TEXAS BOARD OF WATER ENGINEERS

Durwood Manford, Chairman
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BULLETIN 5914

A STUDY OF DROUGHTS IN TEXAS

Prepared by
The Late Robert L. Lowry, Jr.
Consulting Surface Water Hydrologist
for
Texas Board of Water Engineers

December 1959

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(TO THOSE NOT ENTITLED TO FREE DISTRIBUTION)

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FOREWORD

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 drought. It is only when the deficiencies in rainfall are great or prolonged, that the land is experiencing a drought. Droughts are not something new - man has had to contend with them throughout his existence.

As Tannehill (see ref. 1) so aptly put it:

> "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."

Early recorded history makes frequent reference to droughts and resulting famines. Tree-ring studies in the Southwest have now extended knowledge on dendroclimatology back about 4000 years. During this period there is ample evidence of droughts. Another means of extending the record back to prehistoric climatic changes is based on the thickness of annual layers of clay and silt deposited in quiet waters of lakes that are subject to freezing in winter and thawing in summer. In such a study each annual deposit is called a varve. These varves also indicate periods in the past in which droughts have seriously affected the land.

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 lies. As long as the climate is influenced by the circulation of air around the earth, there will be changes in the precipitation pattern at any given spot. Just as certain as there have been droughts in this country in the past, there will be droughts in the future. The time of the next drought cannot be exactly foretold, but it will obviously follow a period of normal or excess rainfall. Who knows that it may not occur next year?

Agricultural losses resulting from the recent drought in Texas, which was seriously effective between 1950 and 1956, have been estimated by experts to have exceeded 3 billion dollars. It is probable that in Texas losses in farming and ranching alone have exceeded the aggregate loss due to all other climatic phenomena including floods, hurricanes and tornadoes, throughout the years.

Whereas, manifestations of most weather phenomena particularly the more destructive type are rather sudden, and the results are rather obvious, droughts materialize so slowly and their effects are so long delayed, that the damage is usually done by the time it is realized that a drought is being experienced. Of further importance is the fact that the effects of drought are usually widespread, frequently involving entire states, and sometimes all of the United States. By comparison, areas affected by the other weather phenomena are usually quite local.

ACKNOWLEDGEMENTS

Several agencies of the Federal and State governments have made information available to be utilized in the development of this report. Included among these agencies are:

International Boundary and Water Commission, Department of State

U. S. Weather Bureau, Department of Commerce

U. S. Geological Survey, Department of the Interior

U. S. Bureau of Reclamation, Department of the Interior

U. S. Agriculture Stabilization Committee, Department of Agriculture

Texas Board of Water Engineers

Texas Department of Agriculture

Texas Department of Health

Department of Agricultural Economics and Sociology, A & M College of Texas

Texas State Library

Bureau of Business Research, University of Texas

A STUDY OF DROUGHTS IN TEXAS

INTRODUCTION

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 make every effort to keep supply in excess of demand. Hence, shortages in water in the cities are not generally as frequent or serious 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 carryover 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."

J. C. Hoyt defines it thus: (See ref. 2.)

> "Drought conditions may be said to prevail whenever precipitation is insufficient to meet the needs of established human activities."

These definitions are incomplete and do not provide a quantitative means for measuring drought. General A. W. Greely, the last military chief of the Federal Weather Service (U. S.), appears to have been the first to point out the need for a quantitative scale for use in connection with the term drought. He suggested in 1888 that: (See ref. 3.)

> "....the term be used only for those parts of the country where the average precipitation exceeds an inch in each month."

Gen. Greely also remarked that: (See ref. 4.)

> "....from an examination of the records it appears that droughts are very severe whenever the rainfall for one or more months is less than 50 percent of the average amount, and it is suggested that the drought unit indicate a deficiency to be determined with reference to the average monthly amount during the time in which the drought prevails."

Henry (see ref. 5) in 1906 proposed and used a definition of drought substantially as follows:

> "Drought: A drought is considered to exist whenever the rainfall for a period of 21 days or longer is but 30 percent of the average for the time and place."

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.

None of these various definitions is 100% applicable to a discussion of droughts as related to Texas. The lack of a generally applicable definition of drought is noted by Linsley, Kohler, and Paulhus (see ref. 6) 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 (see ref. 7) 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 also falls short because it does not consider the time of occurrence of rainfall. For instance, a deficiency of less than 10 percent of the annual rainfall, if it occurs during the growing season, would be much more severe in its economic implications than a deficiency of 25 percent of the annual rainfall that happened to occur in the non-growing season.

The following discussion of droughts by Hoyt (see ref. 8) is worthy of repetition:

> "In considering droughts the division of the country into three sections with respect to precipitation - the humid East, the arid West, and the intermediate semi-arid states must be kept in mind. In the humid East precipitation is usually adequate to supply the needs of vegetation without irrigation, and other activities are limited by the water supplies that can be conserved. The semi-arid states constitute a section that may be either humid or arid, depending on weather conditions in a particular year."

These same divisions are present in Texas - the humid East, the arid West, and the intermediate semi-arid part of the State.

A recent U. S. Weather Bureau publication (see ref. 9) states:

> "Drought is difficult to measure objectively. One gauge is its impact upon livelihood of the population in the area. This is closely related to the effects of meteorological factors on crops, pastures and water supply. Because these effects can only be estimated, a somewhat less adequate measuring rod must be employed. The drought is expressed here in terms of lack of rainfall as compared to that usually expected."

Palmer (see ref. 10) provides a generalized definition of drought by stating:

> "From a meteorological standpoint drought may be considered to be a relatively temporary departure of the climate from the normal or average climate toward aridity. This assumes the economy of the region is more or less in step with the average climate and is, therefore, not seriously affected by the normal ups and downs of the weather."

For the determination and comparisons of droughts in this study Hoyt's definition has been used: drought conditions exist when there is an annual deficiency in precipitation of 15 percent or more.

AVAILABLE DATA

Records of rainfall in Texas generally begin about 1889, although a few stations were started much earlier; some in the 1850's. The longest rainfall record in Texas is that for Austin, which began in 1856 and is continuous with the exception of a few months in 3 years. Sixty-seven stations were in operation in Texas in 1891. This number gradually increased to 249 stations with published records in 1940. A large increase in the number of rainfall stations occurred after World War II, with records published for 643 stations in 1957. These publications of the U. S. Weather Bureau formed the basis for this study.

Information on temperature, evaporation, and relative humidity for Texas is generally adequate in coverage, although not as abundant as the rainfall records. However, since none of these items is as erratic as rainfall in occurrence, the same density of stations as required for rainfall is not necessary. Temperature records were obtained from the annual Weather Bureau publications. Evaporation data were based on publications of the Board of Water Engineers and the Weather Bureau. Relative humidity data were obtained from monthly U. S. Weather Bureau publications for the period 1940 through 1957.

Streamflow data used herein were obtained from the Water Supply Papers of the U. S. Geological Survey and the Water Bulletins of the International Boundary and Water Commission. Records of runoff in Texas generally begin in 1924, although a few records are available for earlier years. The longest continuous record in the State is that for the Rio Grande at El Paso which began in 1889. Other long records include the Brazos River at Waco and the Colorado River at Austin, both of which date back prior to 1900. A gradual increase in the number of gaging stations in Texas took place through the years, with the first large expansion coming in the period 1938 to 1940, when 100 new stations were placed in operation.

Climatologic and hydrologic data for Texas are readily available. These data have been collected by various Federal and State agencies. The situation with respect to the assembly and publication of information relating to the impact of weather on the economy of the State is not so complete. Data pertaining to floods and flood damage have been collected by the Corps of Engineers. Information on past droughts and drought effects have been collected and published by the U. S. Geological Survey in connection with studies covering the United States. The information that is available is not in detail for the State of Texas. A deficiency of information exists with respect to the economic impact of past droughts on the State's economy, although certain general studies have been made as to the effects of the 1950-1956 drought.

Data on the effects of droughts as used in this report have been obtained from publications made available by the Texas State Library, the Bureau of Business Research of the University of Texas, the Department of Agricultural Economics and Sociology of the Agricultural and Mechanical College of Texas, and from the annual reports of the Department of Agriculture, and others.

VARIATION IN ANNUAL RAINFALL

Previous reports (see ref. 11) by the U. S. Geological Survey covering droughts in the United States have used average annual rainfall for each state to show the annual variations. Such procedure is adequate for small areas where there is no great difference in the rainfall characteristics from one part of the area to the other. Many of the smaller states fit into this category. Texas, however, does not lend itself to this treatment. The land area of Texas is approximately 264,000 square miles, with an airline distance of about 800 miles from Dalhart to Brownsville or from El Paso to Orange. Of more importance, however, is the fact that the annual rainfall varies from less than 10 inches in an average year on the western side of the State to more than 50 inches along the eastern boundary. With the great distances involved and the wide variation in annual rainfall, a mean value of rainfall for Texas is not only useless but it is misleading.

In an effort to resolve the difficulties imposed by the size of Texas and the variation in rainfall, and yet show the natural fluctuations in annual rainfall that do occur, the State has been arbitrarily divided into four areas. These areas are of about equal width, which means that there is the minimum variation in rainfall over each. They are not of equal area, but for the purposes they serve, the smaller variation of rainfall in each is of more importance.

The four areas into which the State was arbitrarily divided are shown as small insets, Fig. 1.

The average rainfall over each of these areas was calculated on the basis of selected precipitation stations, all of which have rainfall records that can be extended back to about 1889. This average rainfall in each case is an arithmetic mean derived without weighting. It is not indicated, nor is it assumed, that this average is equivalent to the exact average rainfall over each area. But it is assumed that the figures so obtained provide an index to the rainfall over each area, and adequately reflect the relative fluctuations in the annual rainfall, which have occurred in the past. The number of available rainfall stations within or adjacent to each area varies, with a total of 46 stations involved.

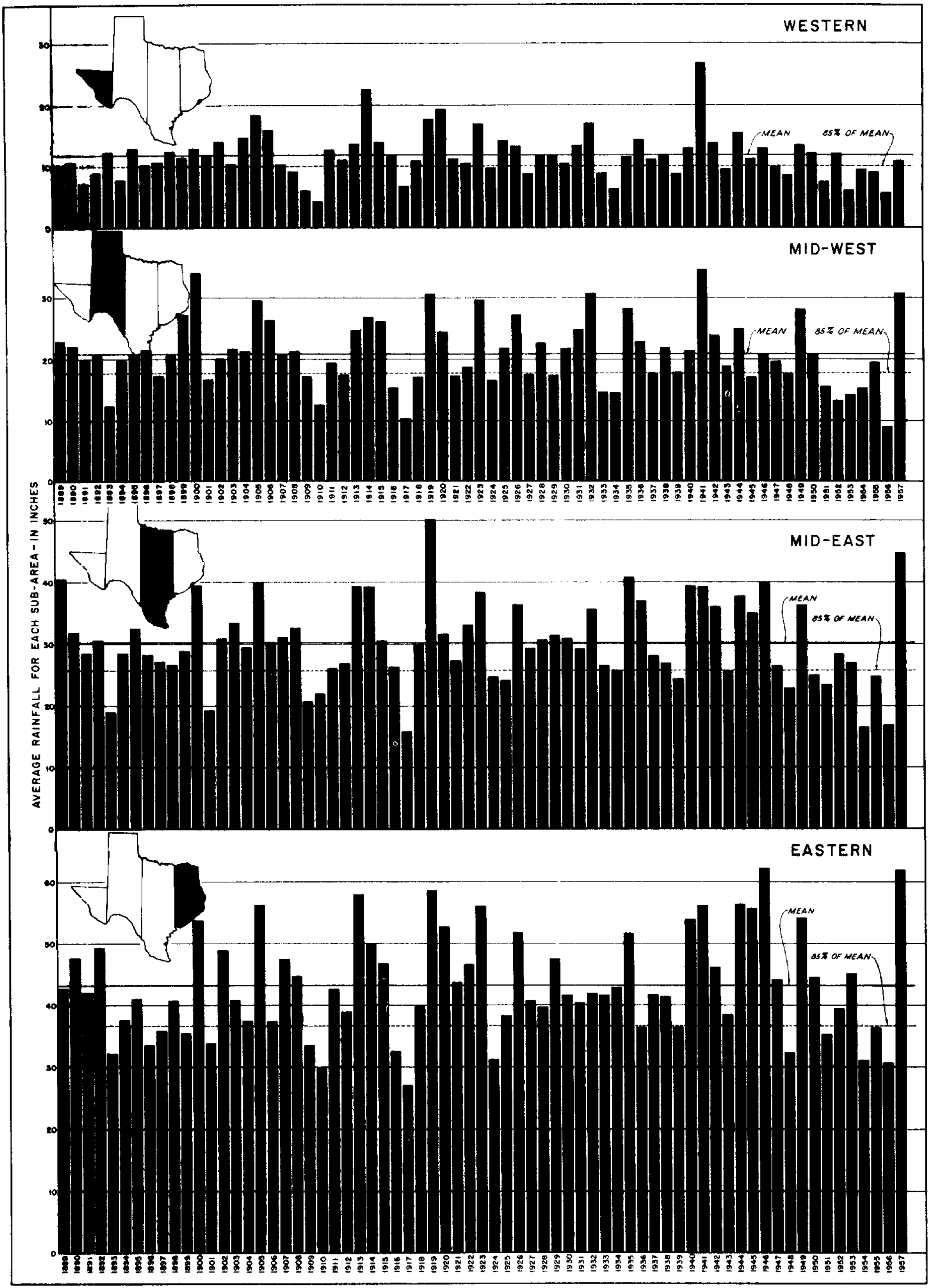

FIGURE 1

VARIABILITY IN ANNUAL RAINFALL FOR FOUR AREAS OF TEXAS

Annual average rainfall for the 69-year period, 1889 through 1957, for each of the 4 areas has been plotted on the chart, (Fig. 1) with the westernmost area represented at the top, and successive areas to the east arranged in order below. The mean annual rainfall for each area is shown in the following tabulation - in which 85% of the mean is also shown:

AREA OF DIVISION	MEAN ANNUAL RAINFALL	85% OF MEAN ANNUAL RAINFALL
Western	11.74"	9.98"
Mid-West	20.89"	17.76"
Mid-East	30.29"	25.75"
Eastern	43.09"	36.63"

Lines representing these figures have been shown on the appropriate charts. Bars showing annual average rainfall values for each of the 69 years are shown on the charts for the 4 areas. The bars on the diagram for each of the respective areas are plotted to the same scale. Thus, the contrasting lengths emphasize the variation in annual rainfall, not only from year to year over the same area, but also they indicate the relative difference in rainfall between different parts of the State.

As previously mentioned the upper diagram on the chart shows the year by year rainfall for the most westerly sub-division of the State. Mean annual rainfall for this area was found to be 11.74 inches. The most noticeable thing about this diagram is the wide range in annual rainfall. Only once in the period of 69 years were there two successive years having approximately the same annual rainfall - that was 1928 and 1929, which both had an annual average about equal to the long-time average. Most of the other years show the rainfall to be either above or below the long-time average.

The extreme range in annual rainfall in the Western area is from about 4.2 inches (1910) to 26.7 inches (1941). Within the period shown, there are 28 years in which the rainfall was above the average; 5 years of approximately average rainfall; and 36 years that were below the average. Of the 36 years in which the rainfall was below average, 18 years had less than 85 percent of the long-time average.

The next chart below shows the annual average rainfall for the Mid-West area, which includes the Panhandle of Texas and the area south to the Rio Grande. Average annual rainfall for this area is 20.89 inches. Only rarely does the annual rainfall happen to coincide with the average, and more rarely does it happen that the same rainfall is observed for two consecutive years. Once during the 69 years covered by this study there were two successive years in which the rainfall was approximately the same in this area. This was in 1933 and 1934, both of which were drought years, with the rainfall far below normal. The extreme variation in annual rainfall ranges from about 9 inches (1956) to 34.4 inches (1941). Within the 69-year period shown, there are 31 years in which the annual rainfall was above average; 4 years of approximately average rainfall; and 34 years in which the annual rainfall was below the average. Out of the 34 years which had below the average, 21 years had rainfall less than 85 percent of the mean annual rainfall.

The next chart, representing the Mid-East area, includes what is generally referred to as central Texas. Average annual rainfall for this area, based on the 69-year record, was found to be 30.29 inches. Only two years had approximately this average rainfall. All of the remainder fluctuated widely either above or below this mean rainfall. There were 32 years in which the annual rainfall was above the average, and 35 years with less than the average rainfall. There were 15 years out of the 35 low years in which the annual rainfall was less than 85 percent of the long-time average. The extreme range in the variation of annual rainfall for this area was from 15.9 inches (1917) to 50 inches (1919).

The lower chart represents the Eastern area, where the long-time average annual rainfall is 43.09 inches. No single year had this exact rainfall. There were 29 years in which the annual rainfall was above the long-time average, while the remaining 40 years had below average rainfall. Three of these years had a rainfall of approximately 85 percent of the average. Out of the remaining years that were below average there were 14 years in which the annual rainfall was less than 85 percent of the average. The extreme range in the variation in annual rainfall was from 27 inches (1917) to 62 inches (1946).

These figures have been summarized in Table 1.

EXTENT AND SEVERITY OF DROUGHTS

DETERMINATION OF DROUGHT PERIODS

The time of occurrence, extent and severity of a number of droughts has been determined for the State in relation to the rainfall records. The preliminary finding of occurrence of droughts was determined by the preparation of mass curves of accumulated annual rainfall at 46 stations with long-time rainfall records covering the period 1889-1957. Forty of these were Texas stations with the remaining six in adjacent states. These stations are listed in Table 2. Periods of rainfall deficiency as indicated by the slope of the mass curves were then studied in detail.

As previously shown the definitions of droughts vary with the type of water use, the place, and the length of time covered by the drought. Hoyt (see ref. 7) used departures from the mean annual rainfall as the criteria for determining drought. Henry (see ref. 12) also indicated that the annual rainfall was adequate for the purpose, as per the following quote:

> "The facts hereinbefore presented lead to the belief that in the great majority of cases the total annual precipitation may be used as a criterion on drought."

Rainfall has been shown to vary for the different areas of the State, and with respect to time at the same location. Rainfall is erratic in point of time whether the unit of study is day, week, month or year. Each precipitation station measures the rainfall at a given point. Since rainfall is quite erratic in reference to area it is evident that some points may have received more rain and some less than the amounts specifically measured in the same general area. However, the past measurements can be utilized as indices of the rainfall for the general area in which the station was located. The calendar year has been used herein as the unit of time for rainfall data.

