GEOLOGY AND GROUND WATER IN THE IRRIGATED REGION OF THE SOUTHERN HIGH PLAINS IN TEXAS

PROGRESS REPORT NO. 7

By

J. R. Barnes, W. C. Ellis, E. R. Leggat, R. A. Scalapino, and W. O. George

With a section on Quality of Water, by Burdge Irelan

PREPARED IN COOPERATION WITH THE UNITED STATES
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March 1949

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ABSTRACT

The water-bearing formations of the Southern High Plains in Texas are of Triassic, Cretaceous, Tertiary, and Quaternary age. Only a few wells obtain water from the nonmarine Dockum beds of Triassic age, and the potential value of the Triassic ground-water reservoirs appears to be small. Cretaceous formations are found only in the southwestern part of the area where yields of 500 to 1,000 gallons a minute are obtained locally from porous limestones and from basal sands that average about 12 feet thick. The Pliocene series of Tertiary age is represented by the Ogallala formation of alluvial origin, which is the most important water-bearing formation in the region. The Ogallala has an average thickness of about 300 feet, and approximately two-thirds of the saturated portion of the formation is composed of sand from which some wells yield as much as 2,000 gallons a minute. The Ogallala formation has been hydrologically isolated from the surrounding region by erosion, and the source of additions to the ground-water reservoir is from infiltration of water precipitated on the area itself. Deposits of Recent age yield only small quantities of water for domestic and stock use.

The average precipitation upon the irrigated districts of the South Plains is about 20 inches a year, and the average loss from evaporation pans is about 70 inches a year. Because a large part of the precipitation falls as showers of low intensity most of the moisture is evaporated or temporarily retained in the uppermost soils and then evaporated or transpired by vegetation. Most of the recharge to the ground-water reservoir occurs in periods of excessive rainfall by penetration from the surface in areas of sandy soil, and by seepage through the beds of intermittent streams and depression ponds. The average annual recharge to 9,000 square miles in the High Plains, which contained most of the irrigation wells in 1940, was estimated by White, Broadhurst, and Lang to be on the order of 30,000 acre-feet a year.

Ground-water use on the South Plains was relatively negligible until irrigation from wells was started in 1911 at Plainview, Texas. Development soon spread to other districts, but irrigation met with only moderate success until about 1935 when drought and greater mechanical efficiency of pumps and power units stimulated activity. Since 1935 the rate of installing

pumping plants has generally shown an increase from the preceding year, and according to reports from pump distributors approximately 3,000 wells were equipped during 1948. Approximately 7,500 irrigation wells had been completed by January 1, 1948, and on the basis of pump sales it is estimated that 10,500 wells were equipped for operation by January 1, 1949. The yields of wells range from about 300 to 2,000 gallons per minute and average about 750 gallons per minute.

During 1948, it is estimated that 1¼ million acre-feet of ground water was pumped on the South Plains, of which about 97 percent was used for irrigation. The withdrawals for public, domestic, and industrial supplies were approximately 35,000 acre-feet; the combined pumpage for the cities of Lubbock and Amarillo accounted for 19,700 acre-feet of this amount.

During the 11-year period from March 1938 to March 1949 about 18 million acre-feet of saturated material was unwatered; the approximate extent of the net water-table decline in the South Plains was as follows:

Area affected in acres	Decline in feet 1938-1949
1,100,000	0 - 5
700,000	5 - 10
500,000	10 - 15
118,000	15 - 20
29,000	20 - 25
11,400	25 - 30
7,400	30 - 35
3,700	35 - 40
3,400	40 - 45
2,800	45 - 50

It is estimated that about 8 million acre-feet of saturated material was unwatered during 1948. The greatest declines of the water table occurred in areas of heaviest withdrawals; but if the withdrawals had been uniformly distributed the unwatering would have caused an average water-table decline of about 1.9 feet throughout the entire irrigated region.

From the information obtained in a number of tests, the radius of influence of a pumped well was found to extend at least half a mile after a few days of pumping. In some districts the interference between closely-spaced wells is sufficient to increase the pumping lifts several feet during the irrigation season.

Results of field and laboratory tests indicate that the specific yield of the Ogallala formation ranges between 15 and 20 percent. The thickness of the saturated formation averages approximately 200 feet over 4¼ million acres comprising the principal irrigation region. From these data the available storage is estimated to be on the order of 150 million acre-feet, of which about two-thirds lies within 200 feet of the surface.

Successful irrigation on the High Plains indicates that the chemical character of the ground water is satisfactory for most crops. Analyses of samples from numerous wells, which have been published in the county reports, show that in general minerals harmful to the soil are present in relatively small amounts. The water, although hard, is usually acceptable for industrial and public supplies. In many parts of the region the concentration of fluorides is excessive and mottling of teeth is prevalent. The Texas State Department of Health recommends that growing children residing in such areas drink treated water in which the fluoride has been reduced to about 1.0 part or 1.5 parts per million.

