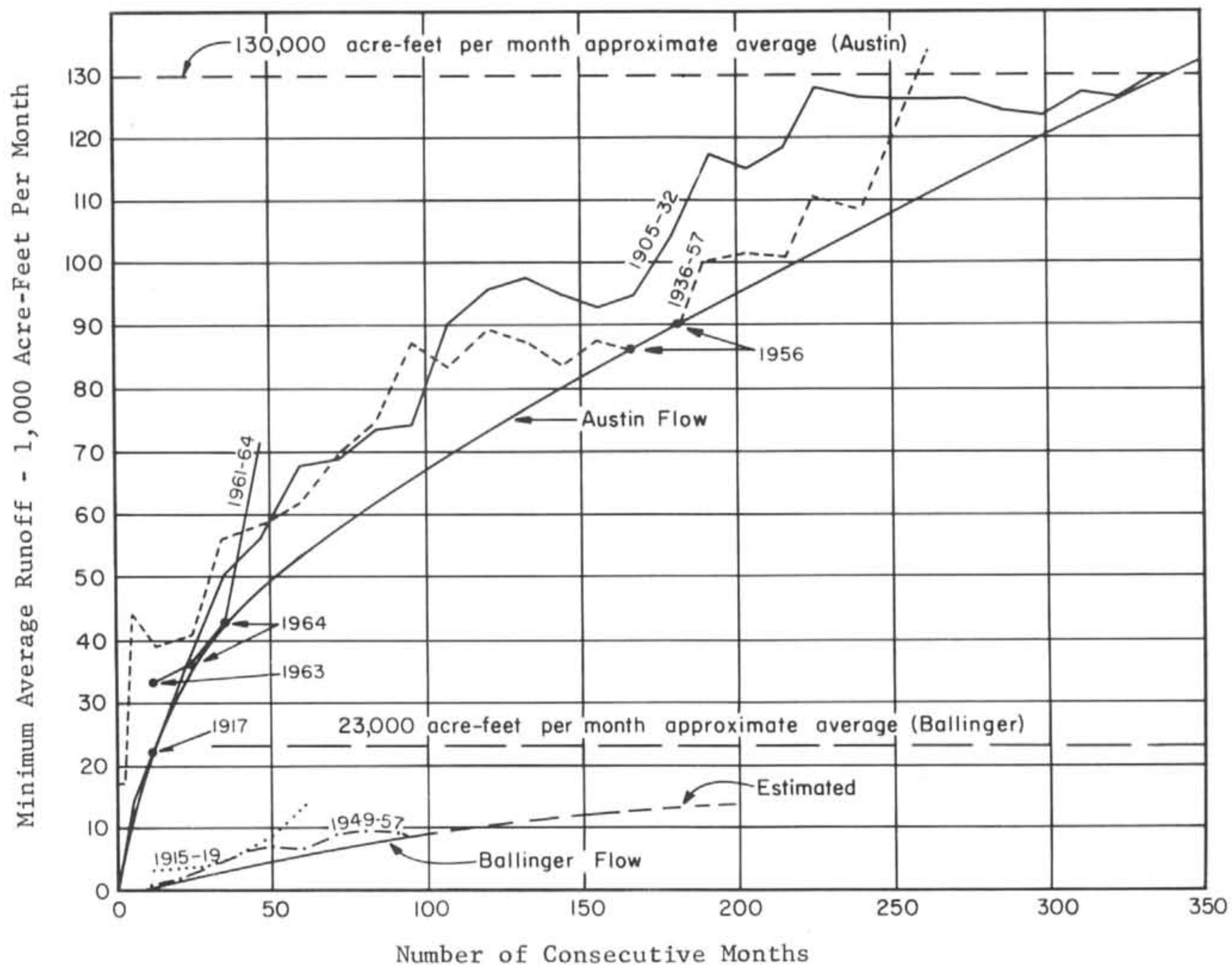

Figure 2

Typical Runoff Envelope Curve for Colorado River, Texas

TABLE 2.--FIRM YIELD OF HYPOTHETICAL SINGLE RESERVOIR ABOVE AUSTIN

Use of Austin Runoff Envelope Curve to Obtain Combined Watershed Yield

Assume: I) Total storage = 2,500,000 ac-ft
Average area = 30,000 acres
Average evap. = 3.6 ft/yr = 0.3 ft/mo

II) Add 1,000,000 ac-ft of storage capacity
Total storage = 3,500,000 ac-ft
Average area = 30,000 (3.4/2.5) = 42,000 acres
Average evap. = 3.6 ft/yr = 0.3 ft/mo

General Equation: $Y = \bar{I} + \frac{S}{T} - \bar{e}\bar{A}$

Time in months	Example I: $Y = \bar{I} + \frac{2.500}{T} - 9.0$			Example II: $Y = \bar{I} + \frac{3.500}{T} - 12.6$		
	$\bar{I}$	$\frac{S}{T}$	Y	$\bar{I}$	$\frac{S}{T}$	Y
10	20	250	261.	--	350	357.4
20	31	125	147.	--	175	193.4
30	39	83.3	113.3	--	117	143.4
40	45	62.5	98.5	--	87.5	119.9
50	49	50.0	90.0	--	70.0	106.4
60	53	41.6	85.6	--	58.3	98.7
70	57	35.7	83.7	--	50.0	94.4
80	60	31.3	82.3	--	43.7	91.1
90	63	27.8	81.8*	--	38.9	89.3**
100	67	25.0	83.0	--	35.0	89.4
150	82	16.7	89.7	--	23.3	92.7
200	94	12.5	97.5	--	17.5	98.9
250	107	10.0	108.0	--	14.0	108.4
300	120	8.3	119.3	--	11.7	119.1
350	130	7.2	128.2	--	10.0	127.4

* Firm Yield = 81,800 ac-ft/mo
= 981,600 ac-ft/yr

** Firm Yield = 89,300 ac-ft/mo
= 107,160 ac-ft/yr

the system yield,* and the corresponding number of months is the critical period for the system.*

The yield by Strategy II can be obtained using a trial system yield based upon some arbitrary increase above that obtained by Strategy I; this yield can then be applied to the system by emptying the reservoirs in a specified sequence and computing the emptying times for each. The runoff rate at the end of the total time must then be compared with the trial system yield. Successive trials may be necessary, increasing or decreasing the trial system yield according to whether it is smaller or larger than the runoff rate at the end of the total time.

It appears that a computer program can be developed readily to obtain yields first by Strategy I and then by Strategy II. The procedure can be applied to a series of storage increments and reservoir combinations. From these results it should be possible to plot approximate curves for system yield versus system storage.

The two strategies are illustrated in Figure 3.

CASE 3--Yields Allocated to Several Demands; Return Flow and Inflow Below Last Storage Point.--It appears doubtful a general procedure can be set up for this general case. Instead it is proposed to approach it as a process of successive refinements as discussed below. In most cases it will be helpful to apply one or all of the procedures described above as a first step in this process.

DETERMINATION OF OPTIMUM YIELD FOR AN ACTUAL WATERSHED

A. As the Sum of Individual Reservoir Yields Plus Inflow Below the Last Storage Point

The maximum yield of the watershed with a system of reservoirs can be obtained rather readily, so long as it is considered to be merely the sum of the individual reservoir yields, and so long as local demands upon individual reservoirs are of minor importance. Either of the strategies previously discussed, or a combination of them can be applied. In addition, an assumed operating rule may be necessary to apportion the releases between the various reservoirs. Two such rules are described in Reference 1, the first on pages 448-451, the second on pages 455-458. Using the simplified inflow curves and the method of yield determination previously described, it should be possible to program a computer to develop the watershed yields on this basis. For this condition the system yield is defined by equation (1); that is, it is the sum of:

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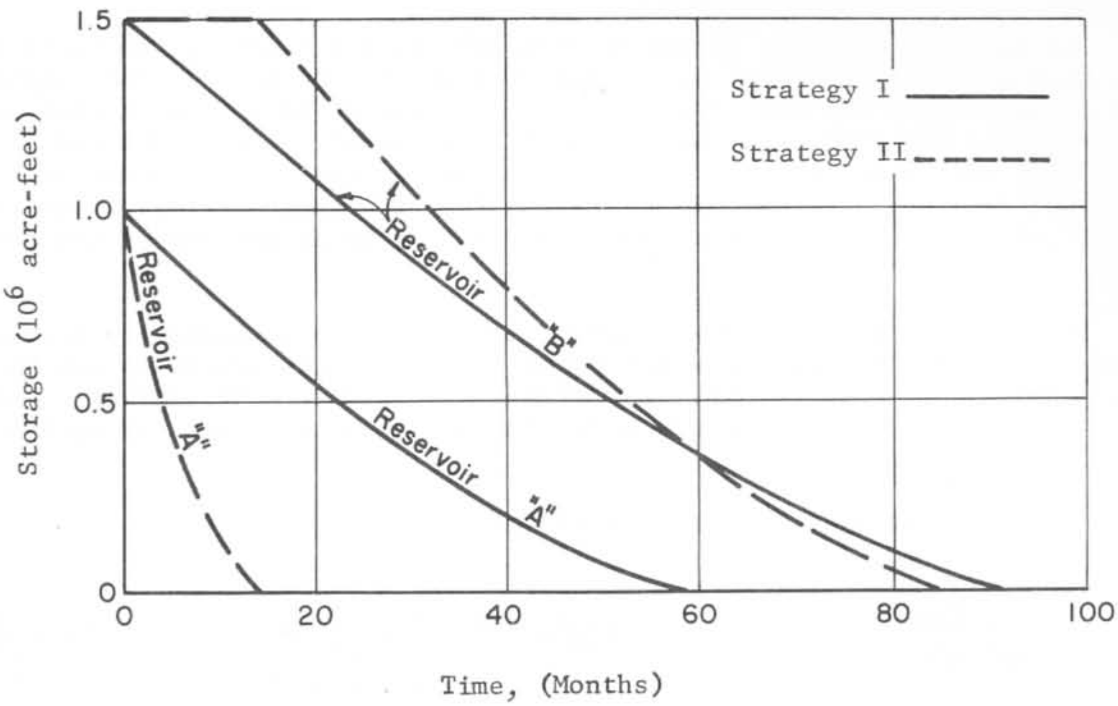
* These statements may not be precisely true in all cases, but it is believed they represent a sufficiently close approximation for the purposes required. In detailed application a more accurate expression of system yield may be desirable considering each reservoir to be emptied at the time when its yield up to that time is equal to the inflow rate at that time. This is illustrated on Figure 3.



A two-reservoir system equivalent to the single reservoir analyzed in Table 2 was analyzed. The data assumed for the two reservoirs are:

	Capacity (acre-feet)	Avg. area (acres)	Portion of total inflow
Reservoir A:	1,000,000	18,000	50%
Reservoir B:	1,500,000	12,000	50%

Average Evaporation = 0.3 feet per month

The results of the analyses are as follows:

	Res. A	Res. B	Total
Strategy I: Simultaneous Drawdown			
Number of months to empty	60±	90±	
Firm yield, 1000 acre-feet per month	37.8	44.6	82.4
Strategy II: Sequential Drawdown			
Number of months to empty	14±	71±	85±
Firm yield of system (1000 acre-feet per month)			86.5

Figure 3

Yield of a Hypothetical Two-Reservoir System Above Austin
(Using Austin envelope curve, Figure 2, to define the inflow)

(1) The system reservoir yield, plus

(2) The usable inflow plus return flow below the last reservoir. In order to obtain this yield it is necessary to vary the releases from storage, not only with the pattern of use, but in accordance with the amount of usable downstream inflow. For the approximate yield studies previously discussed it can be assumed that this variable release does not materially affect the reservoir yields. However, in the final step of analysis it will be necessary to introduce the variable release rates.

B. Adaptation to Other Factors

It appears probable that watershed yield on the basis described above should be obtained first for almost any reservoir system. Doing this will establish certain working limits within which further adjustments can be made. Such adjustments can reflect local demands, water rights, and several other factors. Each of these would impose further constraints on the releases and operating rules. In many cases the system operation of certain reservoirs in the watershed must partly or wholly be subordinated to local use. However, in the planning process it may be desirable to determine the difference in system yield which would result if such reservoirs were operated so as to maximize system yield, rather than to be subordinated to local use.

A tentative set of generalized rules for apportioning releases between reservoirs will be needed as part of the adaptation of the system to other factors. These may include provisions for creating vacant storage space where the probable runoff is such that it might otherwise spill and be lost. When these rules have been formulated it may be necessary or desirable to program a second approximation of the system yield before proceeding with the economic optimization of the system.

C. Economic Optimization

The procedure for economic optimization has not been studied in detail. However, it appears that after the yields from several alternate reservoir systems have been separately maximized, reservoir cost factors can be introduced. The alternate systems can then be compared, either on the basis of water costs or on the basis of benefit-cost ratios. In complicated systems it may be desirable to make an economic optimization by the "response surface" and "steepest ascent" procedure previously mentioned.[1G]

D. Selection and Analysis of the Final System

All of the studies described above can be considered as preliminary to the selection of the final system on which the optimum watershed yield should be based. Selection of this system will require several types of decisions, many of which can only be made on generalized economic, political, and legal bases. Such decisions will involve the allocation of yields between different portions of the watershed, between competing uses, and the further decisions on degree

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[1G] *Op. cit.*

of security to be provided against risk of less than full yield during periods of extreme drought. In some instances the decisions may be based principally upon obtaining the system which optimizes the benefits. In other cases the feasible cost or value of water in each portion of the watershed will also enter into the decisions.