TABLE 1

RAINFALL VARIATION OVER TEXAS

	Areas of the State			
	Western	Mid-West	Mid-East	Eastern
Average Rainfall in Inches Period 1889-1957	11.7	20.9	30.3	43.1
85 Percent of Average Rainfall	10.0	17.8	25.8	36.6
Minimum Annual Rainfall	4.2	9.0	15.9	27.0
Year of Minimum	1910	1956	1917	1917
Maximum Annual Rainfall	26.7	34.4	50.0	62.0
Year of Maximum	1941	1941	1919	1946
Number of Years with Rainfall above Average	28	31	32	29
Number of Years with Average Rainfall	5	4	2	0
Number of Years with Rainfall below Average	36	34	35	40
Number of Years with Rainfall 85 Percent of Average or Less	18	21	15	17

Average Rainfall

As a base from which to measure deficiencies in rainfall (and that is what a drought is), it was necessary to select a period of rainfall that was common to a sufficiently large number of stations to be representative of conditions over the State. Fortunately, through previous study, it was known that the period from 1924-1956 (33 years) was representative of a much longer time interval, as shown by the comparative figures in Table 2. Also, it was known that about 300 rainfall stations in the State (or immediately surrounding it) had records that were continuous for the period, or that could be extended to cover the period by correlation. This period was, therefore, adopted as the standard time interval for which all departures from the average could be measured.

A map of the State was prepared to show this 33-year average rainfall for all of these stations. Lines of equal rainfall (isohyetals) were then interpolated between the points.

Use was made of many additional stations for individual drought periods, depending upon the span of years for which the records were available. These stations were properly located on the map and the average rainfall was determined from the lines of equal rainfall. All deficiencies have been measured from the common base, as above described.

Rainfall Deficiencies

For all of the early droughts the annual rainfall was listed for each station. As the number of stations increased greatly after 1947, only about 300 selected stations were used for the droughts after that time. The rainfall was tabulated for the full period of low rainfall, plus a year preceding and one year following. The annual departure from the long-time average rainfall for each station was then calculated. With these departures calculated, it was then possible to place the limits on the drought as to beginning and ending.

The years of drought were not always the same for all stations. It frequently happened that the drought started earlier in one part of the State than it did in another part - and the end of the drought was also quite variable. Thus, there were often individual rainfall stations which had deficiencies in rainfall in years either before or after the so-called drought. Only those years were included in the drought period in which the greatest number of stations showed deficiencies.

After the years to be included in the drought were determined, the annual departures from the mean were accumulated for each station and isohyetal charts were plotted showing the accumulated negative departures in inches. These accumulated deficiencies were then converted to an average annual deficiency as a percentage of the mean annual rainfall. These percentages were plotted on the small inset maps of each chart. The areas included within the 15 percent dashed lines on the inset maps were considered to be in droughts. Areas with the higher percentage deficiencies were generally those which had experienced the more severe drought effects.

Descriptions of Historical Droughts

A description of each of the droughts which has occurred since 1889 has been prepared, together with a chart showing the extent of each drought.

TABLE 2

COMPARISON OF AVERAGE RAINFALL FOR TWO PERIODS AT CONTROL STATIONS

Units: Inches

	Average Rainfall	
Station	1889-1956	1924-1956
Abilene	23.61	22.85
Albany	25.23	24.80
Amarillo	20.28	19.34
Arthur City	39.95	40.40
Austin	33.03	31.90
Beaumont	52.03	52.42
Boerne	31.95	30.52
Brenham	39.44	38.30
Brownsville	24.97	26.86
Brownwood	26.49	26.20
College Sta.	37.94	37.90
Corpus Christi	25.58	26.80
Corsicana	36.04	35.89
Crosbyton	20.82	20.80
Cuero	33.90	32.36
Dallas	34.14	32.70
Eagle Pass	20.07	19.51
El Paso	8.18	7.66
Fairland	28.13	27.60
Fort Clark	20.85	19.83
Fort McIntosh	18.83	18.30
Fort Worth	31.56	30.63
Gainesville	35.05	33.87
Galveston	42.80	43.38
Hallettsville	34.86	34.67
Haskell	23.19	23.37
Houston	44.70	43.08
Huntsville	44.73	45.02
Lampasas	29.02	28.92
Llano	24.91	26.62
Longview	43.98	43.38
Luling	31.85	32.11
New Braunfels	30.47	30.81
Palestine	39.26	38.66
Paris	40.60	42.81
Plainview	20.34	19.07
San Antonio	26.39	26.24
Temple	33.89	33.18
Waco	33.53	31.15
Weatherford	31.15	30.69
In Adjacent States		
Mena, Ark.	52.71	52.79
Texarkana, Ark.	46.29	48.72
Shreveport, La.	42.54	44.37
Lk. Charles, La.	56.15	54.81
Ag. College, N. M.	8.19	8.03
Carlsbad, N. M.	13.21	11.61

The duration of these droughts varied from one to four years with the exception of the most recent drought which lasted from 1950 through 1956 in some parts of the State. Droughts of less than one year have not been considered in this study. Other single years of recorded rainfall not included as droughts, had local rainfall deficiencies of 15 percent or more. However, each of these occurred between years of average or greater than average rainfall, and none had either the areal coverage or severity to justify classing them as individual droughts.

Drought of 1891 - 1893

Isolated drought conditions prevailed over parts of the State during these three years. While only about 65 rainfall records were available at this date, they indicate accumulated deficiencies of rainfall in excess of 40 inches in the Beaumont area and more than 30 inches at Luling. The rainfall deficiencies in inches and the average annual deficiencies as percentages of the mean annual rainfall for this drought are shown on Plate I.

Two general drought areas with deficiencies of more than 15 percent of the mean annual rainfall, as shown by the small inset map, involved narrow areas generally along lines between Del Rio and Fort Worth and between Luling and Richmond. Further small drought areas also occurred with widely scattered centers in Harley, Culberson, and Dickens Counties.

While small rainfall deficiencies extended over much of the State, only these relatively small areas were seriously affected. This drought followed several years in which the rainfall had been above average. It is probable that the ground water had not been seriously depleted. It is noteworthy that most of the affected area was in the semi-arid region of the State with only a small portion of the humid area being affected.

Drought of 1896 - 1899

Although records of rainfall for this period are few, they show this to be one of the most severe droughts, in terms of deficiency in inches, that has been experienced since 1889. Three widely separated centers show an accumulative deficiency of greater than 50 inches in the four years. Two of them show a deficiency of more than 60 inches. Of these three centers two are near the coast, while the other is far inland. The two which are near the coast are at opposite ends of the Texas Coastline - one near Brownsville; the other near Beaumont. Paris, near the Red River in northeast Texas, is the location of the third center. These separate centers are shown on Plate II.

The two main surrounding areas that show evidence of the drought are separated, with above normal rainfall in between. The area of greatest deficiency was along the eastern border of the State, and near the coast, where a total deficiency of more than 90 inches is indicated. It undoubtedly is associated with the center in northeast Texas, although a part of the area between the two centers was only slightly affected by the drought.

The center of high deficiency near Brownsville spread northward along the coast, and then extended inland to south-central Texas, with most of this part of the area having only a small deficiency.

As shown by the small inset map, there are two centers in which the average annual deficiency was above 40 percent, with the highest percentage being in the southern tip of Texas, where the maximum deficiency was in excess of 60 percent of the mean annual rainfall. In spite of the fact that the accumulative deficiency in inches was greater in southeast Texas, the percentage deficiency was much less than near Brownsville, because of the higher mean annual rainfall in the Beaumont area.

In terms of the percentage of the mean, and according to the definition which limits drought to those areas with deficiencies in annual rainfall greater than 15 percent, this drought was fairly well limited to south and east Texas, with a few isolated centers scattered elsewhere in the State.

More than three-fourths of the State, including most of central Texas and all of west Texas, seemed to have escaped this drought.

Drought of 1901

This is the only drought that has been considered in this study which consists of a single year (until 1953, which was part of a 3 drought series). The reason for its inclusion is that it followed the 4-year drought of 1896 through 1899 by only one year. Even though it is classed herein as a separate drought, it is quite probable that the effects of the previous drought had not been overcome, and it might more appropriately be handled as a continuation of that earlier drought. In fact, there were only two years of more or less average rainfall over most of the State in the interval between the 1896-1899 drought and the still earlier one of 1891-1893. It is doubtful whether full recovery of the depleted ground-water storage as a result of the first drought had taken place by the time the second drought started. There was practically no surface storage in existence at the time. The accumulative deficiency in inches is shown on Plate III.

Examination of the three charts (Plates I, II, & III) shows that certain areas of the State were adversely affected by all three of these droughts. These areas are along the coast, with the southern tip of Texas and the coastal area of east Texas both being in the drought area for all three periods. Thus, these areas were in drought for eight years out of the eleven during the period 1891-1901. Possibly, the recent drought, which extended generally from 1950 through 1956, was not the longest drought of record.

This early drought had the greater deficiencies in total rainfall through central Texas and the southern part of east Texas. A larger area in northeast Texas was exempt from the drought effects, as well as practically all of the western half of the State.

With the deficiencies shown in terms of the percentage of the mean annual rainfall, on the small inset map, it may be seen that over half of the State was within the limits of 15 percent. The greatest percentage drought was along the Rio Grande, where the deficiency in this single year was more than 70 percent. A large area along the Rio Grande and extending almost continuously to the Red River through central Texas had a deficiency of more than 40 percent.

Drought of 1909-1912

The heart of Texas and well into east Texas was more widely affected by this drought than it had been by most of the others. This drought was more wide-spread. Numerous isolated centers had accumulative deficiencies in rainfall in excess of 40 inches for the four years, and two areas in northeast Texas had deficiencies in excess of 60 inches.

A strip along the border in east Texas, and all along the coast, plus most of the Panhandle and far west Texas apparently missed this drought but all of the remainder of the State showed these rainfall deficits.

The areas affected by this drought are shown on Plate IV.

In terms of percentage of the mean about three-quarters of the State was within the area of drought with respect to the definition which includes all areas with deficiencies in annual rainfall in excess of 15 percent. While the drought was wide-spread the percentage deficiency exceeded 20 percent in only about one-fourth of the area of the State. Areas in which the deficiencies were greater than 30 percent were rather limited, with the largest such area being north and east of Dallas.

Of the early droughts for which there are available records this was the most prominent drought that had been experienced in north-central and northeast Texas.

Low rainfall caused lower runoff, and consequently water shortages were experienced by many of the cities in central Texas. Incident to the water shortages there were serious fires in at least three of the larger cities in Texas: Dallas, Houston and Fort Worth.

Drought of 1916-1918

Most of Texas was adversely affected by this drought as shown on Plate V, with only the extreme western part and the Panhandle being excepted. The greatest deficiencies of rainfall were along the coast and the southern part of east Texas, where a large area indicated deficiencies in excess of 30 inches for the three-year period. Several smaller and isolated areas had deficiencies greater than 40 inches during this time.

In the midst of this wide area that was accumulating deficiencies in rainfall, there were three widely separated areas which had nearly normal rainfall. One of these areas was along the Rio Grande in Starr and Hidalgo Counties. Another extended westerly from San Antonio through Uvalde County. And the third was an area surrounding Dallas and Fort Worth and extending northward to the Red River.

The small inset map indicates that practically the entire State was affected by the drought to a certain extent. Four small areas - all far apart, show deficiencies greater than 40 percent of the mean annual rainfall. Two of these are in south Texas, while the other two are in west Texas. The percentage deficiency was generally greater in west Texas than it was in east Texas, because of the lower mean annual rainfall in west Texas.

Based upon a drought determination defined by deficiencies which equal or exceed 15% of the annual rainfall, practically the entire State was in a drought at this time. Except for extreme west Texas, only two areas were exempt from the effects of this drought. These were the area west from San Antonio, and the other from Dallas and Fort Worth northward to the border of the State.

In the succession of droughts across Texas as indicated by the early rainfall records, this was the most severe in its impact on the economy of the State that had been noted to that time. This was probably not entirely due to the physical shortage in rainfall, which was wide-spread, but due more to the greater population and the increased development that had taken place in Texas since the earlier droughts.

Drought of 1924-1925

This drought, which lasted only two years, affected most of the eastern two-thirds of the State. Accumulative rainfall deficiencies of over 40 inches occurred along the eastern border in Sabine County with deficits of over 30 inches occurring in six more counties in that general area.

Another small area with greater than 30 inches of deficiency was located in the northeastern corner of the State and included parts of four counties. Rainfall deficiencies for the drought are shown on Plate VI.

Deficiencies in excess of 30 percent of the mean annual rainfall as shown on the small inset map were located along the mid-section of the eastern border, along the Red River from Bowie County to Clay County, and in three small areas centered in Blanco, Coryell, and Gonzales Counties. Areas with deficiencies of less than 15 percent, or with no deficiency at all, included the High Plains, extreme west Texas, the Lower Rio Grande Valley, and the central Gulf Coast. The aggregate of these areas amounted to about one-third of the State.

Drought of 1933 - 1934

Notable deficiencies in rainfall during this drought were general across a wide area extending southwest from the northeast corner of the State near Texarkana to the Rio Grande. There was then a bend across the northwestern part of the State in which the deficiencies were not so great. North of this band of small deficiencies, the Panhandle was more seriously affected by the drought. An area all along the coast, and extending inland approximately 200 miles from the coast, suffered only slight deficiencies in rainfall. Most of the southern half of this area actually had more than the mean annual rainfall and an average for the two years. The distribution of this drought is shown on Plate VII.

While the depth of the deficiencies in inches was not great over a great part of west Texas, the drought was much more severe in this section than in central Texas as revealed by the small inset map, which shows the average annual deficiency in terms of percentage of the mean annual rainfall. All of the western half of the State showed a deficiency greater than 15 percent of the mean annual rainfall except two small areas in the Panhandle. Most of this area had a deficiency in excess of 30 percent for the two years, with the maximum deficiency in southwest Texas being greater than 60 percent.

This particular drought in Texas represents the eastern extension of one of the most severe droughts ever experienced on the southern Great Plains. The upper area in the Panhandle was included in what was popularly called the "Dust Bowl".

Details of this drought have been documented by Hoyt with the results published in Water Supply Paper No. 680 - "Droughts of 1930-34".

Drought of 1937-1939

This drought affected two distinct areas entirely apart from each other, and separated by a zone from east to west across the central part of the State. The northern area extended from the Louisiana border northwesterly to the Red River across north-central Texas. The southern area included the entire coastal area and extends west to intersect the Rio Grande all the way from Laredo to Del Rio. The greatest deficiency in inches was along the eastern border of the State near the coast, where the three-year cumulative deficiency was more than 40 inches. Aside from this small area there were several isolated centers in south Texas and along the coast in which the total deficiency within the drought period was greater than 20 inches. In the northern drought area there was only one small area in which the accumulated deficiency was more than 20 inches. The areas affected by this drought are shown by Plate VIII.

In percentage of the mean annual rainfall most of south Texas came within the limits of the 15 percent deficiency which defines a drought. One small area had a deficiency in excess of 30 percent. A relatively small area in north Texas fell in this category, with no high percentage deficiencies.

Drought of 1950-1952

About half of the State was adversely affected by this drought, with accumulative deficiencies in rainfall of more than 10 inches. Even though it was wide-spread, the deficiency in rainfall for the three years was not great except in a few isolated spots. Most of north Texas, the Panhandle, and west Texas were free from its effects, with many spots in central and east Texas also exempt. Three widely separated areas had a total deficiency of more than 30 inches. These areas are shown on Plate IX.

The small inset map, upon which the drought is shown as the average annual deficiency in rainfall in terms of percentage of the long-time average rainfall, shows all of the southern part of the State and most of central Texas included in the limits of 15 percent deficiency.

One thing that made this drought so greatly noticed was that it followed a 10-year period during which rainfall in general was high with both 1941 and 1946 having rainfall much in excess of normal.

Drought of 1953

This year has been handled separately because it is not like the drought years which immediately preceded it, nor is it similar to those three years which followed directly after it. In eastern Texas, along the coast, and several strips in northern Texas there was no drought during the year. Actually, rainfall was in excess of the average in the above areas. Most of central Texas and all of west and southwest Texas, however, had deficiencies in rainfall. This distribution of the drought and non-drought is shown on Plate X. The result of this distribution in rainfall was that part of the State continued in drought while another part got some relief from the deficiencies which had prevailed throughout the preceding three years.

Drought of 1954 to 1956

Most of the droughts that have been experienced in Texas since rainfall records became available have been preceded by one or more years of above average rainfall. This drought is an exception, however. In more than one-half of the State, drought conditions had prevailed throughout the preceding four years. Only parts of the eastern half of the State were afforded a certain amount of relief in 1953.

The drought which started with 1954 proved to be one of the most widespread, as well as one of the most severe that has ever been experienced in the State. All sections experienced deficiencies in rainfall, but these deficiencies were much less along the Rio Grande and in west Texas than elsewhere. Considerably more than one-half of the State, including all of central and east Texas, had accumulated deficiencies in excess of 20 inches for the three-year period. About half of this area had total deficiencies in excess of 30 inches, and a small area extending far inland from the coast had a total three-year deficit of more than 40 inches. The areas affected by this drought are shown on Plate XI.

The small inset map shows that only five rather minor areas scattered across the northern part of Texas, variously located from the Louisiana border to New Mexico, had average annual deficiencies in rainfall that were less than 15 percent. It is probable that the aggregate of these areas was less than five percent of the total area of the State. With the deficiency shown in terms of percentage of the long-time average annual rainfall, it can be noted that more than one-half of the State, including most of the southwest part, plus the upper part of the Panhandle, had an average annual deficit of more than 30 percent, and a large part of this area was short by more than 40 percent of the average annual rainfall.

For the western part of the State where the drought was continuous for seven years, this was the longest drought that has been experienced in Texas. The nearest approach to such a situation in some parts of the State was from 1891 to 1901, an 11-year period in which 8 years out of the 11 were drought years. Since none of the three non-drought years provided much excess rainfall, there was probably a full eleven-year period at that time during which carryover storage would have been required. Lack of development then precluded the disastrous results which are associated with the more recent drought.

Summary of the Eleven Droughts Since 1889

Not all of the droughts which have been experienced in Texas have affected the same area. As a means of comparison, the area that was enclosed by the line representing an annual rainfall deficiency of 30 percent of the long-time average during each drought has been used. These areas each appear on the small inset map, with all droughts represented, except the year 1953, which was not shown in that form. For convenience, the different droughts have been placed into three groups.