As the water levels on the High Plains decline the yields of wells will be reduced and the water must be lifted from greater depths. At some depths below the surface an economic limit of pumping may be reached long before the supply is exhausted. Because such a large percentage of the total rainfall is lost by evaporation from the soil, it seems that methods of salvaging this water should be of primary concern.

Although ground water is considered to be a replenishable resource, the rate of recharge on the Southern High Plains in Texas is so low compared to present pumpage that for practical purposes withdrawals may be considered as coming from storage. If present trends in the rates of pumpage and water-level decline continue, some localities may be seriously affected in from 5 to 10 years. In other larger areas where the wells are widely spaced, the water-level declines and mutual interference are negligible; and if the wide spacing is maintained and present rates of withdrawal are not increased the life expectancy of large-scale pumping may be extended for a much longer period of time.

INTRODUCTION

The High Plains in northwestern Texas, first settled in the decade following the Civil War, has been one of the most rapidly developed regions of Texas. The remarkably level surface and large proportion of tillable land make the region well adapted for farming especially where ground water is available for irrigation. In recent years, the development of irrigation from wells has substantially reduced crop failures resulting from droughts and has materially increased the yield of farm products in a large part of the High Plains. Thus, a stable long-range economy is greatly dependent upon continued withdrawals of ground water to supplement rainfall.

Previous reports

The geology and water resources of the High Plains have been studied for many years.

The results of some of the earlier investigations have been published in Federal and State bulletins. 1/

Since 1936 systematic ground-water investigations, carried out by the Texas State Board of Water Engineers in cooperation with the Geological Survey, United States Department of the Interior, have given more detailed attention to the source and available supply of water underlying the Plains.

Between 1936 and 1946, inventories of water wells in 33 counties in the High Plains were published in mimeographed form by the Texas State Board of Water Engineers, as follows:

County	Year of publication	County	Year of publication
Andrews	1937	Hartley	1938
Armstrong	1940	Hockley	1940 *
Bailey	1937	Howard	1937
Briscoe	1946	Lamb	1938 *
Carson	1939	Lubbock	1937 *
Castro	1939	Lubbock	1945
Dallam	1937	Martin	1936
Dawson	1938	Midland	1938
Deaf Smith	1938 *	Ochiltree	1939
Deaf Smith	1946	Oldham	1938
Donley	1942	Parmer	1938
Ector	1937	Potter	1938
Floyd	1938 *	Randall	1938
Floyd	1946	Roberts	1940
Gaines	1946	Swisher	1938 *
Glasscock	1937	Swisher	1946
Hale	1938 *	Terry	1944
Hale	1946	Yoakum	1945
Hansford	1936		

* Out of print.

The mimeographed bulletins give tables of well records, well logs, and water analyses, together with maps showing locations of the wells listed. The records of water-level measurements in several hundred observation wells throughout the region have been published annually in U. S. Geological Survey Water-Supply Papers 840 for 1937; 845, 1938;

1/ Johnson, W. D., The High Plains and their utilization: U. S. Geol. Survey 21st Ann. Rept., pt. 4, Hydrography, pp. 609-741, 1901: 22nd Ann. Rept., pt. 4, Hydrography, pp. 637-669, 1902.
Gould, C. N., The geology and water resources of the eastern portion of the Panhandle of Texas: U. S. Geol. Survey Water-Supply Paper 154, 1906.
Gould, C. N., The geology and water resources of the western portion of the Panhandle of Texas: U. S. Geol. Survey Water-Supply Paper 191, 1907.
Meinzer, O. E., Ground-water resources of Portales Valley, New Mexico. (Manuscript report in files of U. S. Geol. Survey, Washington, D. C.)
Baker, C. L., Geology and underground waters of the northern Llano Estacado: Univ. Texas Bull. 57, 1915.
Theis, C. V., Burleigh, H. P., and Waite, H. A., Ground water in the southern High Plains, U. S. Geol. Survey memorandum for the press, October 30, 1935.

886, 1939; 909, 1940; 939, 1941; 947, 1942; 989, 1943; and 1019, 1944. Records for later years are in course of publication.

Purpose and scope

The purpose of these investigations is to obtain facts that will aid in the proper utilization and conservation of ground-water supplies, and to make these facts readily available to the public. The more recent investigations have included studies of the regional geology with special reference to the stratigraphy in relation to water-bearing strata, the source of the underground water, the percentage of water that the sands will yield to wells, and the recharge and natural discharge of the underground reservoirs. These data have been published in a series of six progress reports released by the Texas Board of Water Engineers on the following dates: (1) July 1938, (2) December 1940, (3) April 1943, (4) May 1944, (5) May 1945, and (6) January 1947. The second progress report (1940) has been published by the U. S. Geological Survey as Water-Supply Paper 889-F.