A possible aid in making these decisions was discussed by Professor Percy H. McGauhey, at the Seminar on Management of River Basins. Mr. McGauhey described an approach used in California--this he described as an "input-output" approach. It involved dividing the economy into sectors, both as to type of production and geographical location. Procedure from that point was to supply a use of water into any one of these sectors; to determine what related development would occur in the other sectors; and in turn what water requirements would be generated in these other sectors.* The total spectrum of water requirements, or series of spectra thus generated then would serve as a basis for apportioning the water use between the several sectors, so as to provide the optimum development for the overall economy of the region. Whether such a sophisticated approach can be used in the near future in Texas may be questionable. However, some basis for allocating water supplies between different areas of the State and different uses must be made by the time water shortages become acute, whether such shortages be produced by the physical lack of water, or by the high cost of supplying local deficiencies from remote sources.

In any event, after the above decisions have been made, the previously described approximate yield determinations can be refined in the light of the system selected and with the yield allocations finally decided upon. It is believed that in many cases this final determination will be merely a refinement of previous ones, and that with the experience gained in making these studies, the final determination can be made without a great deal of effort.

In many cases it will be necessary or desirable, after the system and the allocation of yield is well defined to make a final "proof" operation of the system. This will probably be a complete simulated operation, using some modifications of actual historical flows, together with actual evaporation rates, variable demands, losses in transit and all pertinent factors. It appears probable that the procedure developed for the Nile River by Morrice and Allan[8] could be utilized at this stage.

SUMMARY OF COMPLETE PROCEDURE

Appendix B shows a schematic diagram of the entire suggested optimization procedure. It is in the form of a flow chart of the type used as an initial step in writing a computer program. However, this chart is a combined one for operations by man and by computer. The computer is visualized in this case as a highly developed calculator, which performs routine computations to aid the man in reaching decisions.

Only in the final step is an elaborate machine program required. It is believed that one of the programs previously discussed could be adapted at this

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* See also <u>Scientific American</u> for April 1965.

[8] Morrice, H. A. W., and Allan, W. N., Planning for the Ultimate Hydraulic Development of the Nile Valley, Proc. Inst. Civil Engrs. 14, 1959, p. 101.

stage. The purpose of this final step is to demonstrate that the simplified models of runoff, evaporation, and reservoir operation used in the optimizing process will give results substantially in accordance with conventional detailed simulated operation based upon a repetition of real events.

Although several of the operations shown on the chart have not been studied in detail, it is believed that they can be successfully developed. When this is done it would be possible to apply the complete procedure to a watershed reservoir system, and obtain the following results:

1. Maximum theoretical system yield based upon several trial combinations of individual reservoir locations and amounts of storage and upon alternate operating strategies.

2. Economic comparisons between the several reservoir combinations for which maximum system yield has been determined.

3. Use of maximum yield and economic comparisons to select an actual reservoir system which will best meet both local and system water uses.

4. A detail "print-out" showing the operation of the finally selected system, during the repetition of a representative series of historical runoff and evaporation events, combined with projected water demands and with estimated modification of watershed characteristics.

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APPENDIX A

DETERMINATION OF APPROXIMATE AVERAGE AREA AND EVAPORATION FACTORS (EXCERPTS FROM REFERENCE 9)

1. General Discussion and Notation

All of the derivations are based upon the following empirical formulas for the area, A, and volume, V, of a reservoir, expressed in terms of its depth, d:

$$A = Kod^{m} \tag{4}$$

$$V = K_1 d^{n} \tag{5}$$

In these formulas the depth is measured in feet above a base elevation to be determined, A is expressed in acres, and V in acre-feet. The exponents m and n, and the coefficients Ko* and K_1*, are determined for each reservoir as described later on. Note that Ko and K_1 are not dimensionless coefficients; their units depend upon the values of m and n.

Formulas (4) and (5) can be made to apply accurately to reservoirs for which the area and volume curves plot as straight lines on log-log paper. For many reservoirs such plots will approach straight lines for at least a part of the depth range, and these formulas will apply accurately within such a range; others may plot as several straight line segments of different slope. In the latter cases formulas (4) and (5) can only approximate the actual conditions by adopting the average slope of the several segments. However, the effect of such an approximation may be surprisingly small as affecting the yield of the reservoir, particularly if this average slope is determined over the range of drawdown for which the yield is to be determined.

2. Determination of Exponent n

Approximate values are shown on Figure 1(a) and (b) of this Appendix. More accurate values can be obtained by the procedure indicated below.

Using formula (6), $n = \frac{Ad}{V}$, the values of n for several trial values of Eo (base elevation) are worked out in the following table.

GIVEN			COMPUTE	TRIAL SOLUTIONS							
				Trial 1 Eo = 50		Trial 2 Eo = 55		Trial 3 Eo = 60		Trial 4 Eo = 58	
E_1	A	V	A/V	d	n	d	n	d	n	d	n
94	21 000	302 000	.0695	44	3.06	39	2.82	34	2.37	36	2.50
90	17 500	225 000	.0780	40	3.13	35	2.74	30	2.35	32	2.49
80	9 500	90 000	.108	30	3.24	25	2.70	20	2.16	22	2.38
74	6 000	41 000	.164	24	3.92	19	3.12	14	2.30	16	2.62

Using the last column, n = 2.5.

* Not required for the purposes of this discussion.

3. Determination of Approximate Average Area

In the absence of detail operation studies, it may be assumed that the average area for any low-flow period is that which corresponds to the average volume, defined as:

$$\overline{V} = \frac{Vmax + Vmin}{2}.$$

Substituting K_2 Vmax for Vmin,

$$\overline{V} = Vmax\,\frac{(1 + K_2)}{2}. \tag{7}$$

$$\text{Now } \overline{d} = \left(\frac{\overline{V}}{K_1}\right)^{\frac{1}{n}}, \text{ from (5),}$$

$$\text{and } \overline{A} = \frac{n\overline{V}}{\overline{d}},^{*} \text{ from (6).}$$

Substituting in the above from equations (7) and (5),

$$\overline{A} = n\overline{V}.\left(\frac{K_1}{\overline{V}}\right)^{\frac{1}{n}} = nK_1^{\frac{1}{n}}.\ \overline{V}^{(1 - \frac{1}{n})}$$

$$= nK_1^{\frac{1}{n}}\ Vmax^{(1 - \frac{1}{n})}\left(\frac{1 + K_2}{2}\right)^{(1 - \frac{1}{n})}. \tag{8}$$

In a similar manner,

$$Amax = nK_1^{\frac{1}{n}}\ Vmax^{(1 - \frac{1}{n})}, \text{ or } Vmax^{(1 - \frac{1}{n})} = \frac{Amax}{nK_1^{1/n}}.$$

Substituting the above value of $Vmax^{(1 - \frac{1}{n})}$ in equation (8),

$$\overline{A} = Amax\left(\frac{1 + K_2}{2}\right)^{(1 - \frac{1}{n})}. \tag{8'}$$

A chart for solving Equation 8' is found on Figure 1(c) of this Appendix.

DETERMINATION OF RESERVOIR EFFICIENCY FOR MINIMIZING EVAPORATION

It is sometimes desirable to compare the relative efficiency of two or more reservoirs with respect to their ability to minimize evaporation losses, all other factors being equal. It is obvious at once that the reservoir affording the greatest depth for the same storage volume will generally be most

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* Obtained from equations (4) and (5) by differentiating (4) and substituting in (5).

n = 2 n = 2-1/3 to 2-1/2 n = 3 n = 3-1/2 to 4

Figure 1(a)

n Values for Characteristic Reservoir Cross Section Shapes

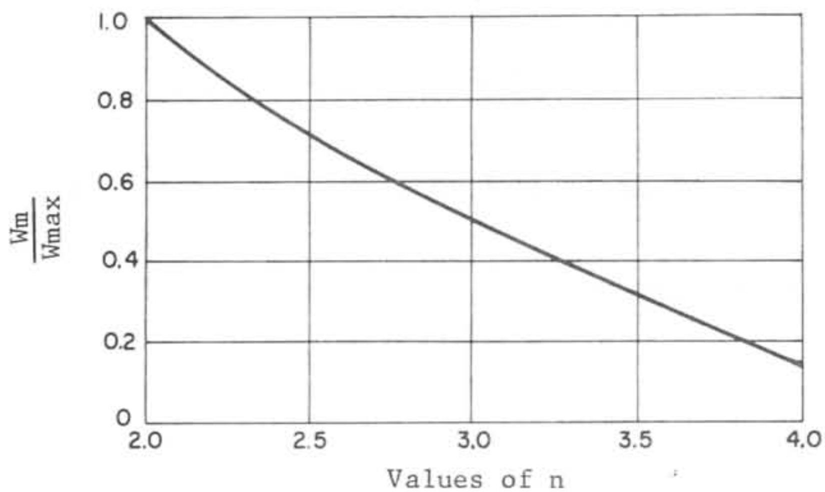

Figure 1(b)

n Values in Terms of $\frac{W_m}{W_{max}} = \frac{\text{Reservoir width at mid depth}}{\text{Reservoir width at full depth}}$

NOTE: If A_{max}, V_{max} and d_{max} are known, $n = \frac{A_{max} \cdot d_{max}}{V_{max}}$

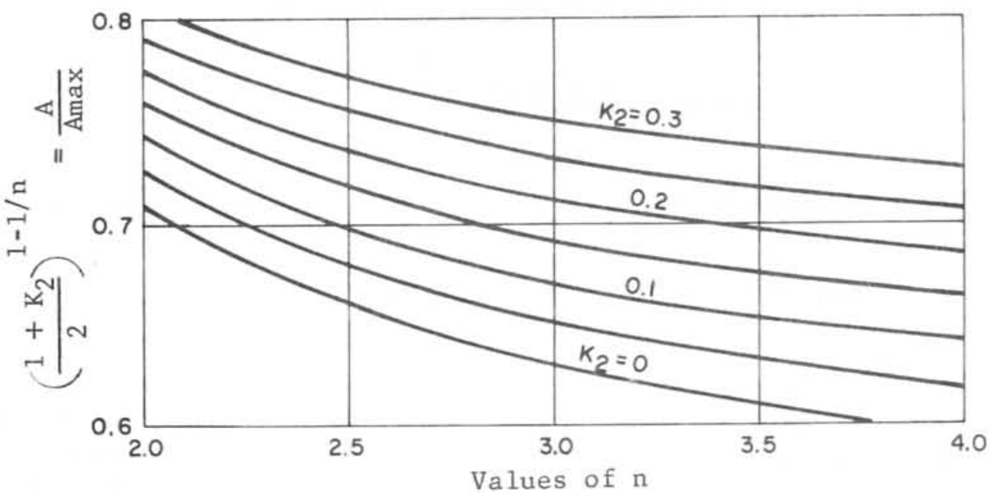

Figure 1(c)

Average Area in Terms of Amax, Amin and n efficient, but the effect of other physical characteristics is difficult to evaluate without detailed studies, and since the other factors are seldom in fact equal, such studies would have to be made especially for this purpose, using hypothetical values of inflow, evaporation, and amounts released, so chosen as to be equivalent for the reservoirs being compared.

An unexpected dividend provided by the method of analysis developed herein is a means of measuring relative reservoir efficiency directly from the reservoir properties alone; in fact, for reservoirs of the same depth, the relative evaporation loss is found to depend only on the exponent n and the dead storage ratio K_2, as developed below.

Let the term EF represent the evaporation factor for a reservoir, this factor being defined as the ratio of total evaporation loss to the effective storage volume. Then using the previous notation

$$EF = \frac{\bar{A}\sum e}{Vmax(1 - K_2)} \tag{9}$$

$$\text{but, } \bar{A} = Amax\left(\frac{1 + K_2}{2}\right)^{(1 - \frac{1}{n})}, \text{ Equation (8'),}$$

$$\text{and } \frac{Amax}{Vmax} = \frac{n}{dmax}, \text{ From Equation (6).}$$

Substituting in (19),

$$EF = \frac{n\sum e\left(\frac{1 + K_2}{2}\right)^{(1 - \frac{1}{n})}}{dmax\ (1 - K_2)} \tag{10}$$

If $\sum e$ and dmax are taken as equal for two or more reservoirs, the <u>relative</u> evaporation factor, denoted by EF' is EF x $\frac{dmax}{\sum e}$, or

$$EF' = \frac{n\left(\frac{1 + K_2}{2}\right)^{(1 - \frac{1}{n})}}{1 - K_2} \tag{11}$$

Values of EF' are shown below for K_2 = 0.1 and 0.3 over the full range of n, together with the ratio of EF', in each case, to its value for n = 2.

	Values of n				
	2	2-1/2	3	3-1/2	4
EF' for K_2 = 0.1	1.659	1.939	2.237	2.531	2.844
Ratio to value for n = 2	1	1.17	1.35	1.53	1.72
EF' for K_2 = 0.3	2.303	2.757	3.214	3.670	4.137
Ratio to value for n = 2	1	1.19	1.39	1.59	1.79

SYSTEM OPERATION OF RESERVOIRS TO OBTAIN OPTIMUM YIELD DURING DROUGHT[a]

Discussion by Olen Rucker

OLEN RUCKER.[b]--This subject is indeed a large one and the writer appreciates the necessity of limiting its scope. He will therefore add to the presentation additional thoughts rather than consider analytically the procedures set forth by the author. The comments, which will not necessarily be within those limits, are, however, pertinent to planning a water supply system.

The writer would first like to discuss three often-used terms which appear in the title--optimum yield, yield, and drought. Optimum denotes best for limits imposed and desired results. This term, unless preceded by hydrologic or some other limiting term, must include all costs and all benefits. Use of the term yield has been modified by the words firm, safe, average, etc., each with a specific meaning such that the word by itself becomes questionable. Drought, being the key word for discussion, has already been amply described. The writer would like to add, though, a prerequisite to determining a period of drought as it is used in this paper. A period of drought in this sense, only becomes defined as a result of hypothetically operating a water supply system through a historic or synthetic sequence of supply and demand events.