The areas affected by the early droughts were generally spotted, as measured by the 30 percent lines. The drought of 1891-1893 shows only three small areas that were so affected. These are all in the southern or southwestern part of the State. The drought of 1896-1899 did not overlap any of these areas of the earlier drought, but affected two areas at opposite ends of the Texas Coast, plus two more smaller areas along the Red River. These first two droughts were of three and four years' duration respectively. The third drought in 1901 was for a single year. The deficiency in rainfall in that one year was wide-spread, enveloping about half of the southern part of the State, plus a much smaller area in north-central Texas. Most of the western, northwestern, and northeastern portions of the State were not seriously affected by any of the three droughts.

The droughts which occurred in the mid-part of the record also varied as to location. The drought of 1909-1912 shows three small areas in which the average annual deficiency in rainfall was greater than 30 percent of the mean annual rainfall. The drought of 1916-1918 was much more wide-spread. The largest area affected was in the southern half of the Mid-West area. Numerous smaller areas in south and east Texas were affected, but in no case did these areas overlap the areas which suffered most in the previous drought. The next drought, which took place in 1924-1925, had a number of scattered centers in which the rainfall deficiency exceeded 30 percent of the long-time mean annual rainfall. All of these were in the eastern half of the State, and they were so distributed that they missed the location of the two previous droughts except for one small overlap in north Texas. The drought of 1933-1934 had a large area within the limits of the 30 percent line, but it was confined wholly to the western half of the State. It overlapped for the most part the large area that was affected by the earlier drought in 1916-1918. This drought was the extension into Texas of a much larger drought centered around the "Dust Bowl", which is made up of parts of five States: Texas, Oklahoma, New Mexico, Colorado and Kansas. After a lapse of two years another drought was in progress within the State during 1937 to 1939. However, it was not as severe as most of the others, and only one small area in south Texas had a rainfall deficiency as high as 30 percent.

The recent droughts, (or the one continuous drought) since 1950, have been more serious than previous droughts, not only because of their severity, but also because of the large area affected. During the early part of the drought (1950-1952) the areas of greatest percentage deficiency in rainfall were the southern and western parts of the State, with the largest concentration of the drought effects in what is generally known as southwest Texas. This was followed by a single year (1953) in which some relief was afforded from the drought in east Texas where it had not been too severe previously. All of west Texas continued to be influenced by drought. Starting with 1954 one of the most severe droughts ever experienced in Texas was under way. It generally increased in severity with each year through 1956. In that time it had spread to include more than half of the State within the limits of the 30 percent deficiency line. West Texas was the most seriously hurt by this drought because it was continuously under drought conditions for more than seven years. In some parts of the western area, there was complaint of drought even prior to 1950.

Further details concerning these droughts have been brought together for comparison in Table 3, with the same four divisions of the State used as before.

Severity of Droughts

The analysis of rainfall deficiencies during drought periods just described with the results given in Table 3 shows the deficiencies in terms of inches and tells when the most serious annual deficiencies occurred. That analysis divides the State into four sections and shows average rainfall deficiencies in each section. Data on rainfall deficiencies in terms of percentage of the mean annual rainfall for each of the four sections are given in Table 4.

The greatest deficiency as a percentage of the mean annual rainfall was taken as the indicator of the most severe drought in each area. This was followed by the second largest percentage deficiency being rated the second most severe drought, and the method extended through the eleven droughts. This order of severity is listed for each area in Table 5. The severity of the droughts on a state-wide basis was determined by assigning a weight of 11 to the most severe drought in each area, a weight of 10 to the second most severe, and continuing to a weight of 1 for the least severe drought in any area. The accumulated weighted values for the four sections were then obtained for each drought. These values indicated the droughts to be in the following order of severity on a state-wide basis.

Most Severe	1954-56	Seventh	1950-52
Second	1916-18	Eighth	1924-25
Third	1909-12	Ninth	1891-93
Fourth	1901	Tenth	1937-39
Fifth	1953	Eleventh	1896-99
Sixth	1933-34		

Since the 1954-56 period is the most severe, and since it is immediately preceded by the fifth and seventh ranked droughts, and since it is a continuing series of years of deficiencies without break, it is indicated that this series comprises the most severe seven-year drought period that the State as a whole has experienced within the period of some 70 years for which rainfall records are available.

TEMPORARY SHIFTS IN CLIMATE DURING DROUGHTS

Texas borders on a desert area, and a part of the State lies in the arid region of the Great Southwest. The State has desert climatic characteristics on one side, with humid conditions prevailing on the other. There is an intermediate zone between the two that is neither arid nor humid. This intermediate area constantly changes and shifts in location over an appreciable distance from year to year as the rainfall varies.

In years of more than average rainfall, the humid area expands and moves far to the west. Agriculture under such conditions proves to be profitable without irrigation over a huge area.

TABLE 3

MAJOR DROUGHTS IN TEXAS
THEIR DURATION AND EXTENT

Date	Duration of Drought in Years	Number of Years between Droughts	Refer. to Years	Four Areas of State			
				Western	Mid-West	Mid-East	Eastern
1891			(1)	2 yrs.	1 yr.	1 yr.	1 yr.
to	3		(2)	6.2	12.4	19.1	32.2
1893			(3)	1891	1893	1893	1893
		2					
1896			(1)	None	1 yr.	None	3 yrs.
to	4		(2)	10.2	17.3	26.6	33.6
1899			(3)	1896	1897	1898	1896
		1					
1901	1		(2)	Normal	16.7	19.3	33.8
		7					
1909			(1)	2 yrs.	3 yrs.	2 yrs.	2 yrs.
to	4		(2)	4.3	12.5	20.7	29.7
1912			(3)	1910	1910	1909	1910
		3					
1916			(1)	1 yr.	3 yrs.	1 yr.	2 yrs.
to	3		(2)	6.8	10.3	15.8	27.0
1918			(3)	1917	1917	1917	1917
		5					
1924			(1)	1 yr.	1 yr.	2 yrs.	1 yr.
to	2		(2)	9.7	16.5	24.1	31.2
1925			(3)	1924	1924	1925	1924
		7					
1933			(1)	2 yrs.	2 yrs.	1 yr.	None
to	2		(2)	6.2	14.4	25.7	41.5
1934			(3)	1934	1934	1934	1933
		2					
1937			(1)	1 yr.	2 yrs.	1 yr.	1 yr.
to	3		(2)	8.7	17.6	24.3	36.4
1939			(3)	1939	1937	1939	1939
		10					
1950			(1)	1 yr.	2 yrs.	2 yrs.	1 yr.
to	3		(2)	7.5	13.2	23.3	35.3
1952			(3)	1951	1952	1951	1951
		None					
1953	1		(2)	6.1	14.1	26.9	45.1
		None					
1954			(1)	3 yrs.	2 yrs.	2 yrs.	3 yrs.
to	3		(2)	5.7	8.9	16.4	30.6
1956			(3)	1956	1956	1954	1956

(1) Number of years in drought period when rainfall was less than 85% of long-time mean annual rainfall.

(2) Average rainfall in inches over area of each section in year of least rainfall.

(3) Year of drought period when least rainfall occurred.

TABLE 4

COMPARISON OF RAINFALL IN DROUGHT YEARS WITH THE LONG-TIME AVERAGE RAINFALL

Units: Inches

No.	Drought Years	Western 11.74 Total Dept.	Western 11.74 Ave. Ann. % Def.	Mid-West 20.89 Total Dept.	Mid-West 20.89 Ave. Ann. % Def.	Mid-East 30.29 Total Dept.	Mid-East 30.29 Ave. Ann. % Def.	Eastern 43.09 Total Dept.	Eastern 43.09 Ave. Ann. % Def.
1	1891-1893	- 6.76	19.2%	- 9.92	15.8%	-12.71	14.0%	- 5.91	4.6%
2	1896-1899	-23.2	4.9%	+ 2.84	0	-10.29	8.5%	-26.89	15.6%
3	1901	- 0.08	0.7%	- 4.15	19.9%	-11.00	36.4%	- 9.29	21.6%
4	1909-1912	-12.84	27.3%	-17.21	20.6%	-25.68	21.2%	-28.59	16.6%
5	1916-1918	- 5.75	16.3%	-20.02	32.0%	-18.59	20.5%	-29.93	23.2%
6	1924-1925	+ 0.23	0	- 3.55	8.5%	-11.83	19.5%	-16.82	19.5%
7	1933-1934	- 8.47	36.1%	-12.78	30.6%	- 8.47	14.0%	- 1.85	2.1%
8	1937-1939	- 3.82	10.8%	- 5.61	9.0%	-11.83	13.0%	- 9.85	7.6%
9	1950-1952	- 3.60	10.2%	-13.47	21.5%	-14.41	15.9%	-10.19	7.9%
10	1953	- 5.72	48.8%	- 6.83	32.7%	- 3.43	11.3%	- 2.06	0
11	1954-1956	-11.02	31.3%	-19.35	30.9%	-33.00	36.3%	-31.34	24.3%
Wtd. Mean%		17.7%		18.7%		18.4%		13.7%	

TABLE 5

ORDER OF SEVERITY OF DROUGHTS AS INDICATED BY DEFICIENCIES OF RAINFALL IN PERCENTAGE OF THE MEAN ANNUAL RAINFALL

Order of Severity	Western	Mid-West	Mid-East	Eastern
1 (most severe)	1953	1953	1901	1954-56
2	1933-34	1916-18	1954-56	1916-18
3	1954-56	1954-56	1909-12	1901
4	1909-12	1933-34	1916-18	1924-25
5	1891-93	1950-52	1924-25	1909-12
6	1916-18	1909-12	1950-52	1896-99
7	1937-39	1901	1933-34	1950-52
8	1950-52	1891-93	1891-93	1937-39
9	1896-99	1937-39	1937-39	1891-93
10	1901	1924-25	1953	1933-34
11	1924-25	1896-99	1896-99	1953

All uses of water increase at these times. Farming receives the greatest benefit in increased yields, which place agriculture on a high economic level, with prosperity widespread. This higher economic level in agriculture takes along with a general improvement in the financial structure throughout the area.

Scarcity of rainfall becomes a thing of the past. Shortages of water, which resulted in hauling water for necessities in some communities, and caused rationing of the supply in many others, are all forgotten. Water supply for the cities creates no problem. Industrial supplies are ample, the reservoirs are full, and the future looks encouraging.

In years of drought just the opposite takes place. The line of sufficient rainfall to produce crops shifts far to the east, and the area that is capable of making a profit in agriculture shrinks materially.

As a result of the deficient rainfall, agricultural yields, and business activity in the area reaches a low ebb. Water in storage, providentially captured during earlier years of ample rainfall, is rapidly depleted, by reduced runoff, by increased demands incident to this drought, greater evaporation losses, due to higher temperatures, along with other climatic factors, all of which combine to reduce the water supply. All of these evidences of drought are visible, but they never seem to make a lasting impression on the public.

On the basis of this shifting climate, there are three distinct agricultural areas in Texas, which may be described as follows:

A. The west, where rainfall is universally inadequate for dry farming, although in exceptional wet years such as 1941 there may be enough rainfall to produce certain grain crops.

B. The east, where there is always enough rainfall to produce a crop, even though the monthly distribution is such that agriculture will occasionally suffer.

C. The intermediate zone, which lies between the above two. It is made up of a strip through the heart of Texas extending from the Rio Grande to the northern boundary, which is some 200 to 300 miles in width, and constantly changing in location. It is man's attempt at agriculture in this shifting zone which magnifies the ill effects of drought.

The intervals between past droughts tell a worthwhile story. Between the end of the first drought for which records are available in 1893 to the beginning of the worst drought on record in 1950, the lengths in years for the respective drought-free periods were as follows:

2, 1, 7, 3, 5, 7, 2 and 10.

The shortest was a 1-year interval, while the longest was 10 years. This means that the time in which there will be ample rainfall is limited between droughts to probably about five years on the average. The time to build up reserves is these years in which there is surplus rainfall. In the later years in which drought envelopes the land, there is not enough water supplied by rainfall to meet the ordinary requirements, and no opportunity exists to build up reserves of any kind.

It is in the intermediate semi-arid zone that disaster so often strikes. The difference in location of the outside limits of this zone between a year of ample rainfall and the low rainfall characteristic of a drought year, has been found to be about 200 miles. This shift is either east or west, depending upon the climatic conditions. The area involved is made up of a strip about 200 miles wide, east and west, by about 500 miles north and south, which would include approximately 100,000 square miles. It can be safely concluded that these periodic shifts in climate frequently involve more than one-third of the area of the State, and in cases of severe drought, can seriously affect up to one-half of the total area of the State.

Drought periods are generally characterized by certain climatic phenomena, which may be briefly described as:

Less than average rainfall
Above average temperatures
Greatly increased evaporation rates
Low relative humidity

All of these climatic factors combine in times of drought against agriculture. Taken individually, the effects would not be so disastrous, but even so, the results could be noted. Figures are available for each of the above factors for many stations scattered throughout the State, which show how they act in time of drought as compared with times of ample rainfall.

An examination of the rainfall records during the drought periods, and a comparison of them with the long-time average rainfall has been made for each of the 11 drought periods. The drought periods were analyzed on the basis of the average annual rainfall for the four areas of the State, with the results as shown in Table 4. The total deficiency, determined as the cumulative departure from the long-time mean for the period covered by each drought, was found to vary with respect to the different areas of the State as follows:

	Total Deficiency in Inches		Wtd. Mean % Departure
	From	To	
Western	0	12.84	17.7
Mid-West	0	20.02	18.7
Mid-East	3.43	33.00	18.4
Eastern	0	31.34	13.7

It can be seen from Table 4 that all parts of the State were not similarly affected by the different droughts. The droughts which were the most severe in one part of the State were frequently of minor severity in other areas. The only drought with any degree of severity in all sections was No. 11, the period 1954-1956, which was third most severe in the western half of Texas, but which ranked second and first in severity toward the east.

Temperature records are available for a large number of Weather Bureau stations back to 1924. The records of mean annual temperature were examined for 24 selected stations scattered throughout the State. The long-time average annual temperature was determined for each of these for the period 1924-1957. The average temperature was then determined for the 14 drought years that have occurred since 1924. The results are shown in Table 6 in parallel columns.

TABLE 6

COMPARISON OF MEAN ANNUAL TEMPERATURES AVERAGE FOR 1924-1957 vs. DROUGHT YEARS SINCE 1924

	Long-Time Average	Temp. in Drought Yrs.		Long-Time Average	Temp. in Drought Yrs.
Abilene	65.2	65.9	Falfurrias	73.4	74.1
Albany	65.1	65.9	Ft. McIntosh	73.8	74.5
Amarillo	58.0	60.9	Gainesville	65.0	66.0
Austin	68.3	69.1	Houston	69.9	70.4
Big Spring	63.9	64.8	Kerrville	64.4	65.2
Bonham	63.9	64.7	Lubbock	60.6	61.2
Brownsville	73.7	74.0	Mt. Pleasant	64.5	64.4
Brownwood	65.6	66.4	Nacogdoches	65.7	66.0
College Sta.	68.7	69.2	San Angelo	65.4	66.2
Corpus Christi	71.9	72.4	San Antonio	67.4	70.1
Dallas	66.2	66.8	Temple	67.4	68.1
El Paso	64.4	64.8	Victoria	71.1	71.8

Temperatures given in degrees F.

The difference between the long-time average temperature and the average temperature during the drought years is 0.8 degrees. At first glance, it would seem that this difference is rather small. But when it is considered that this difference applies to each day in the year, it is not so small after all, amounting to approximately 300 day-degrees. The effects of temperature on water supplies during drought is aptly stated in the Old Testament (Job 24:19), "Drought and heat consume the snow waters."

Data on evaporation rates, published by the Board of Water Engineers (see ref. 13) reveal substantial increases in evaporation rates during periods of drought. With the State divided into four areas as shown in this report, the difference in the annual gross evaporation was determined for each area:

ANNUAL GROSS EVAPORATION

	Ave. 1940-'57	Ave. '50-'56	Percentage Increase
Western	90.1	95.8	6.3
Mid-West	79.8	87.7	10.0
Mid-East	72.0	78.0	8.4
Eastern	50.3	55.5	10.1

A weighted mean for the State shows the annual gross evaporation to be nine percent greater during the seven drought years 1950-1956 than it was for the full period since 1940.

Net evaporation losses are obtained by subtracting the effective rainfall from the gross evaporation figures. Since rainfall is deficient during droughts, the amount of rainfall available to offset gross evaporation is less. Thus the net evaporation rates are higher during droughts on two counts:

(1) The increase in gross evaporation rates, and
(2) the reduction in rainfall which would normally offset part of the evaporation.

These higher evaporation rates further deplete the water supplies which already have been reduced by the low streamflow following years of deficient rainfall. The higher evaporation rates affect not only water surfaces, but also the much larger areas of soil and vegetation.

The fourth item in the list of climatic phenomena which generally characterize droughts is the relative humidity. Records of the relative humidity, taken as the average percent at 12:30 p.m., c.s.t., are available for a number of stations scattered over the State, for most of the period since 1940. These records have been summarized for 14 of these stations as shown in the following tabulation:

Comparison of Relative Humidity for Average Conditions with that During Droughts

Average Percentage (12:30 p.m. cst)

Stations	Long-Time Average Relative Humidity	Relative Humidity in Drought	Stations	Long-Time Average Relative Humidity	Relative Humidity in Drought
Abilene	47.0	41.0	El Paso	33.1	29.7
Amarillo	45.0	39.0	Fort Worth	52.0	46.4
Austin	55.1	50.8	Galveston	70.4	69.6
Brownsville	59.7	57.4	Houston	59.2	56.6
Corpus Christi	61.9	59.0	Port Arthur	62.2	61.0
Dallas	53.5	50.6	San Antonio	53.6	48.7
Del Rio	53.0	48.6	Waco	54.9	52.6

The average relative humidity for the 14 stations for the entire period was 54.3 percent while for the drought period these stations had a composite average of 50.8 percent. The relative humidity during the drought was 3.5 percent lower than for the long-time period, which amounts to a reduction of 6 percent in terms of the long-time period. The nine inland stations were found to have had an average difference of 4.4 percent in the relative humidity between the long-time average and the drought years, while the five coastal stations had a weighted difference of only 2.0 percent.

EFFECTS OF DROUGHT ON TEXAS ECONOMY

AGRICULTURAL LOSSES

Agricultural losses in the State during the 1950-1956 drought were tremendous due to greatly reduced yields or, in some places, no crops at all. Many farmers on the Rolling Plains and Edwards Plateau prepared their land and planted seed during three consecutive years without harvesting a crop. Many ranchmen in these same areas have fed supplemental rations to their breeding herds almost the year around since 1951. The cattle carrying capacity of most of the rangeland was seriously depleted at the beginning of 1957 and even with years of more plentiful rainfall in 1957 and 1958 full rangeland recovery has not been achieved in all areas.