The present report, which is the seventh of this series, is limited to that part of the High Plains south of the Canadian River, locally known as the South Plains.

Acknowledgments

These investigations have been made possible through appropriations by the Texas State Legislatures and allocations of Federal funds to match them on an equal or nearly equal basis. Currently the City of Lubbock is sharing in financing this study. The work is being done under the direction of A. N. Sayre, Geologist in Charge of the Ground Water Branch of the Geological Survey, and under the direct supervision of W. L. Broadhurst, District Geologist in charge of ground-water work in Texas. Most of the information on infiltration and natural discharge was taken from Geological Survey Water-Supply Paper 889-F, by W. N. White, W. L. Broadhurst, and J. W. Lang. Appreciation is expressed to pump companies, well drillers, and well owners who generously contributed information and cooperated in obtaining field data.

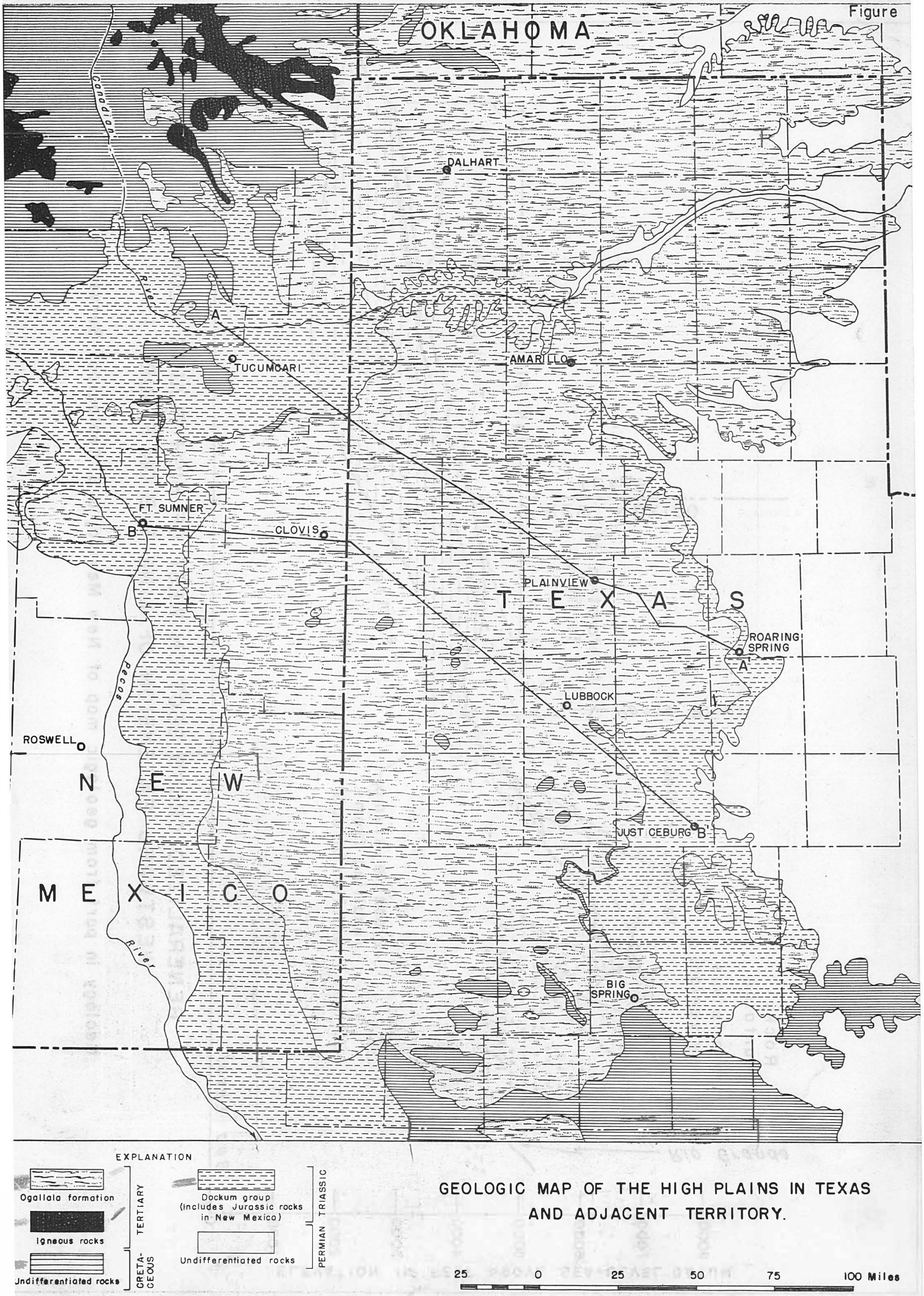
GEOLOGY

The rocks that may be seen at the surface in the High Plains range in age from Paleozoic to Recent. In general, the older rocks appear to have been deposited in an elongate basin extending north and south through the central part of the South Plains. The basin is believed to have been formed in part by a progressive downwarping of deep-seated origin; in part by removal of sediments by erosion between periods of deposition; and in some places by the solution of underlying salt and gypsum, particularly in the Permian rocks, probably during Triassic time.