The author states that to date no one has developed a comprehensive program of general application for planning purposes. The writer wishes to add that no one should. The variables are too complex. This does not mean that we cannot, though, develop programs for computational solution within the social, economic, legal, and technical constraints imposed on a specific region or study area. In fact, defining these constraints are a major problem of any planning effort. We, as engineers, often busy ourselves with problem-solving techniques before we are fully aware of what the problems are. When the constraints are defined, the problems come to light and most often appear even larger than we first imagined. But we know then where they are and what they are and we can attack them head-on rather than groping in the dark, hoping to stumble over the problems and accidentally knock them out.

Although it was necessary to limit the scope of the paper, the writer would like to add a comment about agricultural uses. The agriculture industry which in Texas in 1962 used 86 percent of the total water used for purposes other than hydroelectric power and cooling water for thermal electric plants is being given extensive and complete consideration in the Texas Water Commission's present planning effort. Contrary to traditional assumptions, there is growing evidence that irrigated agriculture can compete with other industries for purchase of water.

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[a] By C. R. Marks.

[b] Head, Surface Water Hydrology Planning Task Group, Texas Water Commission, Austin, Texas.

In regard to water rights, any plan must be formulated within the framework of law existing at the time the plan is to be adopted. The planners, having developed a plan adequately flexible for adjustment to reasonable changes, should in this State feel confident that future legislation, constitutional amendments, judicial interpretations, and administrative policy will tend to implement and compliment the plan. The surface water unit of the Texas Water Commission will in its present planning effort consider existing water rights in hydrologic studies.

The proposition is submitted by the author that in some areas of the State the need for maximum reasonable development of its water supplies may virtually rule out questions of economy as a factor in optimization. Recently, water was drunk by space pilots while orbiting the earth. If the whole purpose of the flight had been to deliver a drink of water to some location in outer space, that drink would no doubt have been the highest priced water ever delivered to a consumer. The point is--fresh water may be had anywhere, in some quantity and and at some cost. If water must be had then all beneficiaries of the supplying system should be willing to participate in the financing. The beneficiaries are not limited to only those consuming the water. They may include the Federal Government, the State of Texas, or a city near a reservoir that is benefited by its recreational facilities. The value to tourism or to the agricultural or other industrial production may be deemed benefits accruing to the State as a whole. However, those engineers who have worked as staff employees or as consultants for cities or water supply districts and authorities are well aware that the only benefits that appear on debt service and amortization schedules are those benefits which are represented by predictable tax and revenue receipts. A major problem of planning a water supply system is in devising means of converting tangible and intangible benefits to predictable income.

This, then, returns us to maximizing benefits within imposed legal and financial constraints and the effect of limiting an optimizing study to a drought period. If a conclusion is drawn as to optimum development based on maximum yield of a system during a drought period, benefits will not have been maximized and the validity of a proposed plan as being optimum may be false.

In summation, the following are submitted for consideration in planning any water supply system:

1. Establish present and future needs.

2. Study all possible alternatives for supplying the needs.

3. Determine all costs accruing to and all benefits that may be derived from each alternative.

4. Estimate the dollar value of each benefit.

5. Determine which benefits can be used to satisfy debt service requirements.

6. Establish financial and legal constraints of all participating entities and maximize benefits within those limits.

7. Select the plan that is best for limits imposed and desired results; then sell it and don't look back.

SYSTEM OPERATION OF RESERVOIRS TO OBTAIN
OPTIMUM YIELD DURING DROUGHT[a]

Discussion by Walter L. Moore

WALTER L. MOORE,[b] M. ASCE.--The title of Mr. Marks' paper, "System Operation of Reservoirs to Obtain Optimum Yield During Drought," suggests to me four different areas of optimization. The first is concerned with the operation of a given reservoir system and hence with the operating rules which will optimize the yield for that system. The second is the planning and design of a system to optimize yield. The third and fourth are concerned with what "yield" is to be optimized. In its more restricted sense yield may refer simply to the quantity of water made available during the drought period and its optimization is the third area of concern. The fourth involves a more general concept of yield considering it in relation to different possible uses. In the latter case optimization of yield would require maximization of some measure of economic net benefit.

Mr. Marks' paper will be discussed in relation to the four areas just described.

First let us acknowledge that we are dealing with an extremely complex problem and no one has yet worked out a method to solve it in all its complexities.

If we are to make progress in developing methods to handle the complexities of the optimization problem, it will be helpful to keep a clear distinction between the first two areas mentioned, the optimum operation of a given system by choice of operating procedures, and the optimization of a proposed system while still in the planning stage. The operation procedures for a given system provides rules governing the apportionment of storage and release of water among the reservoirs in the system, among the various uses, and among the time periods.[1]

The example in Marks' paper, showing how the yield of a hypothetical two-reservoir system (reservoirs A and B) was increased by drawing first from the shallow reservoir A until it was empty and then from reservoir B, shows how operating rules can affect the yield. In this case the yield was for a single purpose and so a simple maximization of the quantity of water represented the optimum yield. In such a case the optimization of yield is the same as the minimizing of all losses, the greatest of which is evaporation.

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[a] By C. R. Marks.

[b] Professor and Chairman, Department of Civil Engineering, The University of Texas, Austin, Texas.

[1] Design of Water Resource Systems, Harvard Univ. Press, 1962, p. 443.

with a fixed operating procedure. The operating procedure developed for that system is described in Chapter 7 of Reference 1. The point to emphasize here is that the two areas of optimization are carried out separately. It is true of course that the operating procedure will affect the optimization of the reservoir system and the characteristics of the system will affect the optimum operating procedure. However in optimizing the system design the operating procedure must be held constant while in optimizing the operating procedure the system design must be held constant. Actually less has been done on optimizing operating procedure than in optimizing system design.

Some additional work to develop operating procedures to maximize yield would seem to be fruitful. In such studies yield should be considered in its more general sense and measured in terms of economic net benefits for the multiple uses of water rather than in terms of maximum yield of water only. The allocation as between various uses would be an important part of the operating rules.

The development of methods for optimizing the design of a system of reservoirs, and of improved methods for operating systems of reservoirs for maximum net benefits, is of great potential value because of the large number of water resources systems that will be built in the near future.

DETERMINATION OF RESERVOIR YIELD FOR DROUGHT PERIODS

DETERMINATION OF RESERVOIR YIELD FOR DROUGHT PERIODS

By William H. Sims,[1] M. ASCE

INTRODUCTION

This discussion on reservoir yield determinations will be limited to the situation where a single surface water supply reservoir must furnish all water needs of an area. This situation is not uncommon in Texas. Many localities depend upon a single reservoir supply or a single reservoir plus a supplemental supply that is undependable, of undesirable quality, or both. Since by definition, this single reservoir is to meet an area's water needs, it could conceivably serve for any one, several, or all, of the legally recognized water uses.

THE YIELD COMPUTATION

Computations involved in the determination of reservoir yields are notoriously simple. Involved is merely the repetitive solution of the well-known storage equation, i.e., the change in reservoir content during a period is equal to the reservoir gains reduced by the reservoir losses during the period. The reservoir gain is the inflow. It could be composed of direct runoff, spring and ground water flow, return flow, and rainfall on the lake surface. Reservoir loss is any water removed from storage for the selected usage situation. It could consist of direct diversions from the reservoir, natural or induced evaporation losses, or releases into the downstream channel for any purpose such as for reservoir regulation, downstream users, or satisfaction of downstream rights.

If the relationship between reservoir capacity and reservoir yield is desired, the storage equation is solved backwards in time, beginning with a depleted reservoir at the end of the study period. If the critical drought period is known, the computation can be shortened by beginning at its end. The maximum reservoir content produced during coverage of the full period of the data indicates the amount of storage capacity that would be required to supply the selected demands imposed upon the reservoir. This series of computations is generally referred to merely as "Yield Computations." A graphical plot of a series of these determinations, i.e., reservoir content versus reservoir yield, will produce the "Yield Curve." An example of a yield curve for a Central Texas reservoir is shown on Figure 1.

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[1] Hydraulic Engineer; Associate, Forrest and Cotton, Inc., Consulting Engineers, Dallas, Texas.

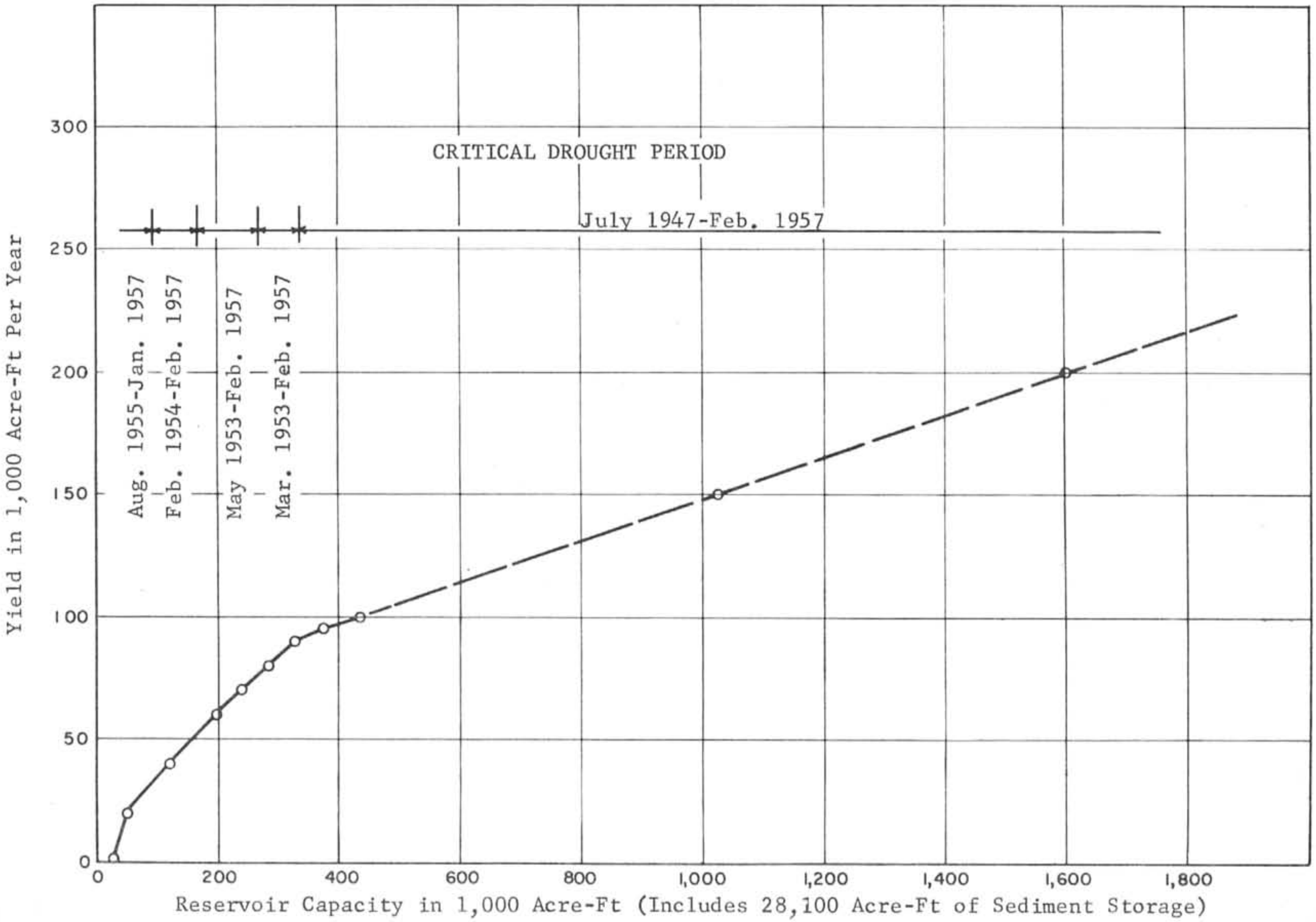

Figure 1
Yield Curve

The yield computations and the yield curve are elemental in hydrologic evaluations of reservoir sites. Assuming that the period of data records used in the yield computations is a representative sample of a hydrologic cycle, then the yield computations indicate the critical drought period associated with particular reservoir storage capacities. The short extremely severe drought period, usually found to be the driest summer, will be found to be critical for the small project. A moderate sized reservoir would contain sufficient carry-over capacity to bridge the short drought, and possibly a 12 to 18-month period would be critical. Projects large enough to essentially control the available resources of the stream have been found to have 3 to 4-year critical drought periods in the eastern parts of the State, and 10 or more years in the hill country and farther west.

While yield computations are run in reverse with respect to time, the "period of record routing" is run normal to the timing of the data. It produces what could be termed a hypothetical operation of the reservoir under study. An example of a typical period of record routing computation is shown on Table 1. It gives monthly details of reservoir gains and losses, and the end-of-month content. This computation is of particular interest to several different types of reservoir users. The electric utility company that plans to construct a generating plant on the lake to use its water for condenser cooling would be greatly interested in the average and the minimum lake stages and their effects on pumping heads, and on average and minimum lake surface area for its cooling efficiency. Those concerned with lake-side recreational developments are always concerned with possible fluctuations in lake stages. This information would be indicated by the period of record routing. Barring the exception that is necessary to prove the rule, reservoir storage capacity sufficient to produce a dependable yield of from 60 to 70 percent of the long-time average run-off at the dam site provides about the maximum practicable control that can be obtained.