Numerous data of the economic effect of this recent drought are available for given subjects in specific areas. An overall dollar-wise evaluation of all the possible effects on the economy has not been made. The Texas Commissioner of Agriculture in an address at Amarillo in April, 1955 stated (in reference to the drought):

> "We have lost a minimum of 2 billion dollars during this natural disaster -- or one-fourth of our agricultural potential. In other words the equivalent of one entire year of production was wiped out by adverse nature." (Based on four years of drought).

As the drought continued, an article in the Houston Chronicle, January 17, 1957, quoted the State Commissioner of Agriculture as stating the loss to farmers during 1956 alone was 750 million dollars. From the above it is seen that for the years 1950-1954, plus 1956, the agricultural losses were estimated at $2,750,000,000. Since drought also was experienced in most parts of the State in 1955 it is indicated that the loss of crops alone exceeded 3 billion dollars during the 1950-1956 period. These estimates do not include losses to ranchers, nor do they include secondary or indirect losses in the trading areas.

It is not the purpose of this report to present an estimate of the losses that were incurred during the drought. The preceding information is given only to illustrate the magnitude of losses which can occur during a drought. Obviously, when large losses are sustained over a series of years by two of the State's basic economic groups, such as farming and ranching, a marked impact on the State's overall economy must result. This impact during the recent drought was state-wide as shown by the fact that 244 of the State's 254 counties were declared drought-disaster areas. Since the intensity of the drought varied over the State, the impact of the drought on the economy of local or regional areas also varied.

Local areas, where farming or ranching, or both, form the basic economy, had more serious economic problems than the State as a whole. Only 15 counties in Texas had populations exceeding 100,000 in 1957 with the remaining 239 counties having populations ranging from about 98,000 to less than 1,000. While these latter counties have cities and towns with some diversification in economy, the less populous counties generally are geared to an agricultural economy. The counties which had an almost complete agricultural economy suffered most during the 1950-1956 period.

The general effects of drought on agriculture and on the economy of an area may be listed as follows:

1. A partial or complete loss of crops (grains or cotton), resulting in loss of income.

2. Overgrazing of rangelands and pasture, with consequent increased soil erosion.

3. Wind erosion of land following the removal or thinning of the vegetative cover.

4. Selling out of herds, including breeding stock, usually at a loss.

5. Loss of use of land after drought ends during the period of time required to restore land to full use.

6. Cost of beginning livestock operations again after drought and maintaining operations until marketing of new stock is possible.

7. Loss of tax revenue.

8. Insect and pest increases (including grasshoppers) which usually occur in wet years, immediately following drought.

9. Loss of income to commerce in local and regional trade areas.

10. Increased personal indebtedness incurred by farmers and ranchers, which will have a continuing effect in good rainfall years following the drought.

11. Cost of State and Federal drought relief.

The effect of the drought on the financial resources of farm and ranch operators was studied for specific areas of the State by A. & M. College. For the Edwards Plateau area, ranchmen lost 38 percent of their net worth between the fall of 1950 and the spring of 1954. This decline resulted from a 20 percent decrease in assets and a 37 percent increase in liabilities.

The A. & M. Study for the Edwards Plateau area shows: (See ref. 14.)

"Approximately half of the ranchers studied have reached the limit of their credit".

"Ninety-seven ranchmen who obtained emergency loans in 1954 had been granted short term credit amounting to 206 percent of the value of their livestock."

"It is reported that many banks in the area are making few additional agricultural loans and are shifting some high risk credit operations to government agencies".

"Most farmers and small ranchmen are forced to obtain or seek outside employment since gross income from farms and ranches no longer meets the cost of operation and family living".

Other A. & M. information shows: (See ref. 14.)

"Credit institutions have performed well during the drought. There has not been a bank failure in Texas attributable to drought-occasioned losses; although in a few instances stockholders have found it necessary to bolster their capital structure to maintain desired liquidity".

"Farmer's Home Administration emergency credit has been of inestimable value in local economics. This agency has kept many farmers in business, and it has relieved the pressure on other credit organizations."

WINDS

All of the adverse affects of drought on agriculture are not caused by lack of rainfall, although there can be little doubt that the rainfall deficiency is the largest single item. Wind is another climatic factor which always contributes to the detriment of agriculture. This is a part of the vicious cycle which seems to operate in times of drought. Rainfall is scarce; clear skies prevail; temperatures increase; wind comes next, and disastrous soil blowing follows.

The records contain statements concerning the destruction of crops, which can be ruined in a few days under the searing action of the dry winds, such as the following:

Holliday, Archer Co. Dallas Morning News, Aug. 24, 1899, - page 4

> "Hot winds have prevailed for the past week, and as a consequence everything in the way of vegetation is either dead or fast dying...."

More attention has been given to the other wind factor in which the results are more spectacular. That is the movement of the soil with the dust storms furnishing the visual evidence. It has been estimated by the Soil Conservation Service (see ref. 15) that during the three-year period, 1954 to 1956 from 10 million to 15 million acres were damaged by wind on the Great Plains each year. It is indicated that although the dust storms didn't get as much publicity during the recent drought as they did in the Dust Bowl days of the 1930's, the acreage damaged was about the same in both periods.

The cause and effect of the winds during droughts are pointed out by Hoyt, with the comment that possibly damage is not the only result that may be expected. The following quote is from W. S. P. 680, p 51.

> "The principal causes of the disastrous soil blowing in 1933 and 1934 were continuous high winds, intensive cultivation, the practices of burning stubble, low rainfall, and lack of organic matter and soil moisture to hold the soil in place -- - - -.
>
> The surface material over large areas of the country, especially in the arid and semiarid regions, consists in part of loess - that is, wind-blown material that has been deposited throughout the ages and has always been more or less subject to movement by winds when it becomes dry ---- Although the effects have been serious in many localities, they were probably not as bad as would be indicated by the photographs and descriptions that appeared in press statements.
>
> The great mantle of wind-blown silt that covers a large part of the interior of the country indicates that dust storms have been a common occurrence in the geologic past. Although we are now chiefly concerned with the damage done by wind erosion in the recent dust storms, it is interesting to note that to these ancient silt deposits, called loess, is largely due the productivity of the great farming regions included in the Mississippi Valley, and there are many who believe that though the effects in the areas in which the dust originates may be detrimental, there may be counterbalancing benefits in areas in which it is deposited."

DROUGHT AID

Aid to drought-stricken areas is not new. Local, State and Federal governments have in times past assisted families or groups affected by natural disasters such as floods, hurricanes, and tornadoes. Since drought is also a natural occurrence, areas seriously affected by drought have also received financial assistance in the past.

Texas has experienced three periods of drought in which the State Legislature has found it necessary to make appropriations for drought relief in the State. The first was in 1887 when $100,000 was appropriated for the "sufferers in the drought-stricken district". In 1918 the Legislature passed an act which authorized counties to purchase seed and feed for resident citizens who were unable to procure such seed and feed otherwise. It appropriated $2,000,000 in

1918, and in 1919 added $1,000,000 more to carry out the purpose of the act. During the 1950-1956 drought the Texas Department of Agriculture assisted agencies of the Federal government in administering drought relief. An emergency appropriation was approved by the 54th Legislature allotting $43,500 to the Texas Department of Agriculture to offset increased expenses in the administration of the Hay Program.

As the 1950-1956 drought progressed farmers and ranchers incurred progressively heavier financial burdens. Range lands were unable to support even a fraction of the existing livestock and supplemental feeding measures were required. The prolonged continuation of the drought required ranchers to change from supplemental feeding to subsistence feeding, which means that purchased feed formed the major part of the livestock food intake.

In order to assist ranchers the U. S. Government instituted a drought-aid program in 1952, shipping in hay by railroad from points out of state wherever surplus hay was available. This hay was then sold to ranchers at reduced prices. During the year, July 1952-June 1953, 106,296 tons of hay were shipped in and sold under this program. Data on hay prices without government assistance in the drought areas are not available but prices for hay in other parts of the State indicate this aid had a value of approximately $1,000,000.

A grain-feeding program was inaugurated in 1953 in place of the hay program. This government-sponsored aid which continued through 1957, provided ranchers with surplus corn, wheat, oats, and cottonseed cake and pellets at greatly reduced prices.

The amount of direct assistance to ranchers during the 1953-1954 fiscal year was estimated from the number of bushels of grain provided (U. S. Department of Agriculture data) and from the difference between the government selling price and the average market price at that time (Market News Service Data). On this basis this direct assistance was estimated at $9,384,000 for that year. Direct assistance data for subsequent years were obtained from the Agricultural Stabilization and Conservation office, U.S.D.A., at College Station:

Fiscal Year		Direct Assistance
1952 - 1953		$ 1,000,000
1953 - 1954		9,384,000
1954 - 1955		12,663,600
1955 - 1956		5,622,500
1956 - 1957		33,142,700
1957 - 1958		1,800
	Total	$61,814,600

This total does not include the cost of the program administration, nor does it include railroad transportation charges.

In addition to the above, surplus food was distributed in quantity to both farmers and ranchers in drought - designated areas. Data on the amount and value of this aid program are not available.

Two other recent Federal emergency programs were also placed in operation to assist the drought disaster areas. These programs provided for (1) financial assistance to farmers in "dust bowl" areas to permit them to take necessary agricultural conservation measures to reduce wind erosion, and (2) the granting of additional emergency credit to farmers, ranchers, and small business men in the drought areas. Both programs were reported to have been of material aid to the individuals affected, but data on the expenditures for this assistance are not available.

EFFECTS ON MUNICIPALITIES

Municipal water supplies for the larger cities are usually planned in advance of actual need to prevent shortages of water during droughts. This planning basically results from the desire of communities to maintain the existing economy of the area and to provide for its expansion. Maintaining the economy in this sense includes the provision for adequate water supplies for both residents and industry, together with a sufficient reserve capacity for adequate fire protection. Many smaller communities do not have sufficient financial resources to provide more than a minimum reserve capacity, if any at all.

Rapid increases in the per capita water uses and a population that has expanded far beyond previous predictions have resulted in many Texas cities being compelled to ration water at some time during the recent drought. Reservoirs that were in operation prior to the drought, and started out with large reserves in storage, came through without shortage in most cases. Reservoirs constructed since the drought started were not able to store large quantities of water, because of low runoff and the increased municipal demands, with the result that they were only partially effective in offsetting drought conditions.

Data are not available for a quantitative evaluation of the economic effects of droughts on municipalities. Some of these effects, however, can be enumerated as follows:

1. The cost of emergency installation of facilities to provide water supplies. For instance, the city of Dallas constructed a pipeline from Red River to the upper Elm Fork of the Trinity River to provide for emergency water supplies. This source was costly since water from it proved undesireable because of the high concentration of salts.
2. Temporary shortages of water discourage industry and may have precluded the expansion of certain industrial concerns at present locations.
3. Unfavorable publicity relating to water shqrtages probably discouraged the locating of new commercial or industrial enterprises in the water-short areas.
4. The future cost of water will increase since ever larger water-storage facilities will be required to supply a given demand and provide an adequate reserve through even more serious droughts than those that have been previously experienced.

EFFECTS ON INDUSTRY

Industrial water requirements are frequently served through municipal water facilities while some industries have independently developed their own supplies. Development of surface water for industrial uses has usually involved some provisions for reservoir storage, although notable exceptions occur. For instance, the DuPont, Central Power and Light Company, and Union Carbide installations on the Guadalupe River below Victoria are dependent upon the base flow of the river without storage. This base flow consists principally of the discharge of springs along the Balcones Escarpment, which dried up in some cases during the recent drought.

The large investments in industrial plants is such that ventures involving millions of dollars are seldom made on a risk basis. The location and installation of new industrial plants is now contingent upon the adequacy of a water supply during droughts. Those industries which had sufficient reservoir storage were not too seriously affected economically by the recent drought.

However, those entirely dependent upon the natural flow of the streams suffered. The discharge of springs into the Guadalupe River was gradually reduced during the drought and in 1956 only San Marcos Springs continued to flow. Plants dependent upon the natural flow of this stream continued their operations in spite of this loss of spring flow and the absence of flood runoff. However, emergency measures such as the construction of recirculating water systems were required to keep the plants in operation. The Corps of Engineers made emergency releases of water from Belton Reservoir in December 1956 to provide water for the Dow Chemical Company.

The effects of the drought on industry in relation to the State's economy were not pronounced during the recent drought. However the drought made industries aware of water supply problems in relation to maintaining existing operations and planning new or expanded facilities. While Texas has many natural resources favorable to an expanded industrial economy, the problem of providing adequate good quality water supplies at reasonable prices may deter industries from locating new plants in the State. Though not a direct effect of drought, this is an emphasis on an already existing problem due to drought.

While the drought produced tremendous agricultural losses, its impact on the State's economy was less pronounced because of the industrial activity and expansion. The Texas Almanac states: (See ref. 16)

> "These years of drought brought smaller agricultural production and income, but they were years of great activity in all other lines of industry and commerce. Texas, with its mineral, manufacturing and other industries, no longer depended upon agriculture as the chief contributor to its prosperity."

EFFECTS ON IRRIGATION

Water supplies are deficient during droughts, and most irrigation from surface water supplies in Texas was curtailed during the 1950-1956 period. Irrigation from ground water supplies continued, but the cost of operations increased.

Irrigation from surface-water supplies without storage facilities was greatly decreased during the 1950-1956 drought. For instance, the Lower Rio Grande Valley, comprising the largest irrigated area dependent upon surface water in Texas, with the water supply largely unregulated prior to the closing of Falcon Dam in August 1953, experienced shortages nearly each year during the period 1946-1953, as shown by Table 7.

The effects of the drought on irrigation projects with storage facilities varied. A statement (see ref. 17) presented to Congress by C. J. Anderson in 1956 states in part:

> "The Red Bluff System embraces 138,000 acres of land. Ordinarily 45,000 acres of land within the district are irrigated with Pecos River water, although, as the drought took its toll the number of acres which could be irrigated from the river has steadily declined until this year (1956) there were only 6,000 acres being irrigated in Texas with Pecos River water. In 1953 no land in Texas was irrigated from the Pecos River."

The El Paso County Unit of the Rio Grande Project experienced deficient water supplies from 1951 through 1956. During these years the allotment of water per acre was far below normal, varying from .13 acre-feet per acre to 3.0 acre-feet per acre, which is the regular allotment.

Water stored in Possum Kingdom Reservoir was released for downstream rice irrigation needs during five of the seven drought years. These irrigation releases were in addition to scheduled hydroelectric power releases, although hydroelectric energy was generated with the irrigation releases. The following amounts were released from Possum Kingdom Reservoir for irrigation purposes: (See ref. 18.)

Year	Acre-feet	Year	Acre-feet
1951	58,285	1954	100,122
1952	90,000	1955	72,312
1953	112,965		

In addition to the 90,000 acre-feet released from Possum Kingdom Reservoir in 1952, an additional 50,000 acre-feet was "borrowed" from Whitney Reservoir and also released for the rice irrigation. These releases were credited with saving a $5 million rice crop near the mouth of the Brazos River. The 1953 Possum Kingdom irrigation release list above includes the repayment of the 50,000 acre-feet to Whitney Reservoir.

Economic studies of ground-water irrigation in the High Plains made by the Texas Agricultural Experiment Station reflect the following effects of the drought during the 1950-1954 study period. (See ref. 19.)

> "Irrigation expansion and increased water use during the drought and near-drought period of 1950-1954 have caused some significant changes in High Plains water supplies and irrigated farm production requirements. Farmers have lowered pumps, dug additional wells, installed underground concrete tile distribution systems, and more than doubled the hours of pump operating time in an attempt to maintain farm water supplies. On irrigated farms developed before 1950, 85 percent have increased their capital investment by 6,642 dollars, while their irrigated acreage was increased by only 28.9 acres per farm. For the areas as a whole, water use per acre increased 72 percent, pump operating time increased 35 percent and the acres irrigated per well declined 26 percent during the five year period. Increased investment and a lengthened pumping season have raised the per-acre water cost from 7.06 dollars in 1949 to 15.05 dollars in 1954."

TABLE 7

WATER SHORTAGES IN LOWER RIO GRANDE VALLEY

Year	Number of Days of Water Shortage	Reference IBWC Water Bulletin Number	Page
1945	43	15	5
1946	50	16	5
1947	30	17	4
1948	109	18	4
1949	few	19	4
1950	122	20	4
1951	193	21	4
1952	Throughout year	22	4
1953	140	23	4

Information compiled by A. & M. College is particularly pertinent with respect to the economics of some irrigation developments. These data show: (See ref. 20.)

> "All irrigation developments are relatively expensive to install and to operate. This is particularly true for those involving small acreages, small irrigation heads, or low capacity equipment. Since the greater part of the irrigated acreage development during the past eight years falls within the small development category, the economic soundness of many of these developments is questionable. With a return to more normal precipitation, many small scale irrigation developments are likely to be abandoned."

The effect of drought on the Texas economy of lands irrigated from surface-water supplies was a general dimunition of income resulting from reduced crop production or no production. This lack of income by farmers is then reflected by a reduction of related business in the general trade areas. Similar effects were noted in areas irrigated by the pumping of ground-water, where the effect on the economy was less, but still a tangible item due to the increased cost of production of crops.

EFFECTS ON HYDROELECTRIC POWER PRODUCTION

Hydroelectric power installations in Texas are generally operated to produce peaking power. Most of the present installations were installed prior to the 1950-1956 drought, and the estimates of potential power production were based on earlier streamflow records. During the extended recent drought the hydroelectric power production in general was below normal.

Power production at the Possum Kingdom Dam as calculated prior to construction was estimated at 78 million kilowatt hours per year. This estimate has since been revised to 53 million kilowatt hours. During the 1950-1956 drought this latest estimate of generation was reached only in 1950. The production in other years of this period was as follows:

Possum Kingdom Generation During Drought Period

Year	Millions KWH	Year	Millions KWH
1950	57.7	1954	46.9
1951	35.6	1955	43.7
1952	12.5	1956	32.5
1953	23.8		

Shortages in hydroelectric power generation had to be made up by steam-generating capacity. Detailed data on reductions in hydroelectric power production and the amount which had to be made up by steam power plants is not available. The effect of this on the economy of the State was not large because steam-electric generating facilities were available to handle the increased load requirements. If these steam-generating facilities had not been available, power shortages would have occurred, which could have had a serious impact on industrial production.