The areal distribution of the outcrops is shown in figure 1. Geologic cross sections along the lines A-A' and B-B' are shown on plates 2 and 3. The surface profiles were determined by instrumental leveling and the lines indicating the position of the water table are based on water-level measurements in wells.

Because of the lack of dependable data, the contacts between formations are not sharply delineated. The apparent steep slopes of the land surface and the water table indicated by the cross sections result from the exaggeration of the vertical scale which is necessary to show the details. The top of the Permian as shown in the cross sections was determined from a number of oil-well logs, using the top of the anhydrite as a marker. Actually, in some places the anhydrite may be as much as 250 feet below the top of the Permian. The cross section in figure 2 is an extension of B-B' and was drawn in part from data shown on the geologic map of New Mexico (U. S. Geol. Survey, 1928), supplemented in part by instrumental leveling.

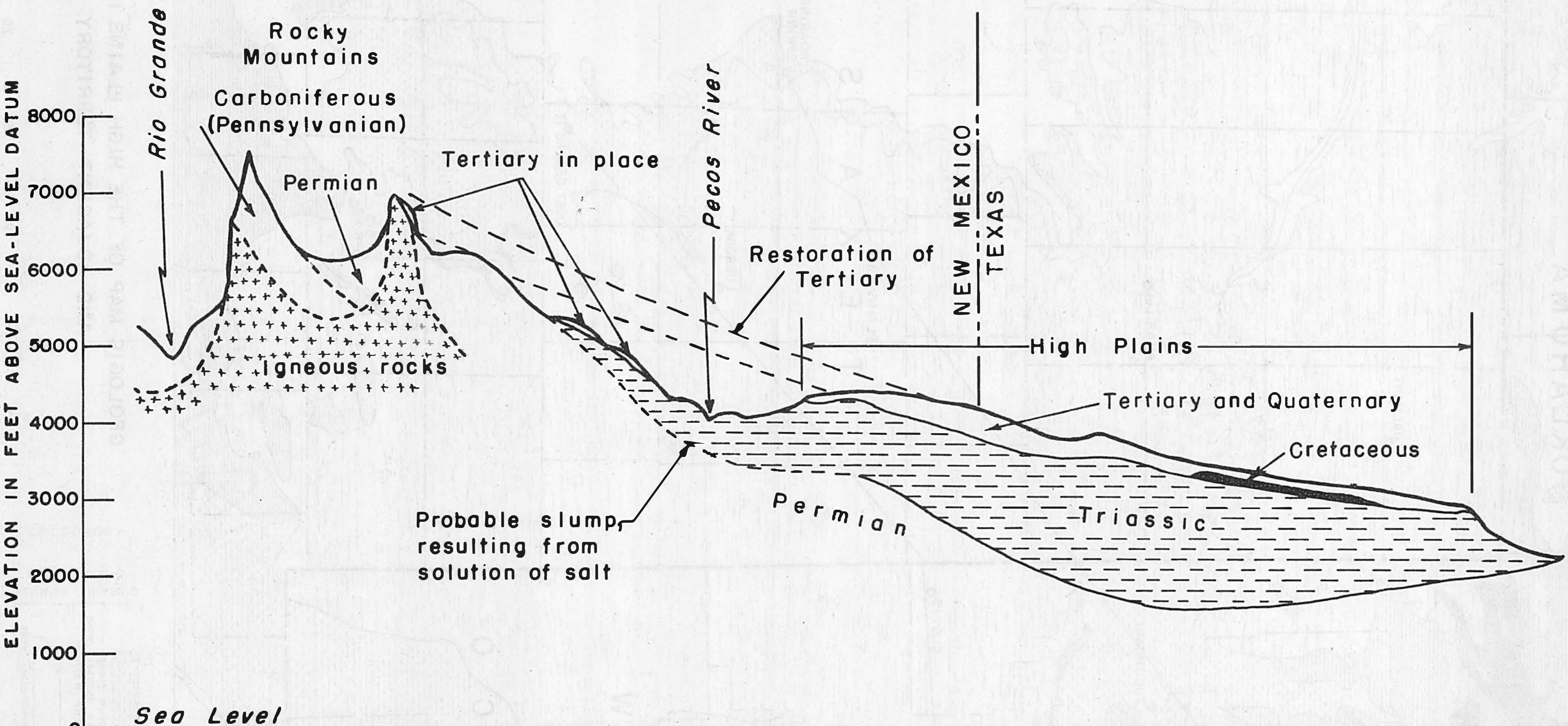
The formations, together with their chief characteristics and water-bearing properties, are listed in table 1 below.