Many consulting firms and governmental agencies involved with water resource studies have found it feasible to use the electronic computer for the yield computation and the period of record routing. Where the engineer's skills and talents are required is in the preparation of the inflow and evaporation data, and the selection of the ground rules that are to apply to the reservoir under study.

By generalizing to some extent, all problems involved in the single reservoir yield determination can be grouped under four headings. These subjects are (1) purpose of the reservoir, (2) analyses of water rights, (3) sediment allowance and sediment distribution within the reservoir, and (4) derivation of inflow and evaporation data for historical and future conditions.

PURPOSE OF THE RESERVOIR

Texas laws dealing with the conservation and utilization of water declared to be the property of the State, sets forth a priority of each type of use with respect to another. These priorities, which are to be followed in the allotment and appropriation of the waters, are as follows:[2]

[2] Art. 7471, Vernon's Civil Statutes.

TABLE 1.--PERIOD OF RECORD ROUTING

[SHOWN ON SLIDE AS FIGURE 2]

RESERVOIR OPERATION NO. 1

DATE	INFLOW ac.ft.	DEMAND ac.ft.	EVAP feet	AREA acres	LOSS ac.ft.	SHORTAGE ac.ft.	SPILLS ac.ft.	CONTENT ac.ft.
Jan	9153	4693	.04-	8552	343-	0	2449	155000
Feb	24582	4693	.03-	8600	259-	0	20148	155000
Mar	4799	4693	.39	8471	3303	0	0	151803
Apr	36963	4693	.09	8535	768	0	28305	155000
May	35103	5364	.15	8600	1290	0	28449	155000
Jun	16933	6704	.26	8600	2236	0	7993	155000
Jul	91896	7375	.32	8600	2751	0	81770	155000
Aug	35821	7375	.67	8600	5762	0	22684	155000
Sep	51141	6705	.30	8600	2579	0	41857	155000
Oct	19649	5363	.57	8600	4901	0	9385	155000
Nov	4444	4693	.53	8410	4457	0	0	150294
Dec	1706	4694	.35	8173	2860	0	0	144446
1950	332190	67045	3.56		30305	0	243040	
Jan	2802-	4693	.19	7856	1492	0	0	135459
Feb	5949	4693	.01-	7888	79-	0	0	136794
Mar	3980	4693	.28	7818	2189	0	0	133892
Apr	3015-	4693	.28	7388	2068	0	0	124116
May	12585	5364	.08	7740	619	0	0	130718
Jun	39445	6704	.06	8108	486	0	7973	155000
Jul	4765	7375	.74	8248	6103	0	0	146287
Aug	4624	7375	.80	7899	6319	0	0	137217
Sep	8666	6705	.58	7836	4544	0	0	134634
Oct	3337	5363	.52	7630	3967	0	0	128641
Nov	4014	4693	.27	7486	2021	0	0	125941
Dec	3145	4694	.27	7304	1972	0	0	122420
1951	84693	67045	4.06		31701	0	7973	
Jan	1271	4693	.18	7088	1276	0	0	117722
Feb	2953	4693	.15	6954	1043	0	0	114939
Mar	1201	4693	.17	6717	1142	0	0	110305
Apr	8094	4693	.14-	6941	972-	0	0	114678
May	42011	5364	.10	8417	841	0	0	150484
Jun	5768-	6704	.75	7776	5832	0	0	132180
Jul	2017-	7375	.82	7055	5784	0	0	117004
Aug	8242	7375	1.09	6728	7334	0	0	110537
Sep	1004	6705	.76	6145	4670	0	0	100166
Oct	857-	5363	.73	5377	3925	0	0	90021
Nov	8432	4693	.17-	5727	974-	0	0	94734
Dec	2670	4694	.08-	5606	449-	0	0	93159
1952	67236	67045	4.36		29452	0	0	

1. Domestic and municipal uses

2. Industrial uses, defined as "Waters to be used in processes designed to convert materials of lower order of value into forms having greater usability and commercial value, and to include water necessary for the development of electric power by means other than hydro-electric."

3. Irrigation

4. Mining and recovery of minerals

5. Hydro-electric power

6. Navigation

7. Recreation and pleasure.

It is common practice to consider all treated water delivered through a municipal distribution system to be for municipal uses. Industrial water then becomes the water used by manufacturing industries, including thermal-electric power generation, which does not pass through the ordinary municipal water treatment and distribution system. Most reservoirs permitted in recent years have been for the dual purposes of municipal and industrial. When such a reservoir is the only source of supply for an area, every effort should be made in the hydrologic analyses to assure that yield estimates are safe and dependable. In water supply planning for municipal and industrial uses, no justification is seen for use of a "drought period frequency" approach to yield determinations. To do so, merely implies that rationing is contemplated, and the industrial user can only feel that its supply will be curtailed first and that it will suffer most. From the viewpoint of the municipality, the Water District, or whatever agency is in control, its water planning activities should recognize that industrial users deserve the same security of supply as do municipal users. An area is in a poor position indeed in its competition with other areas for new industries if this is not reflected in its water plans.

If the reservoir project under study includes irrigation or any other lower priority use, as well as municipal and industrial, a water accounting system, or rule curve, should be developed as a part of the reservoir yield determinations. If the project is large enough to justify the multiple uses, operating rules can be developed that will make the municipal and industrial portion of the project yield just as firm and secure as it would have been without the lower priority usage. The Bureau of Reclamation's "San Angelo Project" is cited as an example of a multiple purpose project containing irrigation as an authorized use. The contract between the agency responsible to the city and the agency responsible to the irrigators defines a water accounting system for reservoir operation that insures a firm supply for municipal and industrial uses and an irrigation supply in sufficient quantity to profitably irrigate 10,000 acres. Although the San Angelo Project involves three reservoirs, the principles involved would apply equally as well to a single reservoir.

ANALYSIS OF WATER RIGHTS

The term "Areal Yield" has been used in reference to the yield of a project if it had no obligation to release water in satisfaction of superior downstream rights. Areal yield values are useful in the hydrologic analyses of the reservoir. It provides a guide in the determination of the maximum practical size for a reservoir at the particular site under study.

It was not until recent years that planners of the single project located in the headwaters of a stream or on a tributary encountered opposition from lower basin appropriators in their efforts to secure a water permit from the Texas Water Commission. It should be remembered that storage and diversion rights in recent years are granted only to apply to "surplus storm and flood waters" and that between appropriators, the first in time is the first in right. The exception is the untested law enacted in 1931 subordinating all future permits for industrial or lower priority uses to municipal needs.[3]

There are often varied opinions, even among experts, as to the extent of the rights conveyed by many early permits and certified filings. Nevertheless, it becomes the duty of the engineer to evaluate all superior downstream rights and compare the results with the available supply at their point of diversion. If a shortage is indicated during periods of inflow at the reservoir, the downstream appropriator is entitled to that water up to either the extent of his right, or to the amount that he can put to a legal beneficial use. It will often be found that adjustments made for downstream rights will have only an insignificant effect on the firm areal yield because the deficiencies occur when the inflow to the reservoir under study is small, or even zero.

A large downstream storage project can create a critical situation for the upstream reservoir because its rights are considered to include the right to be kept filled at all times. Although harsh, this is not an unreasonable position to be taken by owners of the downstream reservoir because each time drawdown begins, it is not known but that a new critical drought period has begun. The best solution to this situation is an agreement providing for the operation of the two reservoirs so as to optimize the control of the resource for the benefit of both parties.

SEDIMENT ALLOWANCE AND SEDIMENT DISTRIBUTION WITHIN THE RESERVOIR

The present policy of the Corps of Engineers is to provide capacity for storage of 100 years of sediment accumulation. This is because justification for their projects is determined from an analysis of 100-year benefits and costs. It is customary for state agencies and municipalities to allow for 50 years of siltation, and firm yield computations assume a capacity situation that will exist at the end of the 50-year period.

The best known source of information on the sediment yield of a watershed is Bulletin 5912, entitled "Inventory and Use of Sedimentation Data in Texas" prepared by the Soil Conservation Service for the Texas Board of Water Engineers, dated January 1959. This bulletin gives the relationship between drainage area and sediment yield for the various land resource areas in the State. In using these data to develop the design period sediment volume, appropriate credit may be given to the sediment retention capacity of the Soil Conservation Service's floodwater retarding reservoirs in the watershed. These SCS projects

[3] Art. 7472, Vernon's Civil Statutes.

normally contain a sediment pool sufficient to contain a 50-year sediment volume. The silt trap efficiency of the project is taken as unity.

For purposes of yield determinations, there are several different assumptions that can be made as to where within the reservoir that the sediment will be deposited. It is obvious from inspection of many existing reservoirs that a substantial amount of the sediment load is located at the upper end, and it is often visible as a delta extending into the lake. There are other instances where much of the sediment is of grain sizes small enough to remain in suspension until well within the main body of the lake before settling.

The most severe assumption with respect to the effect on the project yield is that the sediment will occupy the lowest level in the reservoir. Although it is inconceivable that all sediment entering a lake will be deposited in a level pool at its deepest part, the use of this assumption in yield determinations is often practiced because it produces values felt to be conservative and safe. It would tend to offset those unknown factors which are not accounted for in the yield determination such as seepage and deep percolation losses, and transpiration losses. In areas susceptible to salt cedar infestation, transpiration losses can become substantial if their growth is not controlled.

The other extreme is produced by adjusting both the capacity and the area curves to reflect capacity assumed lost to sedimentation. This procedure could produce overly optimistic yields because the loss in surface area to delta formation does not necessarily result in a proportional reduction in evaporation loss. Vegetative growth on the delta can become dense, and transpiration and evaporation losses can equal or exceed the evaporation loss from a free water surface of equal size.

A third method frequently used is one which includes an adjustment to the capacity curve but none to the area curve. Still another method assumes deposition at a uniform depth over the reservoir bottom which merely raises the datum of the area and capacity curves.

Yield variations of up to 25 percent have been noted between different assumptions as to nature of sediment deposits. On extremely large projects such as Livingston Reservoir on the Trinity River, different assumptions as to nature of sediment deposits have only a minor effect on yield.

DERIVATION OF INFLOW AND EVAPORATION DATA

Streamflow values published in the U.S. Geological Survey Water-Supply Papers are historic natural runoff values at the gaging stations from a constantly changing watershed. To obtain reservoir inflows for use in yield computations, it is necessary to modify the gaged flow for watershed changes that occurred in the past and are expected to occur in the future, as well as for any difference in drainage areas at the gages and at the dam site. The school book solution of this problem is to increase the gaged flow by the amount of all historic depletions to obtain "undepleted runoff," adjust for drainage area, then reduce for the effects of future watershed improvements. Undepleted runoff is the runoff that would occur if there were no ponds or minor reservoirs, no floodwater retarding structures or storage reservoirs, no terraces, contour plowing, diversions, return flows or other man-made changes that would affect the runoff regime of the watershed. The drainage area adjustment could be by ratio of drainage areas, or by other means as appropriate for particular situations. The future condition depletions for the area above the dam site are then computed and subtracted from the undepleted runoff to obtain future condition reservoir inflow. The outlined procedure may sound simple until attempted and then it will become apparent that available data are not adequate to serve as the basis for estimates of either past or future changes in runoff.

The situation is not hopeless, however. Luckily, droughts occurring in the 1950's were critical in most areas of the State. Runoff records collected within the past 15 to 20 years reflect, to a large extent, conditions approaching the ultimate in land management practices, including contour plowing and terracing, hence ignoring these features could not cause significant errors. Of more significance is the recent and future construction of stock ponds and SCS floodwater retention structures. Texas Water Commission permits are not required for the SCS reservoirs where the ponds contain less than 200 acre-feet if the only consumptive use of the water is for domestic purposes. A great number of SCS reservoirs have been built, and many more are planned for future construction. They are usually constructed on small tributary streams to protect downstream cultivated bottomlands from flooding. In many instances, they are ideally located for irrigation usage. The Texas Water Commission is receiving numerous applications for irrigation permits on these reservoirs and undoubtedly will receive even more in the future. Evaporation losses coupled with irrigation uses from the ponds will draw them down sufficiently to prevent spillage in most instances during a critical drought. Unless there is a particular reason for believing that the ponds will spill during a critical drought, the drainage area contributing to the SCS ponds both existing and planned, should be considered as not contributing to the water-supply reservoir under study. If all water originating upstream from the SCS reservoirs is considered lost insofar as the downstream reservoirs' yield is concerned, it probably will not be necessary to adjust the runoff further to compensate for losses from stock ponds.

A technique sometimes used to compute depletions caused by the numerous SCS reservoirs in the watershed is to develop a hypothetical reservoir representing, in one large project, the total surface area, capacity and drainage area of all of the small reservoirs. The inflow and future consumptive uses are estimated, and a period-of-record routing is run. The routing indicates the spillage, and this spillage is the only portion of the runoff originating above the SCS projects that is assumed to reach the water-supply reservoir as inflow.

All water rights in the upstream watershed that are superior to rights available to the reservoir under study should be evaluated. It should be assumed that upstream appropriators will fully exercise their rights to the extent that water is available at their diversion point during a recurrence of the critical drought period. Appropriate adjustments should therefore be made to the computed inflow to compensate for the difference between past actual and possible future upstream diversions. It is not likely that upstream diversions will be entirely consumptively used, and unless it is known that measures will be taken to prevent return flows from entering the reservoir, they should be considered as an increment of the inflow.

Inflow adjustments for an upstream water supply reservoir should consider the upper reservoir to be operating on some assumed future demand. Depending on the circumstances, the demand could either be the reservoir's dependable yield, its permitted diversion right, or an estimate of the probable water requirements at some selected future date. A period of record routing is run to determine spills, using all applicable adjustments to the inflow for future watershed conditions. The spills from this routing and estimated return flow are included as inflow to the reservoir under study.