EFFECTS ON NAVIGATION

Existing navigation facilities in the State are sea-level channels along the Gulf Coast. Since these channels are not dependent upon fresh water supplies there were no economic effects due to decreased navigation caused by lack of water during this drought. Most of the States' agricultural production is transported by railroads or trucks and thus the decrease in crop and livestock production would not be reflected in any significant decrease in water-borne shipping.

EFFECTS ON RECREATION

Drought depleted range lands of vegetation and dried up many small reservoir water supplies. Deterioration of forage and vegetative cover on the watersheds resulted in less available food and sheltered areas for game wild-life as well as domestic livestock. These conditions resulted in smaller game populations and poorer hunting prospects. Many smaller communities in the State bolster their economies by the annual influx of hunters from other areas. Poor hunting conditions during the later years of the drought may have adversely effected these local economies.

Since most of the larger reservoirs of the state provide minimum or dead storage pools, fishing enthusiasts were able to continue their sport during the drought. Smaller reservoirs, which were depleted during the protracted drought, lost income that was normally derived from recreation facilities. Some persons desiring swimming and boating during the drought were inconvenienced by the lack of available facilities and either had to travel farther to take advantage of other facilities or forego the recreation.

When Comal Springs in Landa Park (New Braunfels) ceased to flow in 1956, wells were installed and placed in operation to maintain swimming facilities.

Estimates of the overall effect on the State's economy caused by recreational deficiencies resulting from the drought are not available.

EFFECTS OF DROUGHT ON WATER SUPPLIES

GENERAL

One of the most serious effects of drought is the reduction in streamflow. In Texas, where all runoff is supplied by rainfall, reduced runoff naturally results. Most of the rain that falls is dissipated on the watershed through either evaporation from the soils or transpiration from the plants. These uses take up about 90 percent of the total rainfall as an average for the State. Runoff is consequently limited to the remaining 10 percent of the rainfall. During drought periods, the watershed uses tend to be about as they were before, since nature makes the first use of the rainfall. Runoff, being only the residual, is the first to suffer. The effects of this reduction in streamflow can be shown in a number of different ways. One simple way involves using the figures for annual streamflow at selected gaging stations on such streams as have records of discharge over a long period of time. There are several such stations which provide records since 1924. Certain of these gaging stations have been selected for this purpose from each of the four areas into which the State has been divided. The stations used and the areas in which they fall, are shown in the following tabulation:

- Western -
    - Runoff negligible - no stations selected
- Mid-West -
    - Devils River near Del Rio
    - Nueces River at Laguna
    - Colorado River at Ballinger
    - Brazos River at Seymour
- Mid-East -
    - Nueces River at Three Rivers
    - Guadalupe River at Victoria
    - Colorado River at Columbus
    - Brazos River at Richmond
- Eastern -
    - Trinity River at Romayor
    - Neches River at Evadale
    - Sabine River near Ruliff

The average annual runoff was determined for each stream, in terms of percentage of the mean. These percentage figures for each stream were then combined to obtain the average annual runoff within each respective area - this being also in terms of percentage of the mean. These figures are shown in Table 8.

For each of the three areas of the State that are shown, the first column shows the average annual runoff, as derived from the few gaging stations which had records of discharge for the period since 1924, in terms of percentage of the mean. The next two columns show this runoff separated by years into two groups - first, the runoff in the drought years, and second, the runoff for the years between droughts.

The average percentage of runoff was then derived for each of these separate groups.

In two of the three areas the relation between runoff in the drought years and in the remaining years was identical. These two areas being the Mid-West and the Eastern. The relation found for the Mid-East, which lies between the other two sections, was quite different. The figures for the respective sections are:

Section	Runoff in drought years in terms of the runoff in the years between.
Mid-West	63.5%
Mid-East	47.0%
Eastern	63.5%

With the runoff in drought years being less than two-thirds of that which is experienced in more than half of the years, it is easy to see why water shortages occur. The consequences of these water shortages are far-reaching. The shortages themselves are just the first step in a chain reaction that adversely affects most of the population in the distress area before it is over.

Another way in which the effects of drought can be measured is by the drawdown of reservoir storage that takes place when water supplies dwindle.

TABLE 8

AVERAGE ANNUAL RUNOFF IN PERCENTAGE OF THE MEAN

	Mid-West				Mid-East				Eastern			
Year	% of Mean R. O.	In Drought Years	Between Droughts	% of Drought/Others	% of Mean R. O.	In Drought Years	Between Droughts	% of Drought/Others	% of Mean R. O.	In Drought Years	Between Droughts	% of Drought/Others
1924	65	65			112	112			122	122		
1925	150	150			72	72			46	46		
1926	158		158		89		89		109		109	
1927	65		65		92		92		109		109	
1928	99		99		57		57		53		53	
1929	78		78		128		128		119		119	
1930	161		161		120		120		96		96	
1931	80		80		86		86		73		73	
1932	260		260		162		162		145		145	
1933	66	66			47	47			92	92		
1934	39	39			69	69			92	92		
1935	266		266		223		223		145		145	
1936	160		160		189		189		43		43	
1937	54	54			68	68			67	67		
1938	119	119			145	145			102	102		
1939	85	85			46	46			59	59		
1940	61		61		152		152		132		132	
1941	216		216		257		257		185		185	
1942	83		83		148		148		125		125	
1943	42		42		52		52		53		53	
1944	53		53		148		148		162		162	
1945	69		69		163		163		201		201	
1946	66		66		160		160		201		201	
1947	83		83		92		92		112		112	
1948	121		121		39		39		76		76	
1949	124		124		87		87		109		109	
1950	72	72			66	66			152	152		
1951	34	34			29	29			36	36		
1952	20	20			36	36			53	53		
1953	52	52			71	71			119	119		
1954	141	141			27	27			33	33		
1955	134	134			45	45			49	49		
1956	24	24			23	23			30	30		
Total	3300	1055	2245		3300	856	2444		3300	1052	2248	
Mean		75	118	63.5		61	129	47.0		75	118	63.5

Table 9 shows the reduction in storage at nine reservoirs during recent drought periods.

During the most recent drought there was a reduction in storage of nearly 2-1/2 million acre-feet during the progress of the drought for nine reservoirs for which records are available. The many smaller reservoirs in Texas were similarly affected with the result that there was a total reduction in the water in storage of probably three times the loss on the nine listed reservoirs.

An interesting commentary on the runoff conditions in the State is indicated by the references to the Texas streamflow conditions in the USGS monthly publication "Water Resources Review". These references were listed and the number of occurrences in each of four categories were summarized. These data, contained in Table 10, were then accumulated for four periods as shown below.

Period	Texas Not Mentioned	Stream Flow Above Normal	Deficient Runoff or Drought	Miscel-laneous	Total
1941-1957	46	69	86	3	204
1941-1949	40	40	25	3	108
1950-1956	6	20	58	0	84
1957	0	9	3	0	12

During the 1941 through 1949 period deficient runoff or drought was mentioned for only 25 months out of a possible 108 occurrences or for 23 percent of the time. In the dry years, 1950-1956, deficient runoff or drought was mentioned for 58 months out of a possible 84, or 69 percent of the time. The references to deficient runoff during these dry years were made three times as often as during the previous nine years.

EFFECTS ON MUNICIPAL WATER SUPPLIES

Many municipal water supplies dwindled during the recent drought and some were exhausted completely. These deficiencies in water supply were largely the result of a combination of the following factors:

1. Decreased runoff - consequence of deficient rainfall.
2. Increased municipal demands in water supply.
3. Increased development and interception of the runoff on the watersheds upstream from the city reservoirs.
4. Decreased recharge to ground-water reservoirs.

The decreased runoff has been described herein above. Increased municipal demands result from increased population since storage facilities were constructed, the general increase in per capita daily use of water, and the lack of rainfall which further increases per capita uses during droughts. Included in the per capita use is additional water for such things as air-conditioning, lawn sprinkling, and swimming pools, all of which require larger volumes in time of droughts. Increased development, in addition to the above, has taken place on the watersheds further reducing runoff to the reservoirs during the drought. These increased developments include the construction of reservoirs for municipal and other uses, the installation of stock tanks and flood retardation structures, and the general application of agricultural

TABLE 9

RESERVOIR STORAGE REDUCTION IN TIME OF DROUGHT
(1000 A. F.)

Drought	Reservoir	Max. Storage Preceding Drought	Mo.	Min. Storage After Drought	Mo.	Diff. in Storage
1916-1918	Medina	258.1	May 1915	61.8	Dec. 1918	-196.3
1924-1925	Medina	211.7	Jun. 1924	97.3	Mar. 1926	-114.4
1933-1934	Bridgeport	80.0	May 1933	3.2	Aug. 1934	- 66.8
	Lake Dallas	185.2	Feb. 1932	47.7	Jan. 1934	-137.5
	Medina	233.4	Mar. 1933	71.2	Apr. 1935	-162.2
1937-1939	Bridgeport	122.6	Apr. 1937	49.4	Jan. 1940	- 73.2
	Eagle Mtn.	178.8	Jan. 1937	147.2	Mar. 1940	- 31.6
	Lake Dallas	156.2	Apr. 1937	42.5	Mar. 1940	-113.7
	Medina	278.3	Jun. 1936	1.8	Oct. 1940	-276.5
	Buchanan	932.8	Jun. 1939	601.4	Mar. 1940	-331.4
	Brownwood	150.3	Jul. 1938	106.9	Jan. 1940	- 43.4
	Red Bluff	296.0	Jun. 1937	28.4	Sep. 1940	-267.6
1950-1956	Bridgeport	317.7	Jul. 1950	7.5	Sep. 1956	-310.2
	Eagle Mtn.	220.6	Jul. 1950	65.1	Sep. 1956	-155.5
	Lake Dallas	211.6	Aug. 1950	21.5	Sep. 1956	-190.1
	Medina	48.2	Jun. 1949	2.2	Dec. 1954	- 46.0
	Possum Kingdom	698.2	Jul. 1950	275.1	Apr. 1953	-423.1
	Buchanan	998.9	Apr. 1949	409.4	Feb. 1952	-589.5
	Lake Travis	966.0	Jun. 1949	337.0	Jun. 1952	-629.0
	Brownwood	133.8	Jun. 1951	90.5	Feb. 1953	- 43.3
	Red Bluff	115.0	Feb. 1950	14.4	Sep. 1952	-100.6

TABLE 10

NUMBER OF MONTHS TEXAS RUNOFF MENTIONED IN WATER RESOURCES REVIEW

Year	Texas Not Mentioned	Stream Flow Above Normal	Deficient Runoff or Drought	Miscellaneous	Total
1941	5	6		1	12
1942	7	4		1	12
1943	2	2	8		12
1944	5	5	2		12
1945	3	7	2		12
1946	4	8			12
1947	5	2	5		12
1948	3	2	7		12
1949	6	4	1	1	12
1950	2	5	5		12
1951	2	3	7		12
1952	0	3	9		12
1953	1	3	8		12
1954	0	3	9		12
1955	0	2	10		12
1956	1	1	10		12
1957	0	9	3		12
	46	69	86	3	204

conservation practices on the watersheds. The most effective run-off-reducing practices are contour plowing and terracing. Decreased recharge to ground-water reservoirs was a direct result of deficient rainfall. In some of the ground-water reservoirs, an expansion of municipal, industrial, and irrigation uses of ground water accentuated the effect of the decreased recharge, and water levels declined through the period. This lowering of water levels in some areas was accompanied by a small increase in concentration of dissolved salts.

The decrease in available water supplies from both surface and ground water sources during the 1950-1956 drought has pointed up the need for a re-evaluation of the supplies which can be obtained from existing facilities, which have proved inadequate in many cases, together with the preparation of plans for new projects which will provide adequate water supplies in future droughts for an even larger population and expanded economy. In some areas the development of additional water supplies for existing and proposed municipal uses will require costly projects. The unit cost of water is going up and may well limit the future development of certain cities and towns in the arid and semi-arid areas of the state.

Data compiled by the Sanitary Engineering Division of the Texas Health Department as of July 1, 1953, listed 8 communities hauling water, 28 towns using emergency sources of supply, and 77 municipalities rationing water. In some of the latter cases, rationing was not due to insufficient water supplies, but due to the lack of adequate distribution facilities. This was particularly true in cities which had experienced large increases in population within a relatively short time. The data relating to municipalities with water problems during 1953 are contained in Tables 11, 12 and 13.

A later compilation by the Health Department listed 21 municipalities supplementing their water supplies and 21 municipalities hauling water during the drought. These municipalities are listed in Table 14. These tabulations were made on the basis of available information and may not be complete.

The effects of the drought caused many cities and Water Control and Improvement Districts to provide additional facilities to supplement their water supplies. The development of these additional facilities permitted a reduction in the number of municipalities experiencing water shortages during the latter stages of the drought.

These data are contained in the following tabulation. In this tabulation the term "areas" is used to designate municipalities or water improvement districts.

	1951	1952	1953	1954	1955
Areas Provided New Water Systems	17	23	29	23	41
Areas Provided Additional Wells	113	92	137	96	69
Areas Provided Additional Ground or Elevated Water Storage Tanks	27	-	32	70	56

	1951	1952	1953	1954	1955
Areas Provided Additional Water Pumping Facilities	30	-	19	49	23
Areas Provided New or Expanded Surface-Water Treatment Plants	22	51	25	-	13

Some of the cities developing emergency water supplies had to use water which contained undesirable concentrations of dissolved salts.

The Health Department summary notes:

> "Our records also indicate that at least 33 populated areas provided new impounding water reservoirs or developed new sources of water supply."

With reference to stream pollution effects during the drought the Health Department summary states:

> "With diminishing stream flows, sporadic complaints of stream pollution have been received from farmers and ranchers involving noticeable effects of salt water upon their usual source of water supply. Several municipalities also have expressed some concern as to the possible effect of the discharge of treated effluents from plants upstream upon the quality of raw water. In several instances also sources of water supply of rather poor quality have been developed as emergency supplies. This inferior quality is a result of not only some oilfield brine pollution, but also considerable natural pollution."

Further information as the effects of the drought on municipal water supplies is given in a preceding section relating to the effects of the drought on the economy of the State.

EFFECTS ON INDUSTRIAL WATER SUPPLIES

Water supplies for all purposes were drastically reduced over most of the State during the 1950-1956 period. Industries in general were not seriously affected because provisions for more adequate water supplies had been made. By 1956, however, surface-water reservoirs were largely depleted and some industries had to augment their supplies from other sources, or provide for the reuse of existing supplies.

The water supplies for industries dependent upon existing facilities need to be re-evaluated if expansion of industrial plant capacities is contemplated.

The effect of the drought on industrial supplies has already been shown in the diminution of yields from existing facilities. Industries requiring larger and more firm yields of water to withstand future droughts are faced with the prospect of having to bring those supplies to their location from more distant sources with increased costs, or new plant facilities will have to be located where assured supplies are available or can be obtained at reasonable costs.

Additional related information on the effects of drought on industries is given in a preceding section on the Effects of the Drought on the State's Economy.

TABLE 11

MUNICIPALITIES USING EMERGENCY SOURCES OF SUPPLY*
July 1, 1953

Alamo - Using large capacity wells which are privately owned
Anson - Developed 13 small wells
Brownsville - Drilled wells but water of poor quality
Byers - Pumping water 3.5 miles from spring to water treatment plant
Clyde - Lowering well pumps
Corpus Christi - Using wells located near Cambellton which discharge into Nueces River. Also planning to use industrial wells near Mathis.
Donna - Using large capacity wells which are privately owned
Edcouch - Using cannery wells and drilling city wells
Edinburg - Drilled emergency wells
Electra - Using 16 wells located approximately 8 miles from City. Planning to lay pipeline from dam to pump water into intake tower.
Elsa - Drilling emergency wells
Gordon - Laid emergency pipeline to town of Mingus. At present, a permanent line is being laid to Thurbar Lake, which is owned by the T & P Railroad.
Harlingen - Drilled emergency wells
Iowa Park - Using two shallow wells when use of new lake water is discontinued.
Jacksboro - Extended raw water intake line to deeper water
McAllen - Using cannery wells
Mercedes - Drilled emergency wells
Mission - Drilled emergency wells
New Castle - Hauled water from Graham, until recent rains, but may have to continue hauling operations
Olney - On June 29, City started using well producing salt water to furnish water to distribution system. Established central dispensing point for supplying drinking water.
Petrolia - Drilled shallow wells in Lake. Water pumped to treatment plant.
Pharr - Drilled emergency wells
Raymondville - Using cannery wells
Rotan - Using old gyp water well
San Benito - Drilled emergency wells
San Juan - Using privately owned wells
Sweetwater - Using wells near Roscoe
Weslaco - Using cannery wells

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*Data from State Health Department

TABLE 12

MUNICIPALITIES RATIONING WATER*
1953

Alamo
Alamo Heights
Anson
Amarillo
Aspermont
Benjamin
Blanco
Bowie
Brady
Breckenridge
Bridgeport
Brownsville
Burkburnett
Byers
Bynum
Childress
Clyde
Corpus Christi
Copperas Cove
Crane
Cross Plains
Decatur
Donna
Dublin
Edcouch
Edinburg
Electra
Elsa
Gonzales
Gordon
Granbury
Graham
Harlingen
Harrold
Holliday
Houston
Iowa Park
Jacksboro
Karnes City
Lake Worth
Laredo
Lipan
Llano
Los Freznos
Matador
Mathis
McAllen
Megargel
Menard
Mercedes
Mission
New Castle
Nocona
Olney
Petrolia
Phillips
Port Isabel
Post
Quanah
Raymondville
Rio Grande City
Rio Hondo
Roma
San Antonio
San Benito
San Juan
Slaton
Snyder
Spofford
Stephenville
Sweetwater
Throckmorton
Thorndale
Weatherford
Weslaco
Wichita Falls
Zapata

NOTE: Some rationing above due to inadequate distribution facilities in areas with rapidly expanding populations and water requirements rather than deficient supplies.

TABLE 13

COMMUNITIES HAULING WATER*
1953

Aspermont - Hauling water from Rule
Benjamin - Hauling water from Iowa Park
Hamlin - Hauling water from Rule
Harrold - Hauling water from Electra
Megargel - Hauling water from rural wells
Roby - Hauling water by individuals
Spofford - Hauled from Del Rio
Weinart - Hauled by individuals

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*Data from State Health Department

TABLE 14

MUNICIPALITIES SUPPLEMENTING WATER SUPPLY* DURING RECENT DROUGHT

Cleburne
Coleman
Coolidge
Corsicana
El Paso
Fabens
Gladewater
Gordon
Hamlin
Henrietta
Marlin
Mineral Wells
Muenster
Nederland
Roby
Rosebud
Temple
Terrell
Texarkana
Tornillo
Waco

MUNICIPALITIES HAULING WATER DURING RECENT DROUGHT

Aspermont
Benjamin
Coolidge
Deport
Edinburg
Forney
Harrold
Hamlin
Hubbard
Megargel
Paint Rock
Port Isabel
Roby
Rosebud
Royse City
Roxton
Spofford
Talpa
Temple
Thorndale
Thrall

NOTE: These listings are made on the basis of available information and may not be complete. Some duplication exists between the two lists as a few municipalities supplemented their water supplies by hauling water in railroad tank cars.