GEOLOGIC MAP OF THE HIGH PLAINS IN TEXAS AND ADJACENT TERRITORY.

om geologic map of United States, U.S. Geological Survey, 1932.

mlc - 194



GENERALIZED CROSS SECTION WEST OF HIGH PLAINS ALONG WESTWARD EXTENSION OF LINE B-B' ON FIGURE 1.

Geology in part from geologic map of New Mexico, U.S. Geological Survey, 1928.

Figure 2

Table 1. ROCKS EXPOSED IN THE SOUTHERN HIGH PLAINS IN TEXAS

System	Subdivision	Thickness (feet)	Character	Water supply	Remarks
Quaternary	Recent series	0 - 15	Sand, silt, clay, and gravel of alluvial origin; caliche.	Contain little water. Where sandy, soils aid recharge.	Mainly stream-channel and wind-blown deposits.
	Pleistocene series	0 - 150	Clay, silt, marl, sand conglomerate, and caliche.	Small yields from old stream channels, merges into Ogallala formation below.	Several formations, classified by means of vertebrate fossils.
Tertiary	Pliocene series, Ogallala formation	0 - 400	Clay, silt, fine- to coarse-grained sand, gravel, and caliche.	Abundant supply in most places. Principal source of water in the High Plains.	
Cretaceous	Lower Cretaceous (Comanche) series	0 - 80	Limestone, blue shale, blue and yellow clays; also sand, gravel, and sandstone.	Best water-bearing rocks below the Ogallala. Absent in northeastern part of region.	Erosional remnants underlying the Ogallala formation in southern Lubbock, Bailey, and Lamb Counties, and area to south.
Triassic	Dockum group	50 -1,500	Dark-red shales, cross-bedded, lenticular, and variegated sandy shales and sandstone interbedded with red shales.	Not thoroughly explored. Water generally highly mineralized.	Commonly known as red beds.
Permian		5,000	Soft red shales, sandstones, sandy clays; some gypsum and dolomite. Red clays and shales interbedded with gypsum, some magnesian limestone and dolomite.	Contains little or no water. Water is highly mineralized.	Includes Quartermaster formation forming red buttes and ridges; Cloud Chief gypsum, found only in deep cuts.

Permian system

The oldest rocks exposed on the High Plains of Texas are of Permian age. They are found only at the edges of the escarpment and in the canyons of the larger streams that have cut through the "cap rock". Most of the outcrops of Permian age are of the Quartermaster formation. The underlying Cloud Chief gypsum is found only in the deeper cuts. The Quartermaster formation can be observed in Tule Canyon in northern Briscoe County, at Roaring Springs in Motley County (pl. 4, B), and at numerous places along the Canadian River in Texas. The formation is from 200 to 300 feet thick and consists of soft red sandstones, shales, and clays with gypsum ledges, and a few beds of dolomite. The underlying Cloud Chief gypsum is composed predominantly of that mineral. The total thickness of Permian rocks underlying the South Plains may be as much as 5,000 feet. The upper part of the Permian rocks closely resembles the overlying Triassic rocks, and in some places the two systems are hardly distinguishable. The shales of the Permian generally show bedding planes on the weathered surfaces and are somewhat lighter red than the Triassic shales; the Triassic shales are generally massive and deep red in color.

At no place on the South Plains is water known to be pumped from the Permian formations, and it is believed that only small amounts of highly mineralized water are available.