In making adjustments to inflow for upstream diversions, storage, and return flows, consideration should be given to possible channel losses. As an example, all of the water impounded during a month in an upstream reservoir possibly would have not reached a downstream reservoir even if the upstream project did not exist because of evaporation, seepage, or transpiration losses from the channel. The U.S. Geological Survey has made a number of seepage runs on selected streams to determine intransit losses. Bulletin 5807-D entitled "Channel Gain and Loss Investigations, Texas Streams, 1918-1958," dated April 1960, gives data collected during that period. Undoubtedly, additional surveys will be made which will also be published in future bulletins, and all available data should be investigated before adopting values for intransit losses.

Evaporation data in a form that can be used in reservoir planning studies without further modification are given in Bulletin 6006 of the Texas Water Commission. This bulletin gives monthly values, in feet of depth, of net reservoir evaporation, for each 1-degree quadrangle of area in Texas, covering the period from January 1940 through December 1957. Text material in Bulletin 6006 describes very clearly the method used in computing net reservoir evaporation values which provides a convenient means for the engineer to compute values for earlier or later periods than included in the bulletin. The principal sources for basic data used in these computations, i.e., rainfall and pan evaporation, are the monthly and annual publications of "Climatological Data" of the U.S. Weather Bureau, and the series of publications of the Texas Agricultural Experiment Station entitled "Monthly Summary of Meteorological Data."

One Federal agency in the State has developed a correlation between annual rainfall and evaporation which it uses in preference to accepting the values given in Bulletin 6006. Their method accepts one curve as applicable to the entire State. Historical rainfall values are compiled for the particular reservoir area, and these values are used to read evaporation values from the curve. The annual evaporation values are distributed by months according to a long-time average monthly distribution derived for the reservoir area by interpolation between applicable evaporation measuring stations. The values are then reduced to net reservoir evaporation by methods similar to that described in Bulletin 6006. An advantage in use of the rainfall-evaporation correlation curve is that evaporation values can readily be obtained for any period in which rainfall records are available. However, it has been noted that values given in Bulletin 6006, or as computed from rainfall and evaporation pan measurements, are higher during drought periods than values read from the curve, hence they are the more conservative when used in reservoir yield computations.

SUMMARY

In summary, it may be said that an area which must depend upon a single reservoir for its water supply should be ever cognizant of its firm or dependable yield. Some methods are available for computing reservoir yields on a probability basis. Probability yields could be of some value if properly interpreted, but such values often suggest to the layman a security that is false. I do not believe that an engineer should recommend, suggest, or even imply that an area knowingly gamble with the security of its only source of water. It is to be recognized, however, that there is also a gamble involved in the so-called "dependable yield" values because record droughts have a habit of being broken as do record floods. If consideration is given to the various factors mentioned herein, it is believed that yield values will result that can be called firm, or dependable; and, if the area continues through the years to study and revise its future water requirement projections, and plan and develop its resources to meet future requirements, it will not encounter damaging water shortages.

DETERMINATION OF RESERVOIR YIELD FOR DROUGHT PERIODS[a]

Discussion by A. E. Richardson

A. E. RICHARDSON,[1] AM. ASCE.--The scope and quality of the paper presented by the author has created a problem for the discusser in that little is left to present on the subject, except to emphasize several points which the writer will do.

As the author pointed out, the simplest method of determining the yield-capacity relationship for a reservoir site once the basic data such as inflow, evaporation depths, and selected demands have been determined, is to solve the storage equation backwards in time, beginning with a depleted reservoir at the end of the critical-drought study period. Using this method, the monthly deficiencies in streamflow required to supply the desired demand and the evaporation and other losses are accumulated backwards in time, so that for any month of the study period these accumulated deficiencies represent the amount of water needed in storage at that time to supply the selected demand until the end of the drought period. These accumulated deficiencies will fluctuate in time with the variations in the quantity of inflow in varying sequences; however, the maximum accumulation of deficiencies during the period of record under study will be the amount of reservoir capacity required to supply the selected demand through the critical-drought period.

When utilizing the electronic computer to make these computations it is feasible to run through the entire period of record available; however, when necessary to make the computations "by hand," i.e., with slide rule and/or desk calculator, it is much better to isolate the critical drought period for study than to plow through 20 or more years of monthly computations. However, a word of warning from one who has suffered: Almost without exception the location in time of the critical drought period will vary with the size of demand under study. Generally, the larger the demand the longer the critical period, although under some conditions a series of 10 or more demands of varying sizes will group into only three or four critical periods of different lengths.

My point is this: when making the computations by hand do not assume that just because the maximum reservoir content (accumulated streamflow deficiencies) for the previous yield computation was reached during a particular month and year that the maximum content for the demand you are now working with will occur on that same date. Always carry the computations through until the accumulated deficiencies in streamflow are reduced to zero by inflows prior to the drought period. It might save you a lot of embarrassment.

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[a] By William H. Sims.

[1] Coordinator, Surface Water Hydrology Program, Texas Water Commission, Austin, Texas.

Along this same line, the selected demand could be so large the reservoir capacity necessary to meet this demand could not have been filled by the inflows during the period of record prior to the critical drought period. This may be an indication that the selected demand exceeds the capabilities of the stream. The maximum possible development of a reservoir site is evidenced by the firm annual yield plus the average annual evaporation and other losses being equal to the longtime average-annual inflow. This is merely to say: you can't get more water out of a reservoir than comes in.

The other point I would like to discuss concerns the monthly distribution of the annual demand as used in the reservoir yield computations. Experience has shown that the large variations in monthly municipal demands from summer to winter can affect the firm yield computations. This is due to the variation in reservoir levels and the associated evaporation loss therefrom. Any change in the criteria of operation which will cause the reservoir level to be higher in the summer and lower in the winter, or vice versa, will cause corresponding changes in the evaporation losses because of the higher evaporation depths in the summer. This is especially true of smaller reservoirs where the annual demand is a large percentage of the reservoir capacity, and the critical drought period is comparatively short. Over a long period of time the effect of such changes in criteria would be negligible due to variations in inflow, evaporation depths, etc.; however, it is always best when making hypothetical reservoir operations to select and use controlling conditions which are as realistically representative of actual conditions of operation as possible.

EFFECTS OF DROUGHT ON GROUND-WATER SUPPLIES

EFFECTS OF DROUGHT ON GROUND-WATER SUPPLIES

By J. R. Mount,[1] AM. ASCE

SYNOPSIS

Aquifers are generally dependable sources of water in drought, owing to their properties of large storage capacity and immunity to evaporation losses. Although ground-water supplies are commonly rather inadequate for meeting large-magnitude requirements, they can be advantageously developed as supplemental resources in conjunction with surface-water systems.

INTRODUCTION

Droughts have left many distinguishing marks in recorded history, illustrating that man's problem of a shortage of water has always been twofold. First, he must somehow survive the loss of livelihood that drought has imposed. Second, he must at least provide for the basic water supply which drought may have removed. In particular, in the southwestern United States there is much historic evidence of migration of Indian tribes during droughts, searching for dependable supplies of water. Experiences which these tribal civilizations have had with unreliable surface-stream resources, and the eventual habitation of many Indian communities near springs are testified to by archeologists.

Thus, to the primitive tribes, a drought was principally a condition characterized by an insufficient supply of water for drinking purposes. As civilization progressed, a drought became more associated with its effects on an agrarian economy, and it still retains this general connotation.

However, in today's complex society, the responsibility of safeguarding the welfare of enormous communities which are so dependent on a permanent adequate supply of water implies that droughts must be considered more rigorously than ever before, and on a pre-emptive basis. Because the responsibility of assuring an adequate water supply has been assumed by hydrologists, and because water shortages can no longer be tolerated, the hydrologists' concept of droughts should necessarily be related to reserves of water in storage.

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CONCEPT OF HYDROLOGIC DROUGHT IN RELATION TO GROUND-WATER STORAGE

Surface-water reservoirs are replenished by flow into the reservoirs, which is derived not only from the base flow of contributing streams, but particularly from runoff-producing rain. Hence, a "hydrologic drought" could be associated with a period of insufficient runoff-producing rain. The same period would not necessarily be related to a particular depth of precipitation, but rather to the intensity and duration of storms occurring during the period.

In order for a storm to produce runoff, its intensity and duration must be sufficient to overcome losses, notably those of interception, infiltration, and depression storage. It is indeed possible that there could be some period of time during which a number of small storms taken collectively would yield a significant depth of precipitation, yet produce an insignificant volume of runoff. Nevertheless, during the same period infiltration losses could result in significant contributions to ground-water reservoirs.

For the larger runoff-producing storms, once losses are overcome, runoff varies with storm intensity, but percolation to the water table over large well-drained areas proceeds at a fairly constant rate, independent of storm intensity.

Figure 1 illustrates the general effects of rainfall intensity and duration on percolation and runoff. The illustration shows that for a given storm, ground-water recharge derived from percolation depends mainly on storm duration rather than on storm intensity. On the other hand, runoff volume depends both on storm intensity and on storm duration.

Thus, some period designated a hydrologic drought could occur, and during the period reservoir storage would be seriously reduced owing to a combination of withdrawals, losses, and decreased inflow; but during the same period, aquifers could be sufficiently recharged such that ground-water storage may not have been similarly depleted. Moreover, ground-water storage could in fact be increased during periods when surface reservoirs are being depleted for want of sufficient runoff.

PROPERTIES OF GROUND-WATER RESERVOIRS RELATED TO DROUGHT

Unlike surface reservoirs, the presence of large volumes of water in aquifers does not necessarily guarantee the feasibility of large withdrawal rates, because the rate at which water can move through an aquifer is constrained by the resistance to flow through porous material and by the hydraulic gradient.

Because of flow resistance offered by porous materials, rather steep hydraulic gradients are required for the production of appreciable quantities of ground water, and large magnitudes of water-level drawdown in wells result. This lowering of water levels in wells is not necessarily indicative of depletion; nevertheless, it results in increased pumping costs. For these reasons ground-water supplies are sometimes comparatively inadequate in relation to surface-water supplies for furnishing large quantities of water to areas of concentrated demand.

The property of aquifers to store enormous quantities of water is not easily recognized and is often overlooked, but it is this property which mostly

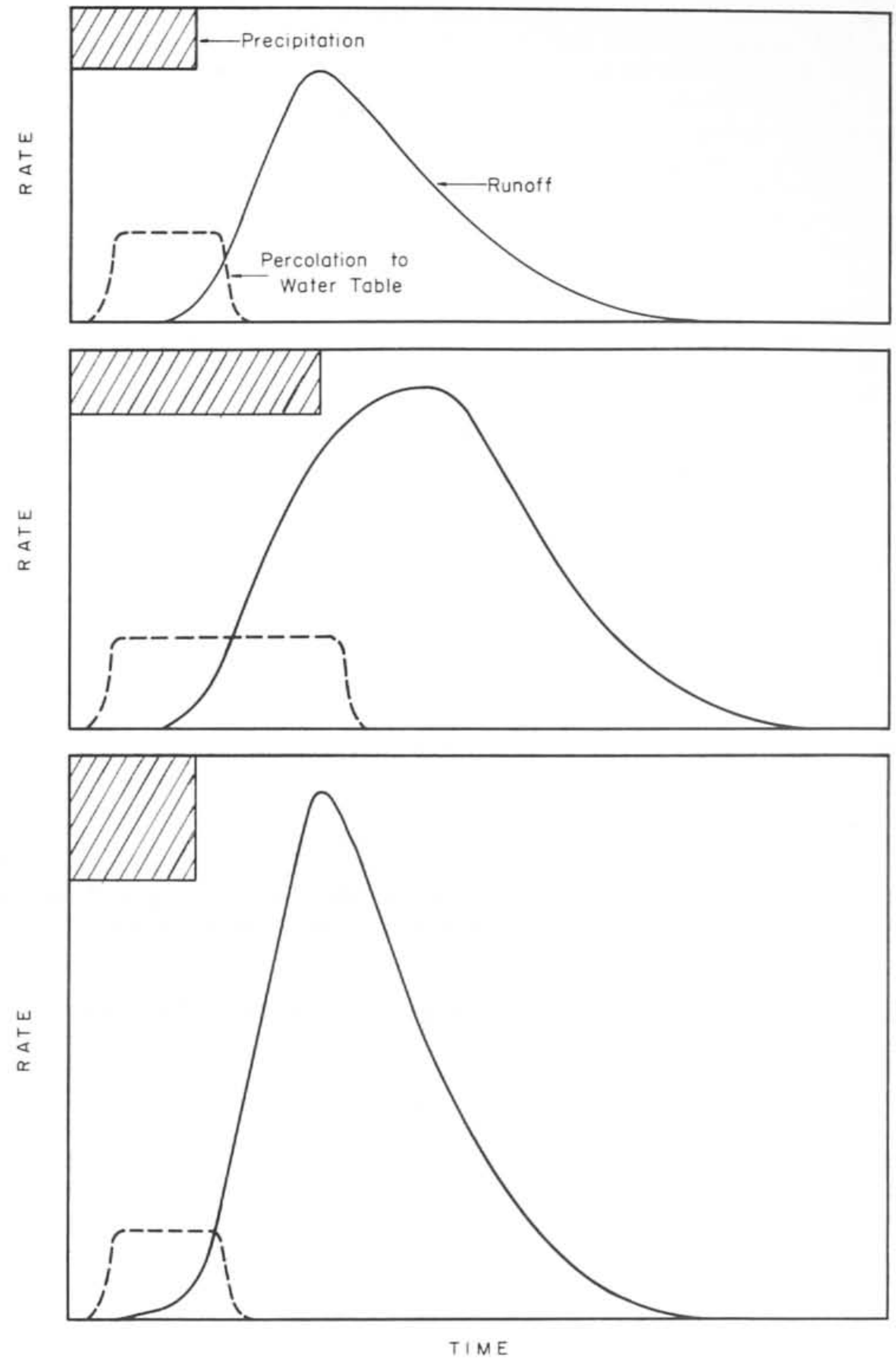

Figure 1

Relationships of Storm Intensity and Duration to Percolation and Runoff accounts for the permanent nature of springflow. The parameter of storage generally applied to water-table aquifers is specific yield. Aquifers composed of sand or gravel have specific yields of about one-fifth, which means that a given saturated volume of the aquifer material will yield about one-fifth of that volume of water when drained. Using a specific yield of one-fifth, a concept of the large volumes of recoverable water stored in aquifers can be obtained by considering the sand aquifers in the Neches River Basin. Here, in only their outcrop areas, the aquifers contain over 25 million acre-feet of recoverable water per 50 feet of saturated depth--more than eight times the total conservation-storage capacity of all existing reservoirs and reservoirs under construction in the basin!