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*Data from State Health Department

EFFECTS ON IRRIGATION WATER SUPPLIES

Irrigation is the artificial application of water by man to produce crops when there is insufficient rainfall to meet plant requirements. During average rainfall years irrigation is needed in many marginal areas, where the amount of water applied by man may not be large. However, during droughts, a larger amount of irrigation water must be applied to make up for the lack of rainfall.

Irrigation projects using surface-water sources usually do not have full water supplies through severe drought periods. During the 1950-1956 drought those projects in West Texas incurred varying degrees of water shortage. The most severe shortages occurred in the Red Bluff Water Power Control District near Pecos where a 100 percent shortage occurred in 1953.

Irrigation in areas where ground water is used is similar to that where surface water is used. Droughts increase the amount of water needed for plant requirements. These increased water requirements combine with decreased recharge, which is a natural result of the drought, to cause a substantial lowering in water levels in the ground-water reservoirs.

Prolonged drought has stimulated irrigation development throughout Texas. The irrigated acreage in Texas has more than doubled in the past eight years. Data compiled by A. & M. College indicate that (see ref.20)

> "....farmers have relied on stock tanks, creeks, sewage effluent; low capacity wells and deep wells as sources of water supply. Many of these developments are much smaller in acreage irrigated and in irrigation head than the developments made before the onset of the present drought."

Needless to say, many of these small projects in the western part of the State were only partially successful, because most of the small ponds and many of the creeks were dry when the needs were greatest, due to the low runoff in combination with the increased evaporation losses incident to the drought.

EFFECT ON WATER SUPPLIES FOR HYDROELECTRIC POWER

Hydroelectric power operations in Texas are operated to produce peaking power. The two general types of operation installed in the State are:

a. Those largely dependent upon flood waters, with related major reservoir storage facilities, and

b. Those largely dependent upon spring flows with only minor storage capacity.

The units included under category (a) are:

Reservoir	Stream
Lake Texoma	Red River
Possum Kingdom	Brazos River
Whitney Reservoir	Brazos River
Lower Colorado River Auth. (6 units)	Colorado River
Red Bluff Reservoir	Pecos River
Falcon Reservoir	Rio Grande

Whitney Reservoir and Falcon Reservoir were placed in operation during the drought. In both instances the generation of hydroelectric power is secondary to certain other reservoir purposes.

Whitney Reservoir pretty largely operates for power on releases made at Possum Kingdom Dam. Only a relatively small capacity for conservation is involved, with the vast capacity of the reservoir above that for power being reserved for flood control. Records of reservoir contents show that the storage has been below the normal operating level for months at a time. Since releases at Possum Kingdom have also been reduced during the drought, the total power generation has been substantially less than full capacity.

Falcon Reservoir is an internationally owned structure operated primarily for irrigation, with flood control storage on top of a large conservation capacity. Power generation is limited to the amount that can be obtained from the irrigation releases. Since this reservoir began storing water in August 1953, the contents have varied widely from near empty to near full stage. As a consequence, the generation of power has been quite irregular.

Power generation data are not available for the Lake Texoma installation, but reservoir-content records indicate water in storage to have been below the maximum power pool level during the period August 1951 to April 1954, July 1954 to May 1955, and November 1955 to April 1957. Since low flow was the chief cause of the lower reservoir contents, power production was naturally lower than it was before the drought.

Data from the Annual Water Service Reports of the Board of Water Engineers for the power generation at Possum Kingdom Reservoir for the drought period has been given in a preceding section of this report. During the 1950-1956 period the total annual production averaged about 36 million kilowatt hours, or only 68 percent of the latest anticipated power production. Records of annual power production at Possum Kingdom, as shown in Table 15 for the period 1943 through 1956, indicate the drought period generation to be about the same as the generation during the seven years preceding the drought. During both seven-year periods the average annual generation has been only about two-thirds of the anticipated power production.

Hydroelectric power generation at Possum Kingdom Reservoir listed in Table 15 includes secondary power generated from irrigation releases for downstream rice growers. These irrigation releases reduced the water in storage and lowered the stage of the reservoir. With the lower reservoir stages less power could be generated with a given quantity of water. Power production at Possum Kingdom was limited during the drought due to deficient runoff and the lowering of reservoir stages by the release of water for irrigation.

Four of the Lower Colorado River Authority power units have been in operation since 1941 and two units (Marble Falls and Granite Shoals) beginning operation 1951. The latter two units have been excluded from drought comparison data, since they furnish no data for the period prior to the drought. Annual water service reports on file with the Board of Water Engineers contain data on the power generated at Buchanan, Inks, Mansfield and Tom Miller Dams. These data are shown in Table 16 for the individual units and accumulated by years. The average annual energy generated during the 1941-1949 pre-drought period was 339 million kilowatt-hours. During the drought period only 202 million KWH were generated by these four units, or about 60 percent of the previous

TABLE 15

HYDROELECTRIC POWER GENERATED
AT POSSUM KINGDOM RESERVOIR UNIT
BRAZOS RIVER

Units: Millions of Kilowatt-Hours

Year	Total Energy Generated
1943	42.1
1944	12.0
1945	25.0
1946	45.6
1947	37.6
1948	26.8
1949	52.2
1950	57.7
1951	35.6
1952	12.5
1953	23.8
1954	45.9
1955	43.7
1956	32.5

NOTE: Data from Annual Water Service Reports on file with Board of Water Engineers.

TABLE 16

HYDROELECTRIC ENERGY GENERATED BY FOUR LOWER COLORADO RIVER AUTHORITY UNITS

Units: Millions of Kilowatt-Hours

Year	Buchanan	Inks	Mansfield	Tom Miller	Sum
1941	109.8	51.1	146.1	84.1	391.1
1942	168.7	49.9	108.7	62.2	389.5
1943	57.2	28.9	181.3	69.8	337.2
1944	77.1	41.0	194.0	70.9	383.0
1945	58.9	28.7	219.2	79.3	386.1
1946	73.3	38.3	192.4	75.2	379.2
1947	50.9	26.7	154.1	63.2	294.9
1948	48.6	26.7	105.7	43.8	224.8
1949	64.2	32.0	122.9	47.2	266.3
1950	33.2	14.7	88.0	35.0	170.9
1951	69.2	32.0	62.8	39.4	203.4
1952	39.7	19.2	53.2	24.1	136.2
1953	32.9	14.0	79.9	29.4	156.2
1954	60.0	22.4	90.7	31.6	204.7
1955	92.2	36.8	165.6	49.6	344.2
1956	49.7	21.4	96.5	32.5	200.1

NOTE: Data from Annual Water Service Reports on file with Board of Water Engineers.

average. Annual generation values are shown to fluctuate considerably during the drought as a result of the irregular water supply. This system was fortunate in that a significant storm in 1952 replenished the storage which had been badly depleted before then.

Red Bluff Reservoir has a small hydroelectric power unit which is operated in conjunction with irrigation releases. Deficient water supplies and low power heads precluded the effective operation of this power unit during the drought.

Two streams in the State have hydroelectric power installations in series which are in category (b) page 49. These units are on the Guadalupe River below New Braunfels and on the Devils River above Del Rio. Both rivers are spring fed streams which had high base flows during the pre-drought period. The sum of the energy generated by the nine small low-head units on the Guadalupe River and the sum of the two units on the Devils River is given in Table 17. These data have the following averages:

Guadalupe River Units		Devils River Units	
Period	Average Annual Generation Millions KWH	Period	Average Annual Generation Millions KWH
1942-1949	72.6	1940-1949	11.9
1950-1956	27.2	1950-1956	8.1

During the drought the Guadalupe River units generated only 37 percent of the pre-1950 average annual energy production while the Devils River units produced 68 percent of their pre-drought average generation. These reductions in energy production are directly related to the reductions in spring flow of these two streams during the drought.

The spring flow on both of these streams is up again, but they will be the first to suffer when the base flow drops down incident to deficient rainfall.

EFFECTS ON NAVIGATION WATER SUPPLIES

Existing navigation facilities in the State are sea-level channels along the Gulf Coast. Since these channels are not dependent upon fresh water supplies they were not affected by low streamflow. Related discussions on the effects of drought on navigation are contained elsewhere in the report.

EFFECTS ON RECREATION WATER SUPPLIES

Decreased runoff and increased water demands reduced the amount of water in storage in Texas reservoirs during the drought. In some instances, particularly with small reservoirs, recreational activities of boating, fishing, and swimming had to be curtailed. Since most of the large reservoirs have minimum or dead storage pools their recreational facilities were able to continue operations. Additional information on the effects of the drought on recreation are given in other sections of this report.

TABLE 17

HYDROELECTRIC ENERGY GENERATED BY UNITS ON GUADALUPE AND DEVILS RIVERS

Units: Millions of Kilowatt-Hours

Year	Sum of 9 Units Guadalupe River	Sum of 2 Units Devils River
1940	*	12.95
1941	*	12.83
1942	79.60	13.93
1943	60.46	14.43
1944	89.74	10.88
1945	86.18	9.87
1946	86.95	10.10
1947	78.46	8.84
1948	41.58	8.63
1949	58.06	16.85
1950	43.33	13.26
1951	30.40	7.25
1952	37.83	4.97
1953	39.91	4.89
1954	19.00	10.28
1955	15.30	10.50
1956	4.71	5.64

*Data not available for these years.

NOTE: Data from Annual Water Service Reports on file with Board of Water Engineers.

CONSIDERATION OF PAST DROUGHTS IN THE DESIGN OF WATER-SUPPLY PROJECTS

GENERAL

Water-supply planning ordinarily includes, among others, that phase of hydrology which pertains to the development and use of surface runoff. Planning, in this sense, is usually thought of in terms of regulating and making useful, part of the water now serving only non-beneficial purposes. There are many ways in which this can be done. One of the first possibilities lies in re-evaluating existing projects to determine whether they can be rehabilitated or expanded to provide additional water in such a manner that it will fit in with existing and future demands for water. It must be understood that planning, no matter how efficiently it may be handled, cannot create additional water. The result of proper planning will, however, make more water available for certain uses at the time it is most needed. A further point for consideration in planning which is often overlooked is the fact that the control and regulation of water always reduces the total supply, because, whenever water is placed in storage for later use nature exacts a toll in the form of evaporation losses. Under present scientific knowledge, there is no way by which this toll by nature can be eliminated, although a start has been made in this direction through the application of certain chemicals to reservoir surfaces, which are known to reduce evaporation losses.

After the possibilities of expanding existing facilities have been exhausted, there is no alternative but to secure the necessary water supplies through the construction and operation of new reservoirs.

While many new reservoirs will be needed in Texas, their construction with related appurtenant works does not comprise the entire water picture. Droughts have been shown to have caused serious effects to the agricultural economy of the State. Changes in agricultural practices and land use do cause changes in surface runoff. Thus, the use of rainfall on the watersheds of the State has a direct bearing on water supply planning, which includes reservoirs. The possible changes of existing agricultural practices is discussed later herein.

It is axiomatic in hydrology that with short periods of record more severe floods and droughts will be experienced than any that have been observed by man. The National Summary for Drought, states: (See ref. 21.)

> "The severity of the present drought has in general equalled or exceeded that of any other drought occurring in the same area since the beginning of precipitation records about the middle of the 19th century. Tree-ring data suggest that there have been no droughts of substantially greater severity in western and southwestern United States since about 1670 and perhaps not since 1570."

It is suggested that the 1950-1956 drought be utilized as the critical period in planning studies which are basin, multi-basin, or state-wide in scope, since (1) the recent drought appears to be more representative of conditions incident to a very severe drought; (2) it may be a single occurrence more representative of a longer period of record than is now available; (3) better records of runoff are available for the 1950-1956 period than for previous droughts; and (4) this drought was severe over all of Texas. Projects of smaller scope which are more local in nature may have experienced a more severe local drought than that during the 1950-1956 period. For these smaller projects these other droughts should be investigated and used whenever practical.

MUNICIPAL WATER SUPPLIES

Planning of water supplies for municipalities usually requires estimating the water requirement for some future date and determining the means to fulfill these requirements. If surface-water reservoirs are to be the sole source of the desired water requirement, these reservoirs must be capable of meeting the full requirement of the city 100 percent of the time. It is only prudent and most municipalities demand that their reservoirs be so designed that there will be available a reasonable reserve supply after furnishing full requirements through the most severe drought of record. This reserve would provide a factor of safety to cover all contingencies that may be caused by increase in water use not previously anticipated, a more severe drought than previously experienced, or a combination of these two, or other occurrences. Therefore the minimum standard in planning for municipal supplies from surface runoff should provide that reservoirs afford the desired yield 100 percent of the time (without shortage) and with the reservoir conservation pool still not empty at the end of the critical period.

The reserve necessary at any point has to be determined in relation to local conditions, and cannot be covered by a general definition.

INDUSTRIAL WATER SUPPLIES

Industrial water supplies as used herein means: (See ref. 22.)

> "Water to be used in processes designed to convert materials of a 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 hydroelectric."

These industrial uses include the tremendous petroleum, chemical, and petro-chemical plants in Texas together with the municipal and privately owned stream-electric plants and the many other plants. Many of the petroleum, chemical and petro-chemical processes require large quantities of water. Regardless of quantity this type of industry represents multi-million dollar investments. Such investments are usually made on the basis of availability of adequate water supplies. Any reduction in the water supply below plant requirements would reduce the industrial output, which would in turn adversely affect the economy of the area. Steam power plants with an obligation to consumers, (both private dwelling and industrial) must likewise have a full supply 100 percent of the time. H. R. Drew states: (See ref. 23.)

> "Water supply for steam plants must have 100 percent availability. Otherwise curtailment of power generation would result with a corresponding burden on the power companies and their customers. The quality and continuity of electric service has steadily been improved and I am sure that no power company would consider building a water supply which might prove inadequate to its needs during drought periods. In fact, the water supply must be adequate to meet future growth, or the plant location will be uneconomical."

Thus the minimum standard of planning for industrial water uses should be the same as that for municipal water supplies.

IRRIGATION WATER SUPPLIES

Reservoirs for irrigation purposes are planned and operated in a different manner than these for municipal or industrial supplies. Municipal and industrial supply reservoirs are usually operated to maintain a given demand throughout the complete period. In so doing the reservoir storage is kept as high as possible. Evaporation losses are therefore higher than they would be if the reservoir were drawn down early in the drought period. This early drawdown to supply the full demand as long as possible is a general practice on irrigation projects where certain water shortages are contemplated and permissible. By having some reasonable water shortages the irrigation project can supply larger areas with water in high or average runoff years and smaller areas during extended droughts.

Irrigation projects usually allocate water in advance of the growing season and farmers within the project can plan their operations accordingly. If a full water supply is allocated the farmers can prepare all their land for irrigation. If an allocation of only one-third is made the farmer can prepare one-third of his land for a full supply, or try to use less water on a larger area.

In a report on the Red Bluff Project, Pecos, Texas, Erickson states: (See ref. 24.)

> "Careful analysis indicates that nothing would be gained by attempting to operate Red Bluff reservoir on an ideal demand basis. Historical operation of the reservoir has been about as efficient and productive as possible under the conditions prevailing. Such operation is consistent with practices now being followed by several irrigation projects in the Southwest. The ideal demand concept is more significant where adequate storage is available to more nearly equate to average long-time flow."
>
> "Red Bluff's water supply is essentially from flood flows of a most erratic nature. Experience in other areas has shown that a water supply of that kind requires storage capacities of from three to five times the average annual flow in order to approach the point of equating releases. However as the storage ratio increases the net yield generally decreases due to mounting evaporation losses."
>
> "Operation of the reservoir on the historic pattern is justified for two reasons:
>
> 1. Floods in the basin above Red Bluff being the chief source of supply, recurrences of floods similar to those which have occurred since the beginning of the century, when records were first started, can be expected in a statistically random pattern. To realize the greatest conservation of this type of water supply, and due to the limited reservoir capacity releases must be made on a short term basis according to the available supply.
>
> 2. Cotton being the most important cash crop of the area can be grown in most years, including those of ordinary short supply,

> since there will generally be water enough to service the acreage which can or should be planted to this crop. Other crops will suffer to a greater or lesser extent depending on whether the recurrence of the flood pattern follows that of the 1920's or the decade from 1943 to 1952."

"The nature of the water supply governs the reservoir operation and demands that every possible conservation measure be taken, as well as good farm practices and management."

These statements bear out the general thought that an irrigation project must equate its operation to the available supply. Storage facilities will usually have sufficient carryover storage to supplement below normal runoff for a few years. If the drought extends over a longer period shortages are inevitable.

Most irrigation projects designed and constructed by the U. S. Bureau of Reclamation make allowances for some permissible reservoir shortages. The amount of these permissible shortages varies with the location of the area, and runoff characteristics, together with the amount of reservoir conservation capacity. No set limits are prescribed although some general "rules of thumb" have been used in initial planning studies:

1. On a long-term record basis the average annual shortages should not exceed 5 percent of the annual project requirement.

2. The shortages during any 10-year period should not exceed an aggregate of a single year's full annual project requirement.

Irrigation shortages will cause some economic hardships for project water users. The hardships will in a measure depend upon the kind of crops grown. For instance, vegetable crops, which require only a 90 to 150 day growing season, can be shorted, and there is still left an opportunity to replant, or produce another crop. Under such circumstances, the hardship might not be too severe. However, if the crop is an orchard, which, if lost, would require years to put back in operation, the hardship could be serious. Severe, prolonged shortages may indicate the project is not feasible. Since economic justification for irrigation projects will govern the overall design, and since runoff characteristics vary through the State, maximum permissible shortages should not be adopted as a design criterion, but alternate studies of proposed projects should be made and final selection of permissible shortages should be based on economic considerations.

Interest in irrigation has increased over the State during the past decade, and particularly during the drought years. U. S. Census of Agriculture data indicate the major portion of the increase in irrigated land has been from the use of ground water. Studies made at A. & M. with reference to irrigation planning state: (See ref. 25.)