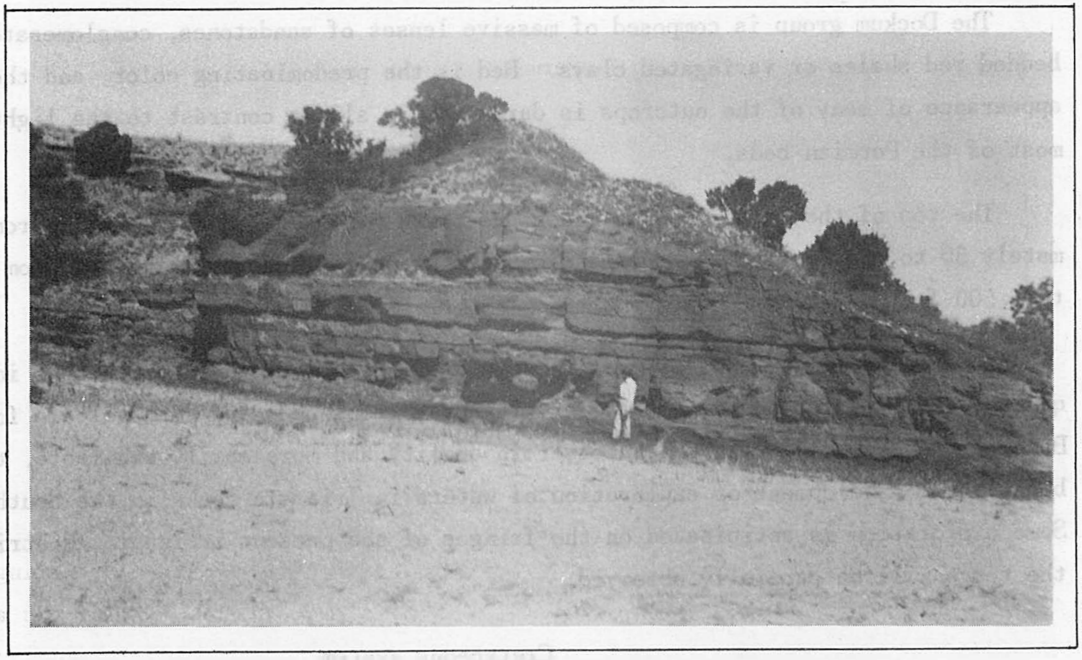
Triassic system

Dockum group.- The beds of the Dockum group, generally considered to be Upper Triassic in age, lie unconformably on the eroded surface of Permian rocks. (See pl. 5.) They are believed to be entirely nonmarine in origin, and probably were laid down largely on the flood plains of braided streams.

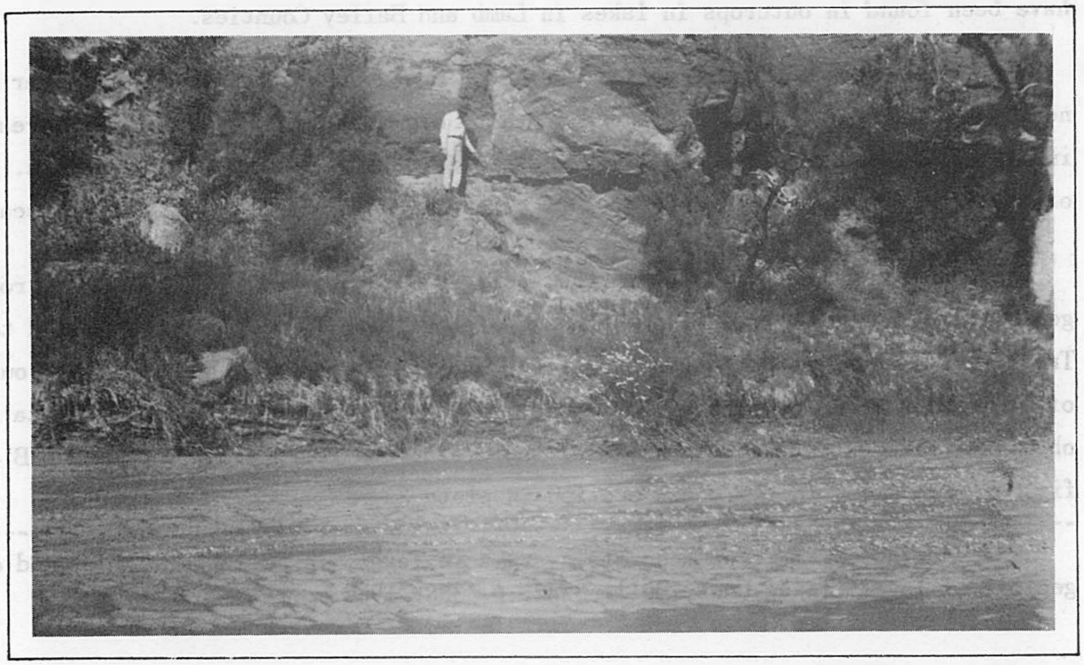
The beds of the Dockum group were deposited in a broad basin underlying the South Plains. According to Adams, 2/ the regional dip of the Triassic beds suggests that the downwarping of the Permian rocks continued through early Mesozoic time. This resulted in a thickening of the beds in the lower or central part of the basin and a thinning of the beds at the margins of the basin. (See pls. 2 and 3.) Triassic rocks are exposed in the main drainage channels and at scattered outcrops south of the irrigated areas. (See geologic map, fig. 1.)

2/ Adams, J. E., Triassic of west Texas: Am. Assoc. Petroleum Geologists Bull., vol. 13, pp. 1045-1055, 1929.