Ground water also is relatively invulnerable to the evapotranspiration losses associated with surface reservoirs. Although significant amounts of ground water are lost by seepage and spring discharge, which constitute base flow of streams, these losses are stemmed during protracted droughts as ground-water levels decline below the base level of the surface-drainage system.

Of particular importance are the characteristics of rather uniform quality and temperature of ground water; these are generally maintained even through severe droughts.

Water levels in aquifers decline in response to two conditions imposed by drought: decrease in recharge, and increase in pumping rates. Figure 2 shows that in areas where insignificant quantities of ground water are utilized, water-level declines are quite small during droughts; the declines result from a temporary imbalance of natural recharge and discharge. In such areas, changes in water levels are associated with changes in ground-water storage. However, in areas where large quantities of ground water are utilized, drought conditions impose even greater demands for water; consequent declines in water level may become appreciable. They are principally associated with the increase in hydraulic gradient which is necessary for transmitting greater quantities of water to wells. The water-level declines do not necessarily reflect significant changes in ground-water storage throughout the aquifer's extent.

AQUIFERS AS DEPENDABLE SOURCES OF WATER IN DROUGHT

Although an aquifer may not be as adequate as a surface-water system for supplying large quantities of water, its comparative invulnerability to the effects of drought should be considered in evaluating its use as an alternate and/or conjunctive supply. An aquifer's large storage capacity and its immunity to evaporation losses preclude the use of often questionable yield-estimation techniques which employ statistical treatment of runoff and meteorological data.

Since the amount of water stored in an aquifer is relatively unchanged as a direct result of drought, transmission properties are not adversely altered. But in heavily pumped water-table aquifers, local reductions in transmissibility may result from the additional drawdown corresponding to increased pumping rates. If pumping is excessive, lowering of water levels causes a notable decrease in well yield, and in this case drought has a serious indirect effect on ground-water supplies.

In some areas, pronounced declines of water level due to increased pumping cause encroachment of poor-quality water into the developed areas. Otherwise,

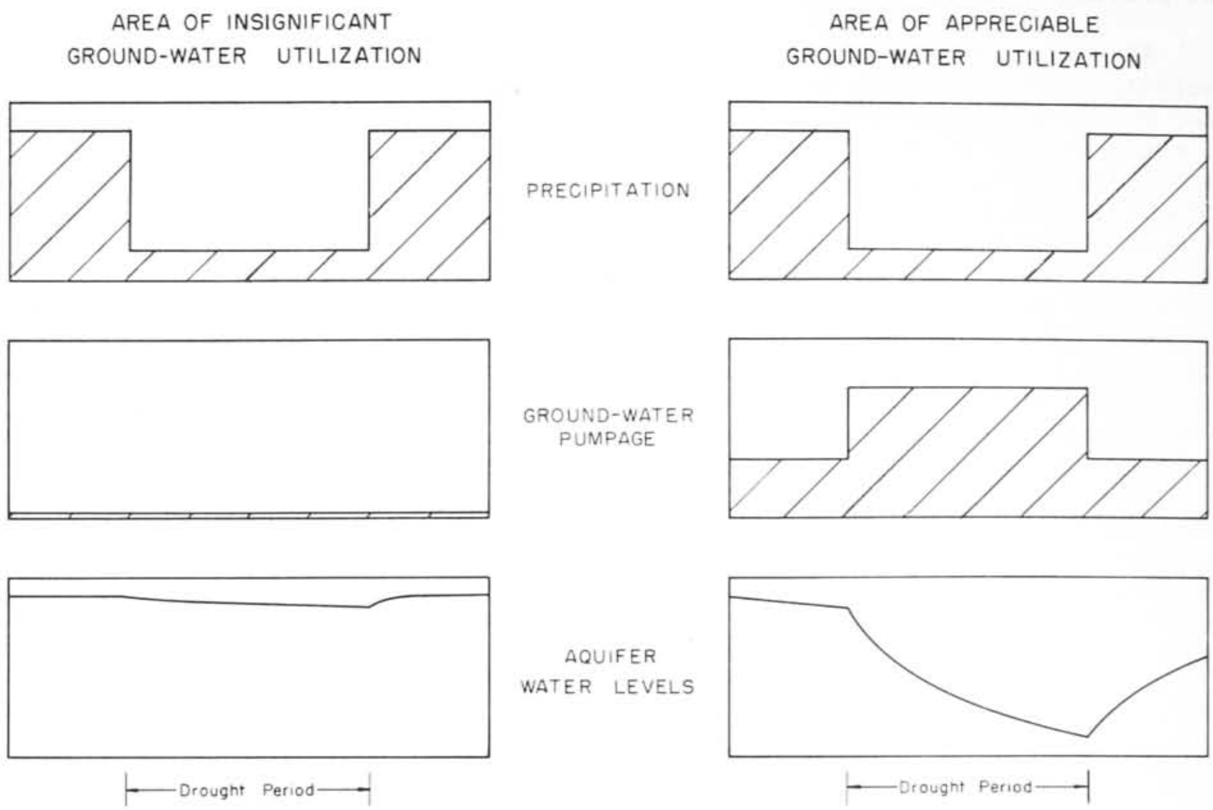

Figure 2
Relationships Between Precipitation, Ground-Water Discharge, and Aquifer Water Levels

ground-water supplies can be expected to maintain their uniform quality throughout prolonged droughts.

Also associated with drought are high evaporation rates owing to decreased humidity. Although greater-than-normal amounts of water are evaporated from lake surfaces during these periods, there is little if any corresponding effect on water stored in aquifers, as the water table is usually well below land surface. Seepage losses, which contribute to the base flow of streams, are even reduced in drought and may cease entirely if the water table declines below the base of the local surface-drainage system.

Since in developed areas, droughts impose greater demands for water, additional pumpage may cause substantial reduction or even cessation of springflow, and in the vicinity of pumping wells notable additional drawdowns of water level occur. Observation of these changes may easily lead to the belief that the water stored underground is being seriously depleted, unless comparison is made of the relatively small volume pumped to the volume stored in the aquifer. Moreover, although reduction or cessation of springflow may be judged a serious condition because of adverse effects on recreation, reduction of streamflow, or temporary loss of a perennial local resource, the effect on the aquifer is positive since losses of water from the aquifer have been curtailed.

UNIQUE CHARACTERISTICS OF LIMESTONE AQUIFERS

Singular consideration is given to ground water contained in limestones or dolomites because properties of storage and transmission for these aquifers differ somewhat from those for sand and gravel aquifers.

In limestones and dolomites, ground water occurs in solution-formed cavities, some of which may be of great size. The cavities generally constitute only a very small fraction of the total rock volume; hence, in relation to sand and gravel aquifers, limestone and dolomites have a comparatively low capacity for storing large volumes of water. On the other hand, water moving through solution-formed openings encounters relatively little resistance to flow; thus very high pumping rates can be obtained from wells which encounter sizeable cavities in the rocks.

Generally associated with limestone and dolomite aquifers are springs, some of which may discharge appreciable quantities of ground water. Because these aquifers are relatively incapable of storing large volumes of water, and because water moves rather rapidly through them, spring discharges during droughts are generally noticeably reduced in response to decreased natural recharge.

Hence, in comparison to sand and gravel aquifers, limestone and dolomite aquifers have large transmission properties and small storage properties, and are indeed sensitive to drought conditions.

EFFECTS OF DROUGHT ON SOME AQUIFERS IN TEXAS

Because changes in pumping rates and changes in water stored in aquifers produce corresponding changes in water levels, hydrographs showing water-level fluctuations can provide a convenient means of evaluating effects of drought on ground-water supplies. In order to show the effects of the drought of 1950-1956 on some of the aquifers in Texas, hydrographs are presented on Figures 3 and 4.

Fluctuations of water levels in four wells producing from sand aquifers in various parts of the State are presented on Figure 3. The hydrographs on the left side of the illustration indicate that where there was no significant ground-water utilization, only small water-level declines occurred both in water-table and in artesian aquifers. The well represented by the hydrograph shown on the upper left part of the illustration is located in northern Crane County, in West Texas, and is completed below the water table in a thick sand deposit. This sand forms dunes on the land surface and is quite conducive to recharge. The well represented by the hydrograph on the lower left is located in Bastrop County, approximately 30 miles southeast of Austin, and is screened in an artesian aquifer, in the Simsboro Sand of the Wilcox Group. The sand is about 100 feet thick and occurs at a depth of about 500 feet. Several wells were drilled in this area in 1942 for the purpose of supplying a military base which was later deactivated, in about 1945. The rise of water level shown from 1946 through 1951 represents recovery owing to cessation of pumpage. The rising trend probably masks what would have been a slight decline in water level during the early 1950's, since the small decline presumably related to the drought does not appear until 1955. The rise in water level following resumption of normal rainfall in 1957 is evident.

The hydrographs on the right side of Figure 3 show that where there was appreciable ground-water utilization, significant declines in water level occurred as a result of increased pumpage during the drought. Pronounced rises in water level following the drought are also evident. The wells represented are located in areas of active ground-water irrigation. The well represented by the hydrograph on the upper right obtains water from alluvial deposits in the Concho River Valley, east of San Angelo. The well represented by the hydrograph on the lower right is located in northern Zavala County, in the Winter Garden area of South Texas, and is completed in the Carrizo Formation, which is a rather prolific and extensive artesian aquifer.

Figure 4 shows the effects which the 1950-1956 drought had on the Edwards Underground Reservoir, an important limestone aquifer which supplies San Antonio. The reduced precipitation during the drought and its effects on spring discharge and water levels is apparent. It should be observed from the illustration that during periods of normal rainfall, most of the water discharged is through springs. During the drought, however, the magnitude of increased pumpage from wells was more than offset by reductions in spring discharge. The largest spring in the area, Comal Springs, ceased flowing during the summer of 1956.

CONJUNCTIVE UTILIZATION OF GROUND- AND SURFACE-WATER RESOURCES

In some areas, present and anticipated future water requirements pose serious problems in regional planning, involving such issues as competition between large users of surface water and eventual inadequacy of ground-water resources.

Where appreciable supplies of both ground water and surface water are available, optimum development of these resources can be approached through