> "Interest in irrigation is increasing over the entire state, even in the more humid sections. In order to irrigate, farmers are resorting to the use of stock tanks, creeks, sewage effluent and wells in addition to allocations from major streams. The Department of Agricultural Economics and Sociology of A. & M. College has pointed out that the recent drought in Texas has led to economic ventures into irrigation agriculture of

> questionable soundness, predicting that many of the small scale operations are likely to be abandoned when more normal precipitation returns."
>
> "The study above emphasizes the necessity of planning irrigation farming on a sound basis and of considering it a means of intensifying farm enterprises with all of the attendant problems, rather than a mere 'crutch' to be used in times of drought. It further points out that in areas of declining water tables irrigation will in time cease to be economical and thus will shift to new areas with more dependable water resources."

The need for adequate advance consideration of potential irrigation projects in Texas in line with the above quoted thoughts cannot be over emphasized.

HYDROELECTRIC POWER SUPPLIES

Existing hydroelectric power installations in Texas are all used for intermittent short duration daily peaking power purposes in conjunction with large power systems. This is the only way that peaking power can be utilized efficiently. H. R. Drew states: (See ref. 23.)

> "In order for hydroelectric power to be most useful to the power system, it must be a replacement for steam generating capacity whenever required, even though it is used for peaking. To put it another way, the power company must be able to defer the construction of the same amount of kilowatts of steam capacity in order to be able to afford the purchase of hydroelectric peaking power. This is important because it means that water must be held behind the dam at all times in order to assure that a head is available to generate power whenever the power company schedules it and this of course means that that much storage capacity is not available for water supply purposes."

The inclusion of hydroelectric generating facilities in planning of new reservoirs in Texas will most likely be a secondary use, which can be developed incidental to other water requirements. The power generation schedule for these reservoirs must be patterned after the primary water conservation requirements of municipalities, industry and irrigation. The development of hydroelectric potential then becomes a matter of determining the amounts of power which could be generated with reservoirs operated during the drought for the aforementioned purposes.

WATER SUPPLIES FOR NAVIGATION

Planning of multi-purpose reservoirs with conservation storage space for navigation purposes will require consideration of other water uses in the area. Vast amounts of water would be required for the development of a stream to provide for a sustained flow which would make navigation feasible. Unless reservoirs for re-regulating navigation water releases are provided, large quantities of water would waste to the Gulf of Mexico. During future drought periods all available water will be needed for municipal, industrial, and irrigation uses, and little will be available for navigation purposes. Planning for navigation facilities may have to consider the economics of navigation projects which would operate during average runoff periods with alternate means of transpiration used during droughts.

RECREATION WATER SUPPLIES

Planning of multipurpose reservoirs is generally governed by criteria for the principal reservoir purposes with recreational considerations of a secondary nature. Most multipurpose projects have small portions of the lower section of the reservoir reserved for anticipated future sediment depletions. These "dead storage" pools usually provide for the continuation of recreational facilities and activities during drought periods. Reservoirs constructed solely for recreational use will require only enough water to offset evaporation losses in order to continue operations through a drought.

EFFECT OF WATERSHED CHANGES ON WATER SUPPLIES

Numerous changes have taken place on the watersheds of the State as water resources have been developed. Hundreds of medium and large reservoirs, and thousands of small reservoirs and ponds have been constructed. Agricultural conservation programs have been instituted to reduce erosion and increase infiltration of water into the soil. Municipal, industrial and irrigation water uses all have increased with time. In recent years a tremendous expansion has occurred in the development of ground-water resources.

It is not the purpose herein to evaluate any of these existing or potential uses, but rather to describe generally their proper treatment with respect to the design of water-supply projects.

Beneficial watershed uses can be separated into two general categories, i.e., those which intercept rainfall (and prevent runoff) and those which store and divert runoff. The first category includes the agricultural conservation practices of contour plowing and terracing, while the latter generally includes reservoir construction and consequent municipal, industrial, and irrigation uses. The development of programs or projects under either category will effect the available water resources of downstream areas. Thus the initiation, completion, modification, or discontinuation of any upstream project must be considered in the design of water-supply facilities.

Streamflow records are obtained under historical runoff conditions, i.e., the records reflect the watershed uses and conditions at the time measurements were made. Streamflow records obtained for previous conditions must be corrected when additional development takes place on drainage areas above the gaging stations. When increased depletions occur, these earlier records must be reduced to make them representative of a common condition of development. These runoff records, under a common condition of development can then be utilized in the design of water-supply projects.

The effects of upstream watershed developments are particularly noticeable during drought periods when rainfall is generally deficient. Agricultural conservation programs and some reservoir projects may cause only minor downstream reductions in runoff when considered on a long-term average basis. However, the effects of these programs are amplified during droughts or deficient rainfall periods and serious runoff reductions may occur.

It is also possible that some increases in runoff can occur. This may be caused by discontinuing an existing water use, the importation of runoff from outside the basin or the modification of an existing use. In these instances the corrections of streamflow records would be positive. The discontinuation of uses might include the reduction in irrigation or industrial water uses for a variety of reasons. The importation of runoff by a municipality from an outside source would require a correction for the additional municipal sewage effluent. Modifications of existing uses could be by the change in reservoir operations by converting an existing reservoir from a hydroelectric generating operation to one supplying a municipal, industrial, or irrigation demand. Under hydroelectric power programming the reservoir is held at the highest permissible stages to develop as much head as possible, with large evaporation losses occurring. If the reservoir is used for other primary conservation uses the stages would be considerably lower with a consequent reduction in evaporation losses. The difference in evaporation losses would require corrections in the water-supply design studies.

ADDITIONAL CONSIDERATIONS

A meeting was held in Wichita, Kansas in January 1957, following a tour of drought disaster areas by President Eisenhower and his advisors. Representatives of State and local groups presented numerous suggestions relating to immediate drought assistance and long-range planning for drought areas. These suggestions were compiled and published in House Document No. 110, 85th Congress, 1st Session. One section of this publication contains recommendations pertaining to water-resource development and is quoted herein in full. (See ref. 26.)

"1. Present Programs in the field of water-resource development and conservation have aided in alleviating disaster from drought and flood. It is believed that these programs should be accelerated and implemented through the following means and in complete cooperation and coordination between Federal, non-Federal, State, and private interests:

(a) Every agency having jurisdiction over reservoirs immediately review its operating criteria with the view of meeting urgent needs by -

Making releases of water from dead storage space not under contract.

Reallocating or encroaching upon existing storage for flood control, navigation, and fish and wildlife in order to provide conservation space on a temporary basis.

(b) Water development and conservation programs currently under construction or authorized for construction in the drought areas be financed adequately even if this requires the granting of priority to construction in these areas.

(c) Water development and conservation programs now under construction, authorized but not started, or being designed, should be reviewed to assure that full advantage is taken of every opportunity to provide conservation space to meet the water supply needs of the drought area.

(d) Water development and conservation programs in the drought area, planned but not yet authorized, be given expedited consideration by all agencies concerned and by the Congress.

(NOTE - There was a substantial body of opinion that the phrase 'planned but not yet authorized' be stricken from the sentence. Also that 'projects' was a more appropriate term than 'programs' as used under item 1. The sentence following was also suggested as an addition.)

Special attention should be given to small irrigation developments that are dispersed over the Great Plains area utilizing the small irrigation projects and the watershed-protection and flood prevention programs.

(e) Multiple-purpose reservoirs be planned and developed by the Federal Government with provision for providing storage for anticipated future maximum water needs, without requiring preconstruction repayment commitments for such storage and that Congress authorize such action.

(f) Immediate attention be directed to conserving water by elimination of phreatophytic growth (water-loving plants and woody-type growth) and to their replacement by species requiring less water where necessary to prevent erosion. Attention should be given to means to eliminate salt intrusion and contamination in order to avoid pollution of the limited supply.

(g) Special consideration be given to repayment requirements of water development and conservation programs in the drought area.

2. There is agreement that the solution to our water-supply problems must start with a sound program of soil conservation. The way we manage our rangelands, farms, and forests on which water first falls largely determines the extent and nature of water runoff and the amount that soaks into the soil.

3. The development of small watersheds in the disaster States be accelerated by additional planning parties under Public Law 566.

(NOTE - Items 2 and 3 were inserted at the suggestion of several respondents. Item 2 was used in reporting to the President at Wichita.)

4. Because of the danger of overdraft of ground-water basins, it was urged that where present State laws are not adequate to regulate the use of ground water, each State enact legislation applicable to the varying problems within that State.

5. The group recommended that the allocation of soil-bank funds to areas where ground-water irrigation is practiced and ground-water supplies are critical be increased to encourage the conservation of water and thereby avoid delayed economic disaster in those areas. This will encourage full participation in the acreage reserve program by all interested farmers, and will provide additional incentive for participation in the conservation reserve program in those areas.

(NOTE - This recommendation deals with matters beyond the purposes of the soil-bank program. Even if desirable, it would be unworkable in terms of the formula for allocating funds.)

6. When water supply is limited, competition for use should be resolved so as to result in the best use of the water to meet the needs of the area. Such decisions should be in conformity with applicable State and Federal laws.

7. The program for pollution abatement under Public Law 660 is not now being utilized to bear especially upon drought emergency problems. The rate of development established by the program is too slow to meet desirable progress in sewage-pollution abatement. It was recommended that either (a) appropriations be increased to the point where immediate needed work can be undertaken or (b) the law be modified as necessary to give special consideration to the drought area.

(NOTE - The desirability of recommending an increase in appropriation was questioned. The following addition was also suggested: In areas of critical water shortages, intensive Federal, State, and local cooperative efforts should be made to (1) develop all available sources of water supply and (2) make the optimum use of available water by water quality management which will permit the reuse of water which is subject to manmade or natural pollution. Within the area of its recognized responsibilities, the Public Health

Service should concentrate on work with State agencies in planning for the development of domestic, municipal, and industrial water-supply needs for the immediate and foreseeable future in drought areas. Such actions would also include investigations concerning specific problems of water pollution confronting the drought area with a view of recommending a solution of such problems.)

8. Basic records on quantity and quality of surface and ground water are essential to current operations and future plans. Programs for collection of these records should be expanded. Interpretive and evaluation studies are a necessary corollary to basic record collection and should be expanded in order to make best use of data needed for water control and use.

9. A particular need is the prosecution of investigation of ground water by the United States Geological Survey in collaboration with States and other agencies. Rate of progress of ground-water exploration has been shown by the present drought to be inadequate, and the areal coverage insufficient. Funds should be provided to accelerate this program.

(NOTE - A change in the cost-sharing arrangement to speed up this work was suggested.)

10. Present hydrologic investigation needs strengthening to resolve more quickly possible conflicts among uses of water which are likely to be competitive for limited water supplies. Foremost among these are upstream reservoirs and conservation measures, their effects on downstream water supplies, effects of diversion of water on quality and quantity, value of water spreading, brush eradication, and controlled burning on water yields (increasing the productive uses of water).

11. Additional basic and applied research on hydrologic processes and techniques is essential for managing water to minimize harmful effects or periods of deficient moisture. Special attention should be given research on uses of water, evaporation suppression, artificial recharge of ground-water aquifers, sediment transport and channel maintenance, streamflow forecasting, saline-water conversion, and control of pollution. With a view to reducing transpiration losses, chemical means and plant-breeding research deserve particular emphasis.

12. Acceleration of basic research in the field of long-range weather forecasting and cloud physics should be explored."

WHAT CAN BE DONE ABOUT FUTURE DROUGHTS

Probably the earliest authentic account of a drought is found in the Bible, Genesis 41, in which there is recounted the dream of Pharoah and its interpretation by Joseph. The drought described was predicted seven years in advance, and came to pass as foretold. So far as known that is the one and only time that a prediction of drought was heeded, and something was done about it in the years of plenty to afford relief in the destitute years that followed. Once the Egyptian plan had crystalized it was placed in operation by what may be considered the first public works agency under the direction of Joseph.

Droughts can be foretold today. By the very nature of things droughts are bound to occur. Rainfall, which supplies all of the water annually visited upon Texas, is quite variable, being affected by the circulation of air about the earth. Just as sure as there are years of plentiful rainfall there will be years of low rainfall.

The drought of recent date is uppermost in the minds of the public, and many have jumped to the conclusion that it was the most severe that has ever been experienced. There is ample evidence, however, to indicate that there have been other droughts of greater severity, and also of greater duration, even though they occurred several hundred years ago. Just when another such drought will strike and overspread Texas is difficult to say. It can be predicted with certainty, however, that there will be a period of lower than normal rainfall that will soon follow the wet years that are being experienced in 1957 and 1958. Whether the deficiency in rainfall that results in that period will be severe and of long duration remains to be seen.

Since droughts will recur man must prepare for them if he is to continue the civilization and economy he has established. Texas could benefit by the lesson of Egypt's preparation for drought under the direction of Joseph. This preparation involved:

1. The development of a plan on a country-wide basis.
2. Placing the plan in operation under the direct supervision of a single agency headed by Joseph.
3. Preparing for drought in times of plenty.
4. Providing reserve amounts, or placing in storage more grain, etc., than was needed by the immediate area.
5. Formulation of rules for distribution of such reserves in the years of distress.

All of these factors are pertinent to planning in Texas for the mitigation of future droughts. While Joseph's work was directly related to irrigated agriculture, the Texas planning must also include municipal and industrial water requirements, both of which take higher preferential ratings than irrigation. The state-wide aspect of water planning offers Texas an opportunity to provide for future droughts and minimize their effect. That this is not only an opportunity, but is an obligation that may be placed in State hands, is indicated by the attitude of the Federal Government as expressed by the President at the conclusion of his inspection tour of the drought-stricken areas early in 1957. In a message to Congress on March 5, 1957, concerning the alleviation of droughts, President Eisenhower stated in part: (See ref. 27.)

> "I draw, in particular, two general conclusions which I want to call to the attention of the Congress:
>
> The first is that administration of emergency disaster programs must be kept close to the local people.
>
> The second is that State and local governments should assume a greater part in alleviating human distress and hardships and in meeting other local needs in times of disaster, calling on the Federal Government only to supplement their own resources."

The development of a plan for Texas will not help the State in any way unless the various parts of the plan are put into operation. This is not intended to imply that the State will have to construct projects, but rather that leadership in the project design and construction will have to be furnished by the State.

Construction of reservoirs during a drought comes under the heading of "too little - too late". In order for reservoirs to perform their designated functions they must be placed in operation before droughts occur, since it is only during these pre-drought years that there will be surplus flood waters which can be stored for use during the lean years to follow.

The development of reservoir sites should include the design for the optimum water development of the site. In some instances immediate uses or customers for all the developed water supply may not be available. Under these circumstances it appears the State should study all possible means of interim financing of this additional storage capacity. These reserve capacities will provide protection against future droughts, and also permit some projects to supply water for new municipal, industrial, and irrigation uses.

Reservoirs are often cited as the "cure-all" for the State's water problems with reference to drought this is not necessarily true. There are all kinds of reservoirs. When properly qualified, reservoirs can provide water supplies to sustain the State's economy through drought as well as flood years. These reservoirs must have sufficient storage to be able to carryover water from periods of surplus through periods of shortage. Small reservoirs may be of some assistance to minor local needs, but they can hardly help regional or state-wide requirements.

Large reservoirs referred to as multipurpose projects are designed to furnish water for more than one purpose. These multipurpose projects, if the storage is adequate, can provide water supplies for municipal, industrial, and irrigation uses, as well as perform the functions for flood control and recreation. While these large units with proper design can accomplish these results, they are costly to plan and construct. Joint efforts under the general direction of the State will be required to accomplish this tremendous planning task.

While large reservoirs can provide for municipalities, industries, and irrigation projects, they can do little to assist the farmer or rancher. Much has been written about the hazards incident to agriculture in areas where rainfall is rarely sufficient to produce full crops. A large part of Texas is so situated with respect to rainfall. In the western area, comprising about one-fourth of the State, the total rainfall is dissipated by evaporation and transpiration, leaving no surplus to gather in the channels and provide running streams. The rainfall in this area is not adequate to satisfy the full requirements of vegetation. Such vegetation as exists is made up of the desert type shrubs, which have adapted their existence to the meager water supply available. The eastern part of the State lies in a humid region, where the annual rainfall is always more than adequate to meet the requirements of evaporation and transpiration, with a surplus left over to provide the runoff. It is this runoff which forms a cushion in drought years between the total rainfall and the plant requirements.

The limits of these eastern and western areas cannot be fixed, because they change with the climate. Nearly half of the State falls between the two. It is this middle area of Texas, in which the rainfall is very unstable, that suffers most in times of drought. It is in this area that water supplies first fail. Reservoirs go dry, and streamflow dwindles. Facts relating to the unstable conditions have been recognized for years-but they have always been unheeded. Hoyt (see ref. 28), in discussing this situation, makes the following statement:

> "In 1873 the Director of the United States Geological Survey (W. J. Powell), in testifying before a Congressional Committee on public lands, indicated that most of the country lying west of Minnesota was an arid region and in the main could not be used for agriculture except by irrigation. Five years later he reiterated this statement before another committee. While irrigation has been successfully carried on in the arid sections, unfortunately it has not been found economically feasible in most semiarid sections. The United States Weather Bureau has repeatedly expressed cautions against any great extension of agriculture in the semiarid States."

In discussing the line which "separates the eastern half of the United States, where the mean annual precipitation normally exceeds the evaporation and transpiration, from the western half, where, except in mountainous areas and along the coast, the mean annual precipitation is normally less than the demands of evaporation and transpiration" - Hoyt (see ref. 29) again states:

> "Powell in 1878 recognized the significance of this line of demarcation. If his recommendations had been followed millions of dollars of drought relief would have been saved, and what is even more important, many present-day problems of rehabilitation, resettlement, and soil conservation would be largely non-existent, for Powell saw with exceptional foresight the necessity for the adaptation of man to soil and climate."

This line of demarcation, as above described, comes down across the approximate center of Texas.

Some parts of the State are wholly unadapted to agriculture, and yet they have been converted from range land to crop land - even though the rainfall is adequate to produce crops only in those years in which the total rainfall exceeds the long-time average. Of course in such areas there are an equal number of years in which the rainfall is less than the average. All such deficient rainfall years, widely acclaimed in the press under the heading of drought conditions, do not necessarily signify that drought conditions actually exist - but only lend credence to the fact that lands have been put under the plow which never should have been cultivated in the first place.

Technical literature contains numerous references to the need for development that is compatible with the rainfall and water resources of the area. Agricultural development in the State is primarily on an individual farm basis, and because of this the type of development generally varies. One farmer may be conservative while his neighbor may plant higher value, greater water-using crops with the hope of ample rainfall. Publications available from A. & M. College provide data on agricultural risks in relation to rainfall for three areas of the State. These and other publications can assist the individual farmer in planning his agricultural program for his own farm. Technical assistance is also available to farmers through the various agencies of the A. & M. College system and the U. S. Department of Agriculture.