PLATE 4



A. PERMIAN SANDSTONE ON NORTH SIDE OF WOLF CREEK, MOTLEY COUNTY, TEXAS.
Photograph by W. N. White.



B. CONTACT BETWEEN PERMIAN AND TRIASSIC ROCKS, JUST EAST OF ROARING SPRINGS, MOTLEY COUNTY, TEXAS.

Photograph by W. N. White.

The Dockum group is composed of massive lenses of sandstones, conglomerate, and interbedded red shales or variegated clays. Red is the predominating color, and the general appearance of many of the outcrops is dark red, in slight contrast to the lighter red of most of the Permian beds.

The top of the Triassic lies under the South Plains at depths ranging from approximately 50 to 400 feet, and the Triassic rocks probably range in thickness from a few feet to 1,500 feet.

Some of the sandy beds of the Triassic are known to yield water that is inferior in quality to the water found in the overlying Cretaceous beds and the Ogallala formation. Because the overlying waters are better in quality and more easily available, there has been little development or exploration of waters in Triassic rocks in the South Plains. Some exploration is anticipated on the fringes of the present irrigation district, and the tests will be carefully observed.

Cretaceous system

Lower Cretaceous (Comanche) series.- During Jurassic time, the beds of the Dockum group were exposed to erosion. In early Cretaceous time, encroaching seas deposited sediments upon this eroded surface. In general, these sediments consist of a basal sand section overlain by yellow and blue clays with a limestone or shale cap. The section varies considerably from place to place. Fossils of Washita and Fredericksburg age 3/ have been found in outcrops in lakes in Lamb and Bailey Counties.

Outcrops (see geologic map) of the Lower Cretaceous formations are rather extensive northwest of the Texas Panhandle and south of Big Spring. Only a few exposures are found in the irrigated areas, generally on the shores of small lakes or depressions. Northeast of the irrigation area no Cretaceous rocks are found along the High Plains escarpment.

Southwest of the line B-B' on the geologic map (see fig. 1), Cretaceous rocks are generally encountered in wells; northeast of this line many wells are drilled to the Triassic red beds without encountering any Cretaceous rocks. The subsurface outline of Cretaceous rocks is probably irregular and cannot be mapped until more data are obtained. The extent and thickness of the Cretaceous rocks along the line B-B' on figure 1 are shown in the cross section in plate 3.

3/ Adkins, W. S., The Mesozoic systems in Texas, in Sellards, E. H., and others, The geology of Texas: Texas Univ. Bull. 3232, p. 358, 1932.

The City of Lubbock drilled nine test holes from 3 to 8 miles north, northeast, and northwest of Lubbock which were observed by J. W. Lang 4/ . Examination of the cuttings from eight test holes show that four of the test holes encountered no Cretaceous rocks. The following Cretaceous sections were described for the other four of the eight test wells.

Test hole 1; 108 feet south and 69 feet east of the NW cor. sec. 6, blk. A; 3½ miles northeast of post office at Lubbock. Surface altitude, 3,212.9 feet.

	Thickness (feet)	Depth (feet)
Post-Cretaceous	134	134
Cretaceous		
Limestone, quartz and flint gravels in upper part, hard, yellow and gray	31	165
Limestone, dense, gray, hard and soft beds	16	181
Limestone and shale, interbedded, gray and dark blue	4	185
Sand, fine, very limy, gray	3	188
Shale, hard, blue-black, and thin beds of gray sand	11	199
Sand, fine- to medium-grained, gray, and a few thin beds of blue shale	16	215

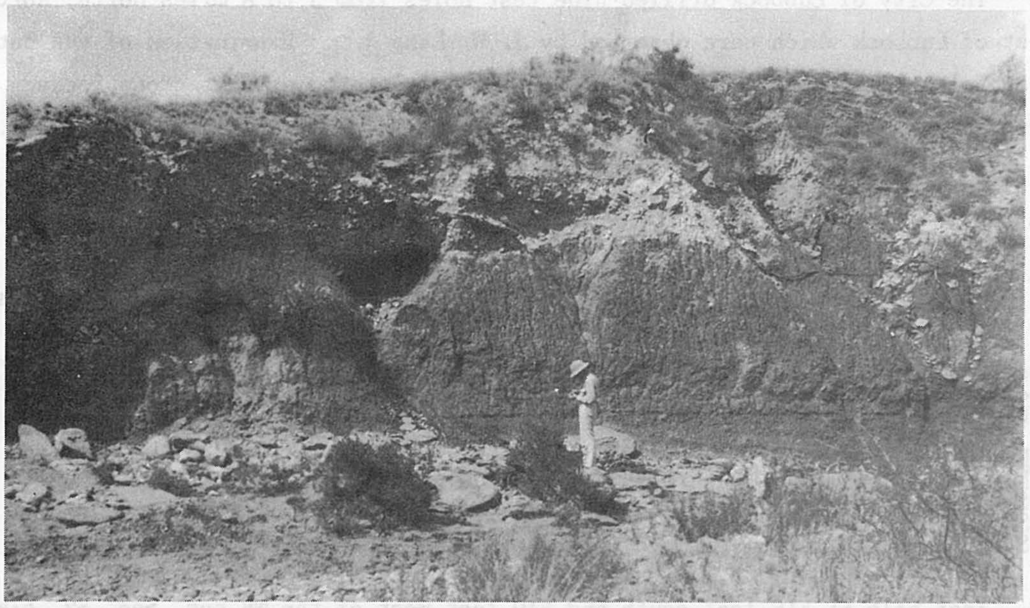
Test hole 6; 415 feet south and 549 feet west of the NE cor. Sec. 52, blk. A; 8-3/4 miles northeast of post office at Lubbock. Surface altitude, 3,241.3 feet.