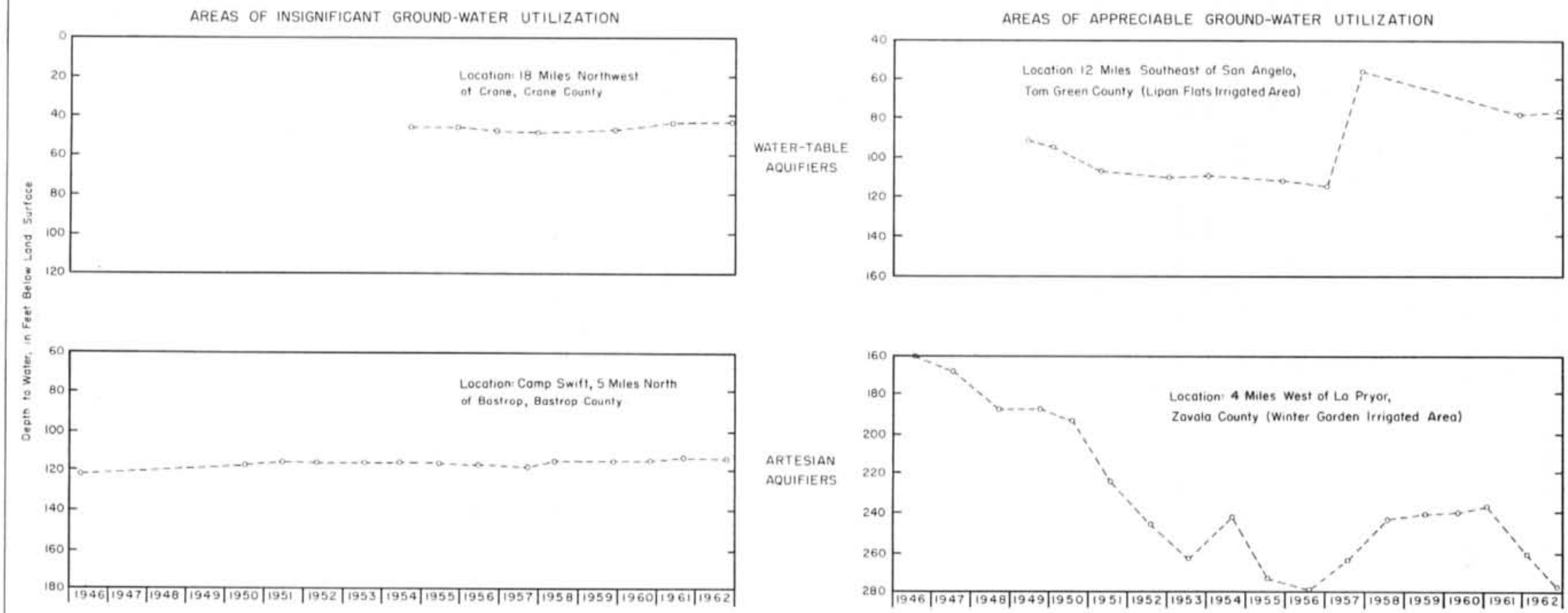

Figure 3

Water-Level Fluctuation in Wells in Selected Areas in Texas

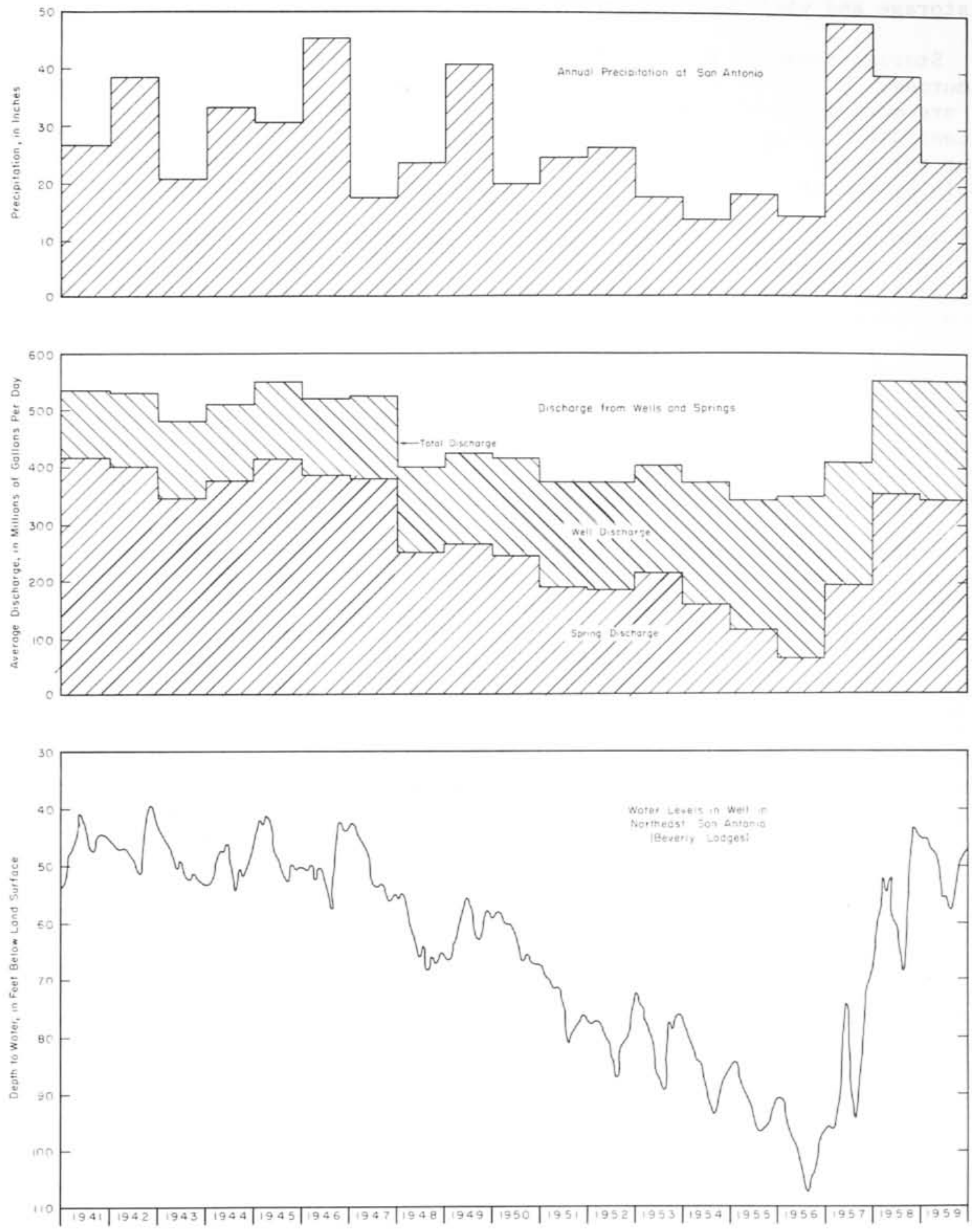

Figure 4

Precipitation, Ground-Water Discharge, and Water Levels in Well in Edwards Underground Reservoir, San Antonio Area water-management programs which effectively utilize the beneficial properties of storage and yield of each source.

Storage capacity is far greater with ground-water than with surface-water resources. On the other hand, surface-water resources are more easily renewable and are more desirable for furnishing large quantities of water to areas of concentrated demand. The coordinated development of both ground- and surface-water resources, then, would provide a desirable means of obtaining a water-supply system having optimum properties of both storage and yield.

Properly managed, conjunctive utilization would be such that ground-water development would be greatest during periods when surface-water supplies are low, particularly during droughts. On a smaller scale of conjunctive use, ground water could be developed for reserve purposes during peak demand periods.

Droughts impose an acute need for the maintenance of surface-water storage. Conservation of storage in reservoirs can be aided materially by making full utilization of ground-water resources during and following droughts, until the surface reservoirs have been adequately replenished. Subsequent water requirements would be obtained principally or totally from surface-water sources, while ground-water resources are being replenished.

Ground water can often be used advantageously during summer periods as a dilutant for improving water quality and as an additional water supply during periods of maximum requirement. Because during summer months chemical quality of surface water generally deteriorates, additional supplies of better quality water are desirable for mixing, and, since ground water does not normally require treatment it can be also a readily available source during peak demand periods, when surface-water treatment facilities are operating at capacity. Furthermore, it is during the summer when most recreational benefits of reservoirs are utilized, and it is essential at this time to maintain reduction in lake levels to a practicable minimum. Since evaporation losses are greatest during the summer periods, decreased use of surface water and increased use of ground water could be of significance in maintaining lake levels.

CONCLUSION

Because of the disastrous potential consequences of drought which impose additional demands on water-supply systems, and because of the need to insure an adequate water supply during prolonged periods of reduced rainfall, available ground-water sources should be investigated and developed as useful and necessary supplies. Owing to their immunity to direct effects of droughts, these underground reservoirs are generally capable of sustaining their yields throughout long periods of inadequate precipitation. Aquifers can provide a source of water auxiliary to surface-water sources not only during drought, but also during summer peak-demand periods.

An orderly plan of ground-water management is not always possible, particularly in states where there are no provisions for ground-water rights. Legislative or legal impediments notwithstanding, optimum conjunctive utilization of total water resources will eventually be necessary. To achieve this, investigations of surface-water resources should proceed in conjunction with investigations of available ground-water supplies. The amounts of water capable of being supplied by aquifers should then be appraised for their most efficient use in conjunction with system operations of reservoirs.

EFFECTS OF DROUGHT ON GROUND-WATER SUPPLIES[a]

Discussion[b] by R. K. Gabrysch

R. K. GABRYSCH,[1] AM. ASCE.--Mr. Mount has touched on several points of comparison between ground- and surface-water supplies and how they are affected by drought. It may be well to reiterate and expand some of those points.

With respect to a sand-type or "reservoir-type" aquifer, it is true that droughts do not significantly affect the amount of water in storage if the aquifer is relatively deep or thick. However, droughts cause increased need for water; therefore, increased pumpage is necessary, and it is the increase in pumpage that has the greatest effect on the ground-water system. That is, water levels will decline in and around points of discharge, be they artificial or natural. In the case of the artesian sand-type aquifer, if the points of withdrawal from the aquifer are at considerable distance from the point of intake or recharge area, little or no direct effect of a drought will be noticed. For instance, between 1950-56 in the Houston area of the Texas gulf coast region, the increase in the rate of decline in water levels experienced at Houston, which is at least several miles from the outcrop of the underlying aquifer, was due to increased pumpage. The aquifer in the area of recharge north and west of Houston remained nearly full. The large cone of depression in water levels in and around Houston grew larger and deeper, creating the greater hydraulic gradient necessary to transmit more water toward Houston to compensate for the increased withdrawal.

An important factor in the artesian sand-type aquifer is the transmission capacity which is dependent on the permeability and hydraulic gradient. Rates of movement in the sand-type aquifer are extremely slow, and infiltration in the area of recharge need be only a small amount to furnish all the water the aquifer could transmit even under very steep gradients. On the other hand, the rate of movement through limestone and dolomite or "pipeline-type" aquifers may be much more rapid. Water entering the recharge area proceeds to the points of discharge in a "pipeline" fashion. Thus, rainfall patterns are reflected by changing water levels in both the "pipeline-" and "reservoir-type" aquifers, but the difference in extent of effect is due to the difference in nature of the transmissive properties of the aquifers.

Another factor to consider in the effects of drought is the withdrawal of water from near-surface aquifers by phreatophytes. These natural "pumping plants" will use more water during droughts because plant usage is dependent (among other things) on rate of evaporation, temperature, and humidity. The

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[a] By J. R. Mount.

[b] As approved for publication by Director, U.S. Geological Survey.

[1] Engineer-in-charge, Ground Water Subdistrict Office, U.S. Geological Survey, Houston, Texas.

root systems of these water-loving plants obtain water from the zone of saturation either directly or through capillary action. Of course, the usage by such plants continues through all climatic cycles, but the rate of usage is accelerated during drought periods.

Certainly, there is a limit to the amount of water that can be withdrawn from a ground-water system under a given set of imposed conditions. This is also true of surface-water systems. Both systems are affected by drought: the surface reservoir is affected by increased use, deteriorating quality, and evaporation; the aquifer is affected by lowering water levels and resultant decreases in storage due to increased pumpage. The ground-water system also may be subject to salt-water encroachment and land-surface subsidence.

The choice of the principal source of water for an area will depend on many factors of which the most important probably are: (1) the availability of usable ground water and surface water, (2) the location of the available supply with respect to the location of the point of need, (3) the quality of existing and potential sources, and (4) the amount of need and problems associated with the development. Where both ground- and surface-water sources exist, both must be developed in a complementary manner. Our water resource is a tremendous asset if developed properly. To develop the resource, due regard should be given to the effects of droughts, and all plans for development should include methods whereby the effects may be minimized. Such plans for ground-water development might include selective pumping in cyclic periods and artificial recharge of ground-water systems during times of excessive runoff and surplus surface water.

SYMPOSIUM ON DROUGHT--SUMMARY

SYMPOSIUM ON DROUGHT--SUMMARY

By Donald Van Sickle,[a] M. ASCE

Several of the discussors have mentioned the difficulty of contributing a worthwhile discussion because of the high quality and thorough coverage of the individual symposium papers. How much more difficult is it, then, to adequately summarize in a reasonable length of time the wealth of material which has been presented and discussed so ably in the two sessions of this symposium?

What is drought? How can we define it? How can we predict it? How can we measure it? How does it affect different people? How can we design water resources development programs to take into account the effects of drought, and thereby minimize these effects insofar as the majority of the population is concerned? These are some of the topics covered by the symposium participants based not only on their extensive experience, but also on their review of the available literature on the subject.

In the first place, what do we mean by drought? The Columbia Encyclopedia attempts to define it as follows:

> "...period of insufficient rainfall resulting in serious damage to crops and other vegetation. Drought cannot be accurately defined in terms of inches of rainfall or number of days without rain because other factors, such as the amount of rain before a long rainless period and the distribution of the amount that does fall, also help to determine the presence or absence of drought.... The causes of drought are not well understood.... Much remains to be learned regarding the causes as well as the methods of combating the effects of drought."

The purpose of this symposium is to determine approximately where we are in learning the causes and developing methods of combating the effects of drought.

Mr. Vandertulip in his Introduction reached essentially the same conclusion as the Columbia Encyclopedia, namely, that "a general definition of drought as related to reservoirs does not appear possible because of the numerous variables involved." He and Mr. Mount did succeed in illustrating that the definition depends to a large extent on the water-using activity involved. For instance, an agricultural definition is based primarily on the occurrence of a continued deficiency in precipitation, whereas a "hydrologic drought" from the

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standpoint of surface water reservoirs is "associated with a period of insufficient runoff-producing rain..... It is indeed possible that there could be... a significant depth of precipitation, yet....an insignificant volume of runoff." While it is possible for this situation to occur, the usual case is not only a deficiency in runoff, but a deficiency in rainfall as well. There is, therefore, no real incompatibility in the fact that the methods of predicting droughts relate the various indicators to total rainfall, whereas the design of reservoir systems considers the actual runoff records for the watershed, using precipitation records only where runoff records are deficient and must be synthesized.

The difficulty in defining drought, naturally, does not make drought prediction any simpler, since it is hard to predict something if you don't know for sure what it is you are trying to predict. As a result, most drought prediction studies are based on predicting periods of deficient precipitation and the degree of deficiency. Mr. Carr's presentation of "the state of the art" of drought prediction is somewhat discouraging for those of us who would like to use the cyclic approach. It is indeed disheartening to learn from Dr. Marmion that some of the publications presenting obviously cyclic weather behavior pattern are based on methods of analysis which guarantee, in effect, that cyclic results will be obtained regardless of the data used. Some of the other prediction techniques described, particularly the statistical probability approach, would appear to have more immediate value in water resources studies pending further evaluation of the cyclic variation and the variation with solar radiation prediction methods. Both Mr. Carr and Dr. Marmion emphasize that the search for such correlations is not over, and that we must not demand too much of our methods of prediction before we accept, at least tentatively, their validity. In the area of drought prediction, then, much remains to be done. It is evident, however, that much past work has been so much wasted effort. Because of the large number of problems in hydrology still requiring concerted study and research, we cannot afford to be so prodigal with our efforts, and future research in drought prediction should be carefully evaluated to ensure that our methods of analysis do not influence the form of the results or predetermine the conclusions.