Farmers can likewise develop physical means of conserving the available rainfall through the installation of terraces and the use of contour farming methods.

A new program that should provide relief from some of the adverse effects of drought is now available through crop insurance. The following material on this subject is taken from the 1958 Yearbook of Agriculture: (See ref. 30.)

> "Insurance does not prevent loss. It spreads the losses of a few among many. By paying a small, definite amount annually a person gets assurance that his burden of possible losses may be distributed over a period of years. Insurance can help stabilize farm income by assuring that even in the event of a disaster a farmer will have some cash to meet his obligations --".
>
> "All - risk Federal crop insurance was available on one or more crops in 818 counties in 1957. More than 330,000 producers were insured."
>
> "This insurance covers the unavoidable natural causes of loss, including drought, flood, hail, wind, frost, winter kill, lightning fire, excessive rain, snow, hurricane, tornado, wild animals, insects, and plant diseases and such other unavoidable causes as may be determined by the Federal Crop Insurance Corporation, which makes the insurance available."
>
> "This coverage is essentially a guarantee."
>
> "Multiple-Peril crop insurance was offered for the first time in 1956 in seven States by about 60 stock insurance companies---
>
> The 1956 multiple-peril crop insurance program got started late, and fewer than 100 policies were sold. These policies covered the perils of drought, plant disease, insect infestation, freezing, windstorm, flood, excessive moisture, excessive heat, and some minor hazards....."

Without cost data on these policies, there is no way that they can be evaluated. However, it is obvious that the rates will be based on the hazards. Therefore, the way is open for the development of a more stable type of agriculture. Where the hazards are greatest the cost of insurance will soon rule out those crops and land uses for which the area is least suited.

FUTURE DROUGHTS

Of special interest for individuals associated with drought studies are two articles that have appeared in newspapers recently concerning future droughts. The first of these, (see ref. 31) credited to Dr. Walter Orr Roberts, predicts a drought of great severity in the 1970's - as indicated by the following article.

> "Great gusty 'winds' from the sun seem profoundly to affect our weather, an astronomer suggested Wednesday.
>
> When these winds die down, it could mean a many-years drought crippling the American Southwest in the 1970's. Weather could change from normal in other areas of the nation also.
>
> Giant explosions of flares on the sun produce the electrified winds which stream upon the earth.
>
> Dr. Walter Orr Roberts, director of the high altitude observatory in Boulder, Colo., is finding indications that the winds are tied in with patterns of drought and rainfall.
>
> When the sun is stormy, rain comes farther south in the United States, by this theory.
>
> When the sun is quiet, in a period of minimum sunspot activity and flares, droughts can sear the Southwest. And about 1970, an extremely low sunspot period is forecast with a minimum of the solar explosions and wind.......................
>
> An absence of solar winds in the 1970's therefore could mean a Southwest drought lasting four to five years with great severity, Dr. Roberts said.

The sun-wind gusts are composed of electrified protons and electrons, carrying magnetic fields. They produce magnetic disturbances on earth, radio blackouts, and northern lights.

By some mechanism not yet spelled out, they could also modify or affect the weather troughs being formed in the Aleutians and other northern regions."

All hope is not lost, however, - according to another prominent scientist (see ref. 32) who visualizes - "A drought-free West Texas..." It is his belief that "underground nuclear explosions might dissolve the impervious feature of West Texas soil and permit Mississippi Valley waters to seep through the soil blockage."

Present research of the causes of drought, and their relation to other meteorological phenomena, have not progressed sufficiently to produce a method for the reliable forecast of the data, length, or severity of future droughts. If a forecast method is developed it will provide a means of planning agricultural pursuits as well as assisting in the scheduling of reservoir operations.

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APPENDIX A

The following speech by H. L. Walster(1)gives more background material on the characteristics of the Great Plains than has been found so conveniently elsewhere. Not all of the Great Plains lie in Texas, and yet a part of the Southern Great Plains forms a very appreciable part of Texas. Facts that are significant to the Great Plains, are therefore, equally important to Texas. This speech(2)was reproduced in Water Supply Paper No. 820, which was titled Drought of 1936. It is reproduced here in full: -

BACKGROUNDS OF ECONOMIC DISTRESS IN THE GREAT PLAINS

By H. L. Walster

The Great Plains--what and where are they, and why are they so frequently in a state of economic distress? From the point of view of the Nation the Great Plains might well be defined as an area of stress and strain: they have been and probably always will be the stage upon which the American people will try their great social and economic experiments. They will also continue to be the stage upon which Mother Nature will reveal herself in the greatest variety of moods, ranging from sumptuous plenty in the bountiful years to niggardly scarcity in the years of drought, hot winds, grasshopper, rust, or other disaster.

E. C. Chilcott, long a native of South Dakota and for many years senior agriculturist, in charge of the Office of Dry Land Agriculture, Bureau of Plant Industry, United States Department of Agriculture, defined the Great Plains as an area of about 450,000 square miles west of the 98th meridian and limited in its western boundary by the 5,000-foot contour. It includes most of North Dakota, the western half of Kansas, western Oklahoma, the panhandle of Texas, and eastern New Mexico. Such is the prosaic geographic delineation.

But the Great Plains are something more than mere geography: They are the land of romance--the land of Buffalo Bill and of Billy the Kid; the land of the cowboy, of the lariat, and the 6-shooter; the domain of the cattle kings, the scene of the lonely vigil of the sheep herder. They are the broad acres from whence are filled the granaries, the oil casks, and the larders of the Nation.

The Spanish legacy to the history of the Great Plains extends back more than 4 centuries to 1530, when Alvar Nunez Cabeza de Vaca first saw a buffalo near the southern margin of the Great Plains. The Spaniard, first white invader of the Great Plains, found a congenial environment. Webb has pointed out that these adventurers came from the semiarid part of western Europe, from a treeless land where they were superb horsemen. When the 4-H Club boy of western North Dakota rides his spotted pony to school today, he little realizes that it owes its spots to the Moorish invasion of Spain and the Spanish dispersal of horses in North America. The story of the Great Plains is the story of the rise and fall of the horse. (See ref. 4.) The horse provided a means of transport to both white man and Indian in a great open country traversed by but few navigable rivers. The next time you see an alleged cattleman trying to herd a bunch of cows with a model T Ford or any other mechanical contraption, just register the fact that you have witnessed the passing of an era; that era was at its zenith when the first herd of Texas longhorns trailed their way to the northern Great Plains.

Those first herds arrived in the late seventies of the nineteenth century. What is now North Dakota had only 2,000 cattle in 1870 by 1880 it had 70,000, and that number had risen to 189,000 by 1886. (See ref. 5.)

The Great Plains have always suffered from two kinds of wrong publicity --- that spread by the misleading optimist and that spread by the misleading pessimist. The Great Plains have always been a happy hunting ground for the boomer and the booster, and they have quite invariably left behind them a sorry trail marked "busted". Beef bonanzas were floated in England and Scotland, and every possible effort was made to exploit the range. The Badlands Cowboy, of Medora, N. Dak., short-lived but vivid newspaper of the North Dakota cow country, records the following incident in one of its 1886 issues:

> Marquis de Mores returned last Thursday evening from his eastern trip and started down the river Sunday with his wife on a hunting expedition. He had completed contracts with the French Government to supply its soldiers with a newly invented soup. He intends to visit Europe soon to make contracts with western-range cattle companies who have their headquarters there for the slaughtering of their cattle.

Then came the severe winter of 1885-86, followed by the equally severe drought in the summer of 1886. George Stewart says:

> Financial confidence, which started to wane in 1885, was almost completely lost, and the winter of 1886-87 gave a body blow to the beef bonanza. When the depression caused loans to be called, credit liquidation brought forced sales and bankruptcy.

The farmer had begun to occupy the western North Dakota range country in the early eighties; these first sod-busters refused to listen to the advice of Major Powell (see ref. 6) -- namely, that "Crop agriculture would not yield a dependable family living in most of this area except under irrigation."

A disastrous rainless season afflicted the early farmer in western Dakota Territory at a very early date. The issue of the Bismarck Daily Tribune for October 15, 1886, contains the following illuminating editorial:

> The Northern Pacific Co. will act upon the advice of its general emigration agent, Col. P. B. Groat, and all farmers along the line of the road whose crops were a total failure this year will be furnished with good seed wheat for next season. This encouragement to farmers at this time will do an immense amount of good, as many who decided to do but little fall plowing for next spring's seeding will now prepare all the ground possible and make up next season for what has been lost this year.

Your particular attention is called to one phrase in the above editorial - namely, "will now prepare all the ground possible."

Officialdom in the person of one Lauren Dunlap also broke into the editorial columns of the Bismarck Tribune on October 1, 1886, with a summary in the Monthly Weather Review. (Mr. Dunlap was attached to the Immigration Office Dakota Territory.) Immigration commissioners are, of course, traditional optimists and, like the rest of us, are not endowed with prevision, although they frequently claim that particular ability. So we find Mr. Dunlap saying anent the drought of 1886:

> Dakota has suffered the same and no more than her sister States in the West from a dry, hot period of weather this summer, the like of which

> has not been experienced before in years. Never since the settlement of Dakota began in earnest has the drought been so general, and it is reasonable to suppose that such an experience as the Territory has now passed through safely, after all, may not be repeated again in the lifetime of the youngest Dakotan.

Subsequent history must adjudge Mr. Dunlap overoptimistic, for his youngest Dakotan was destined to suffer the droughts of 1893, of 1897, of 1900, of 1910, of 1917, of 1934, and of 1936, but it is true that the major droughts have not been confined to the Great Plains.

Opinions with respect to the suitability of the Great Plains to crop farming, into which destiny has now thrust millions of its occupiers, have varied from the days of the first explorers. Maj. Stephen H. Long's 1819-20 expedition across the plains is probably responsible for the label "Great American Desert." His map published in London in 1823 carries the phrase "Great Desert" but does not delineate its boundaries. The early geographies extended the boundaries with little regard to the facts. In 1859 Joseph Henry, the famous physicist of the Smithsonian Institution, wrote in the columns of the American Agriculturist that a "vast extent of country, almost one-half of the width of the American continent, was quite unfit for tillage." Henry (see ref. 7) called the territory from the 98th meridian to the Pacific coast valleys "a wilderness unfitted for the uses of the husbandman." Owen Wister, whose Virginian was wild and wooly and full of fleas, and hard to curry above the knees, characterized Henry's ideas as "rancid with philanthropy and ignorance." (See ref. 8.) Even Horace Greeley, of "Go West, young man" fame, thought that the desert was growing.

The soils of the Great Plains are fertile soils--that is, they contain a great store of available and potentially available plant food; the average lower rainfall of the Great Plains has prevented the excessive leaching of these soils. Such depletion of fertility as has occurred has been largely through the removal of crops and the loss of nitrogen through wastage by fire. The Great Plains exemplify the dictum laid down by Sir John Russell, the world's greatest student of soils: "It is not the crops that exhaust the land, but the cultivation". But although Great Plains soils have not had their fertility exhausted we must remember that they are windswept. Wind-swept soils are always subject to wind-erosion damage. Wind erosion has taken a heavy toll throughout the length and breadth of the Great Plains; water erosion, too, has levied a heavy toll, particularly in the warmer longer season in the southern part of the Plains.

In a short address which the present speaker (Mr. Walster) made to an informal session of experiment-station directors in November 1935, he said:

> Conservation is not congenial to the American temperament. Coronado ventured into the unknown Great Plains to find gold in order that he and his Spanish adventurers might spend it. The cattlemen trailed their herds over the same trails eternally seeking new and distant pastures. The sheepman followed with their still more efficient grass consumers. Both cattlemen and sheepman increased their herds and flocks to the capacity of a particular range, then left it for greener pastures.
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> Then came the farmer--the Plains settler with his plow and his harrow, pulverizing the ancient soil structures and destroying the equally ancient soil cover. Not satisfied with the toll taken by beast and moldboard plow, we invented that most efficient of all methods for destroying

> soil structure and soil cover--dry farming. And how we praised it! What congresses and conference we held to extol the praises of all that it implies! The prospectus for the Seventh Internation Dry-Farming Congress held at Lethbridge, Alberta, Canada, in 1912 stated, "Dry-farming methods can be used with profit upon every acre in every district of the world." The American West and the Canadian took this enthusiastic advice, and they have become "brothers in adversity."

Will a mere rearrangement of fields into alternate strips of crop and summer fallow now so prominently advocated by the Soil Conservation Service ultimately accomplish anything but a mere postponement of that exhaustion by cultivation which Sir John Russell so aptly epitomized? "Were I to succumb to the lure of alliteration, I should be inclined to characterize strip farming as 'planners Palliative'. It is the type of recommendation being greeted with the same cocksure enthusiasm as greeted original apostles of dry farming."

The Office of Dry Land Agriculture of the Bureau of Plant Industry, United States Department of Agriculture, has maintained a series of 23 experiment stations up and down the Great Plains for the last 25 years or more. E. C. Chilcott summarized all the crop work of these stations in United States Department of Agriculture Miscellaneous Circulars 81 and 81, supplement 1, published respectively in 1927 and 1931. * * * * Chilcott sums up as follows:

> The Great Plains area has been and should continue to be chiefly devoted to stock raising, and all agencies interested in the agricultural, social, and economic development of this vast region of more than 450,000 square miles should unite in bringing about conditions that will make possible the fullest development of its natural resources for stock production. Crop production should be aimed to supplement livestock production rather than to compete with it.

Back of the whole story of such degrees of economic distress as the Great Plains have experienced lies the wrong use of the land. To place the sole blame for that wrong use upon the operator or even the owner is to ignore the facts of history. Let us look at some of these facts:

First and foremost lies the fact that land prices and local taxes have in general been too high for the revenue-producing capacity of the land. (See ref. 9.) Men have not been able to afford land ownership; this has meant a growing land tenancy. In eight of the Great Plains States 15 percent of the farmers were tenants in 1880; by 1910, 30 percent of them were tenants, and by 1935, 40 percent. A rising tide of tenancy has not been conductive to livestock farming; the nonresident landlord and too many of the resident landlords still seek revenue from the outturn of the threshing machine.

The farm-debt situation in the Great Plains presents a background to the economic situation which cannot be ignored. The greater proportion of this debt is owed to one or another of the several arms of the Farm Credit Administration. * * * *

American agriculture is young; the agriculture of the Great Plains is still younger, and the agriculture of the northern Great Plains is even younger. The agriculture of that part of the United States east of the Great Plains -- by and large, the humid agriculture of this country -- is relatively old and evolved from a simple subsistence agriculture to its present diversified form. The diversified agriculture of New England, the Atlantic seaboard and the great dairy and corn belt has evolved from a simple cash grain farming with few livestock into a system wherein feed and forage crops provide grain and pasture for the herds and flocks which dominate the landscape.

The agriculture of the Great Plains has had an entirely different history: except in a few rare instances or special locations the Great Plains never had a subsistence phase. Most of our pioneers were surplus producers from the start. The tragedy of the Great Plains lies in the obstinate fact that at fairly regular intervals great portions of the Plains people are forced by the whims of nature to a subsistence level or to charity. The closer historical connection between the initiation of Great Plains agriculture, especially northern Great Plains agriculture, and modern developments in farm machinery and mechanical power foreordained this difference.

The cowboy once dominated the Great Plains; now the cowboy is largely confined to such portions of badlands, sandhills, butte-dominated terrain, and stony, rocky, or gravelly hills as the plowboy has not yet wholly invaded.

The Great Plains was once a cow country: herein its history differs sharply from the history of the land to the east of the Plains. The plowboy has always been rather proud of this conquest of the prairie plains, of his successful drive against the cowman.

The plowed range lands must be rehabilitated; the agricultural lands within the range territory must be made to serve the livestock enterprise. All this requires much planning and more action. Society is not yet wholly ready to help the Great Plains farmer and his neighbors out of a bad situation. Every time government moves to the aid of the economically distressed, the cry of governmental interference is raised. Dudley Stamp says that "Planning the land for the future is essentially the work of securing the optimum use for the benefit of all." Heroic remedial measures will be required to return the Great Plains to their best use, and let me assure you that the so-called best people will not always approve. Plans for best land use must be subject to change. Sir Josiah Stamp, in his 1936 presidential address before the British Association for the Advancement of Science, emphasized what the planner is always up against--to with, "Unknown demand schedules, the unceasing, baffling principle of substitution, the inertia of institutions, the crusts of tradition, and the queer incalculability of mass mind." Sir Josiah Stamp is dealing with imponderables not reducible to maps, charts, or models, the favorite static devices of the planners. We shall have to inject into the best provision we can map for the Great Plains and for agriculture and ranching generally more imponderables than our planning fancies have yet devised. These imponderables will deal with such age-old ideas as hate and love, selfishness and unselfishness, greed and generosity. These imponderables will deal with the spirit of man.

Are we willing to have social control over the land, the greatest of all instruments of production? Then we must have a strong national government, for as (B. H.) Hibbard, in his great history of public-land policies, has pointed out, social control of the land is not possible under a weak government. Social control does not mean abolition of private ownership; properly administered it can mean more lands in private ownership and greater security on the land. Will you agree with Hibbard when he says that "The types of agriculture least suited to a laissez-faire land policy are forestry and grazing?" Laissez-faire implies that the county, the State, and the Nation keep "hands off." When Hibbard published his book, just 11 years ago, he said, "Precedents for giving seed wheat to certain settlers are well established; but precedents for helping them out of a bad bargain altogether, rather than to put up with it, have yet to be established."

But we have had an unprecedented series of drought years and an unprecedented depression since Hibbard reached that conclusion. Drought and depression have written precedents all over this country. We are helping farmers out of bad bargains, and we are protecting ranch lands. Whether or not this era of land reforms upon which we are fairly entered gives us an enduring and worthy land policy and program of conservation of lands and land users will depend upon the intelligence and honesty used in developing the program and the public understanding appreciation of the need for action.

Our approach to some of the fundamental problems in production in the Great Plains has been, from the beginning of settlement, that of a rather blind faith in machines, and with little or no faith in biological science. This is well illustrated by the early adherence to the fallacious notion that "rain follows the plow" and the continuing fallacious notion that we can be saved by some new tillage implement. Improved tillage implements are helpful but they are not the complete answer. The answer to the problems of the Great Plains lies in a more complete ecological approach. More people must come to understand the Great Plains "ekos," the environment about its people, its plants, its animals, we shall be able to deal with the Great Plains intelligently.