Of vital importance to the drought prediction studies is the continuing programs of basic data collection by the U.S. Geological Survey, the Texas Water Commission, and similar organizations. As Mr. Gilbert points out, the scope of these programs is constantly expanding and increased quantities of data are becoming available. Obviously, it is not feasible to begin specialized drought data collection at the beginning of a drought because the beginning of the drought is not defined until the drought is well under way, at which time it is too late. The continuing programs of data collection are the only feasible solution. These continuing programs are organized, therefore, so that the data collected will be useful for analyzing drought and low-flow conditions as well as for determining the many other characteristics so necessary in water resource investigations. Engineers invariably complain about the lack of data available for a particular site, but it is evident from Mr. Gilbert's description that enormous quantities of data are already available, with the rate of data acquisition increasing all the time. The most important part of a data-collection program is the availability of the data for use by interested parties. The use of computers will be necessary to make the large masses of data readily accessible in the most usable form. Publication will of necessity be limited to summaries or averages, as is already the case in many instances. Indeed, perhaps the greatest need is for publications which will summarize the types of data which are available from the various agencies, the forms in which these data can be obtained, and the procedures for obtaining them, so that more engineers will be familiar with data-collection programs already in existence, as well as the newer programs which are proposed.

Mr. Koberg presented the results of an analysis of some of these data insofar as the effect of droughts on evaporation rates is concerned. He demonstrated that evaporation rates during droughts are greater than at other times and explained the reasons why this should be so. His illustration of the variation in evaporation rate along latitude 35° across the United States is of considerable interest and, as Mr. McDaniels pointed out, is additional illustration of the effect of drought on evaporation rates if Las Vegas is considered as undergoing drought conditions when compared with Chattanooga. The significant difference in evaporation rates between drought and non-drought conditions is certainly enough to warrant the use of drought evaporation rates during critical periods in reservoir yield studies, rather than a long-term average evaporation rate. In addition, it indicates the considerable increases in yield which may result if suitable means of minimizing evaporation losses can be developed.

Mr. Claborn has attempted to come to grips with the question: "What is a tolerable water shortage?", and reached the conclusion that the shortage in supply is tolerable until the user does something to improve the supply. He further concluded that this limiting condition is the point at which the marginal cost of the next unit of water exceeds the marginal value attached to this unit by the user. He describes a method of analysis related to the establishment of these marginal values and marginal costs for various types of water use. Mr. Claborn indicates that the economic analysis of the marginal value for irrigation and industrial uses is much simpler to determine than that for residential uses. Mr. Schwab and Dr. Smerdon in their discussions indicate that the usefulness of the method described by Mr. Claborn is limited in practical application because of the limited data available concerning marginal value of water for various uses. If this is indeed the case, then concerted efforts should be made to acquire or develop the data needed for such analyses because, as the demand for water increases and approaches supply limits, economic analyses will be necessary to ensure optimum utilization of water resources. Lack of the necessary economic data will seriously hamper the achievement of this optimum utilization concept.

The first session of the symposium, through Mr. Claborn's paper, was concerned primarily with defining the causes and effects of drought and establishing certain basic concepts. The second session was concerned with the design of water resource projects to mitigate the effects of droughts, and the establishment of analysis procedures for determining design drought conditions, the optimum yield from a system of reservoirs, as well as from a single reservoir, and the use of supplementary underground water supplies during drought periods.

Mr. Gooch has presented a concept for the determination of a design drought, and a simple algebraic procedure for estimating dependable reservoir yields based on the design drought criteria. The simplicity of the proposed procedure makes it ideally suited for preliminary reservoir yield studies while at the same time the indicated accuracy of the method, when compared with actual detailed yield studies, ensures that the yield determined in these preliminary studies will be well within the range of the yield determined by more conventional methods during project design stages. Mr. Meier's discussion indicates several possible variations of the method proposed. It further describes briefly some of the more recent methods of extending streamflow data statistically to provide more reliable estimates of low flows for various durations. Mr. Gooch's "design drought concept" certainly merits consideration by engineers concerned with water resources. The suggestion that the design drought concept would permit the rational determination of regional design criteria for use by State and Federal agencies in evaluating water resource projects is one which should be carefully examined by the agencies concerned.

Mr. Marks has presented a condensed description of the procedures for determining the optimum yield from a system of two or more reservoirs. Even in the condensed form it is evident that the problem becomes extremely complicated. Such factors as geographic location; characteristics of the runoff, the reservoir, the demand and the conveyance system; the amount and quality of return flow and the quality of the runoff itself make the case for a single reservoir complex enough. When these factors must then be considered for two or more reservoirs, and the resulting project must provide an optimum yield, it is seen that experience must play a very significant role until such time as suitable computer programs are developed for these analyses. Mr. Marks notes that such programs are not currently available, and it would seem that the development of programs which can simulate a complex river and reservoir system for purposes of system design should be vigorously pursued. Here, again, is something which can help to ensure the optimum development of water resources, but which is, as yet, not available. The value of operating a series of reservoirs as a coordinated system is illustrated by Mr. Marks' statement, attributed to Col. Wells of the Brazos River Authority, that a coordinated system operation of four reservoirs on the Brazos River will produce a yield 10 percent greater than the sum of the yields of the individual reservoirs. Surely the cost of coordinated operation is much less than the value of the additional yield thus produced.

Dr. Moore and Mr. Rucker, in their discussions, both emphasize the complexities of the optimizing problem, especially in the area of defining what specifically is optimized. Dr. Moore mentions four potential areas for optimization and describes the effect of each on the analysis procedures for reservoir system operation. He further indicates the areas in which he feels further research efforts would be most fruitful. Mr. Rucker notes that perhaps a comprehensive computer program for planning purposes should <u>not</u> be written, although he makes it clear that he means the program should not and indeed could not encompass all of the various social, economic, and legal conditions. He is undoubtedly correct and as he further points out, establishment of the socio-economic and legal constraints early in the planning stages permits a much clearer definition of the actual problem to be solved, whether the solution be by computer or by more traditional methods. Mr. Rucker's mention of the place of intangible benefits or of tangible benefits which do not appear in debt service and amortization schedules in the optimization of benefits from a water resources project, illustrates the frustratingly nebulous nature of the optimization or the maximization concept.

Mr. Sims described the yield determination for a single reservoir as a determination based on "notoriously simple" computations. As is the case in many other engineering problems, the computations themselves are indeed simple, though repetitive, once the basic data are obtained and the parameters evaluated. Computer programs have to a large extent minimized the repetitive computations, but have not as yet eliminated the need for engineering judgement in the assessment of design criteria and evaluation of available data. As Mr. Richardson points out in his discussion, Mr. Sims has provided a most comprehensive description of the determination of reservoir yield. Mr. Richardson, however, has added to the value of the paper by pointing out several potential pitfall areas in the analysis procedure; as well as several points where particular attention might be required to ensure a realistic evaluation of the demand and the evaporation losses.

In the final paper, Mr. Mount has presented a very thorough appraisal of the effect of drought on ground water supplies from various types of aquifers, and has demonstrated the tremendous value of ground water supplies as emergency water sources or reservoirs during periods of drought. Unquestionably, the long lag time associated with the reaction of most aquifers to drought conditions is a most valuable feature, particularly when the large storage capacity and generally high quality of the ground water is also maintained during drought periods. As both Mr. Mount and Mr. Gabrysch, in his discussion, point out however, there are some undesirable effects of drought on ground water supplies. The principal effect is the lowering of water tables because of increased pumping with consequent increases in pumping costs. Also of significance in some areas is the effect of land subsidence and salt water intrusion into the aquifer as a result of over-pumping during droughts. These are effects which can be tolerated if necessary to ensure a firm water supply, particularly if reduced pumping is possible after the drought to permit replenishment of the supply. In some cases artificial recharge may be feasible.

In any event, in a comprehensive water resources program, the value of ground water supplies, and their optimum utilization in the over-all program should be carefully considered. Perhaps if it proves possible to develop computer programs for design of reservoir systems in a complex river basin it may also be feasible to develop programs which will include the ground water resources as well. Such a program would be of inestimable value in truly optimizing the water yield for all of the various demands on our limited water resources.

In summary then it appears that the symposium has indicated the difficulties in defining droughts and predicting them. Some progress has been made in relating evaporation rates, tolerable shortages, and ground-water supplies to drought characteristics, but much remains to be done. Data from the greatly expanded data-collection programs should be of assistance in future studies along this line, although periods of records for these data are generally too short for confident definition of design drought criteria. Analysis procedures for determining reservoir yields are available and in use; however, it is evident that engineers are not satisfied that these methods result in optimum utilization of water resources, particularly in complex river basins with a wide variety of water uses and resulting benefits. As development continues, these complex systems requiring close coordination in system operation will become the rule rather than the exception, and analysis procedures must be developed to meet these requirements. A number of suggestions have been offered to indicate areas where additional research and study are needed. It is hoped that by bringing attention to present deficiencies and by pointing the way to methods of overcoming these deficiencies, this symposium has helped hasten the day when we will make optimum use of all of our water resources.

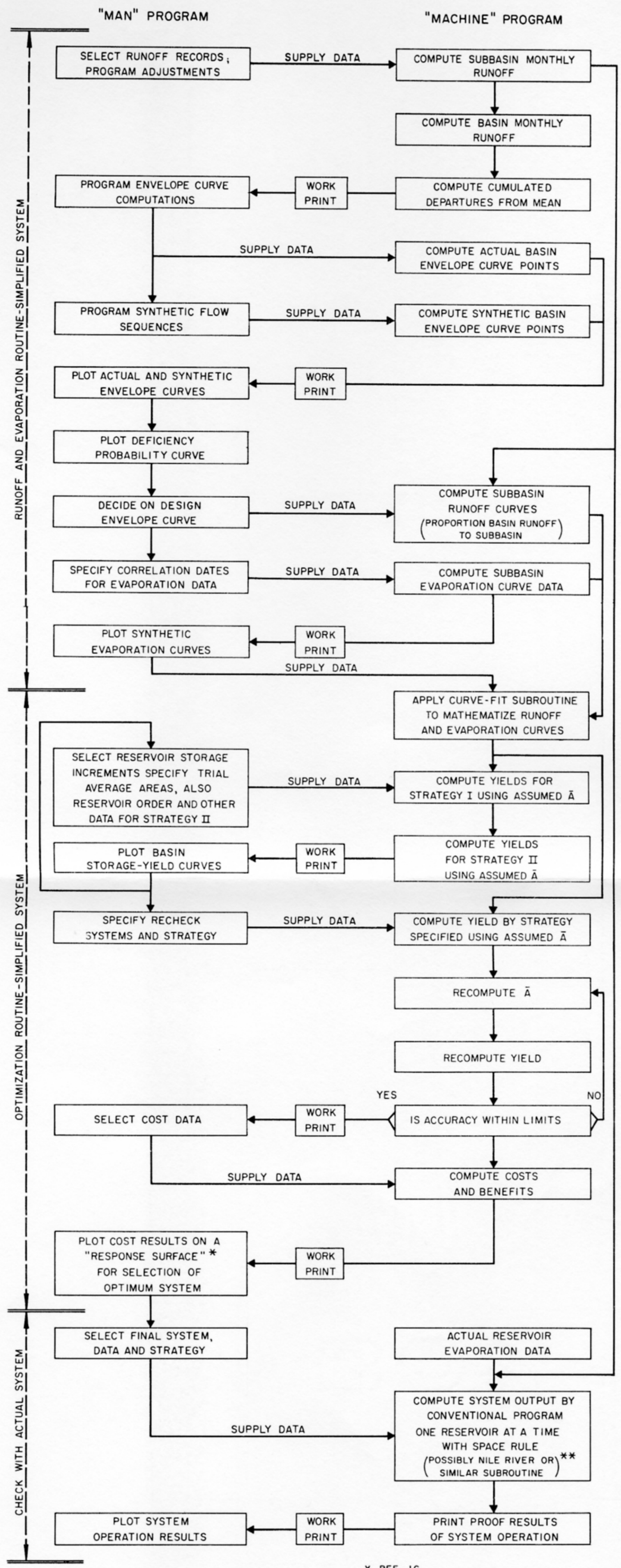
In conclusion, the writer wants to thank, on behalf of the Hydraulics Technical Group and the Texas Section of the American Society of Civil Engineers, the authors of the papers and the prepared discussions for making this symposium possible. Nothing would make him happier than to take credit for the whole thing, but his contribution was of negligible significance. The suggestion for the symposium originated with Mr. John Vandertulip, Chief

Engineer of the Texas Water Commission, and was presented to the Hydraulics Technical Group by Mr. Willard Mills of the U.S. Geological Survey, then Secretary of the group. Mr. Louis McDaniels of the Texas Water Commission coordinated the gathering together of the final drafts of all the papers for publication and thereby relieved the writer of this burdensome task. Finally, we are most appreciative of the contribution of the Texas Water Commission in publishing the papers and discussions, thereby making them available, not only to those Texas Section members who were unable to attend the symposium, but also to the engineering profession as a whole.

APPENDIX B

FLOW CHART

OPTIMIZING YIELD OF A RESERVOIR SYSTEM



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