Post-Cretaceous (?)	160	160
Cretaceous (?)		
Clay, dark-red and blue-gray	10	170
Sand, clean, medium- to Coarse-grained, reddish-buff	10	180
Clay, dark-red, and thin beds of light-gray caliche	13	193
Limestone, hard, gray and buff-colored	3	196
Limestone and clay in thin alternating beds	3	199
Clay, sandy, varicolored	5	204
Sand, fine- to medium-grained, red, and sandy red clay	6	210
Sand, clean, buff-gray	6	216

Test hole 8; 63 feet north and 50 feet east of the SW cor. sec. 3, blk. JS; 7½ miles west of post office at Lubbock. Surface altitude, 3,303.2 feet.

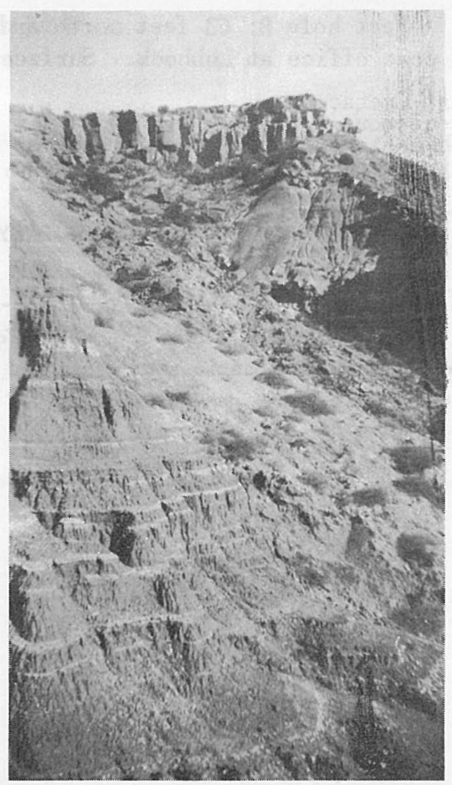
Post-Cretaceous	208	208
Cretaceous		
Limestone, hard and soft layers, gray	27	235
Limestone and shale, interbedded, gray and dark-blue	19	254
Limestone, hard, gray	2	256
Shale, dark-blue	4	260
Sand and shale, interbedded, gray and dark-blue	4	264
Shale, light-blue	5	269
Sand, medium-grained, gray	7	276

4/ Lang, J. W., Lubbock County, Texas, Records of wells and springs, drillers' logs, water analyses, and map showing locations of wells and springs. Texas Board of Water Engineers in cooperation with U. S. Geological Survey, pp. 86-92, 1945.



A. MASSIVE BEDS OF TRIASSIC CLAY OVERLAIN BY ALLUVIAL DEPOSITS OF COARSE GRAVEL, CROSBY COUNTY, TEXAS.

Photograph by W. L. Broadhurst.



B. TRIASSIC SECTION IN PALO DURO CANYON, RANDALL COUNTY, TEXAS.

Photograph by C. R. Follett.

Test hole 9; 5 feet south and 430 feet east of the NW cor. sec. 8, blk. JS; 7½ miles northwest of post office at Lubbock. Surface altitude, 3,296.4 feet.

	Thickness (feet)	Depth (feet)
Post-Cretaceous	180	180
Cretaceous		
Clay, yellow	10	190
Limestone, hard, dense	4	194
Limestone, porous, honeycombed layers	22	216
Limestone, hard	12	228
Shale and limestone, gray and dark-blue	8	236
Shale and limestone, sandy, interbedded, blue	8	244
Sand and shale, hard, gray and blue	9	253

The maximum thickness of Cretaceous rocks penetrated by the test holes is 81 feet and the maximum thickness of water-bearing sand is 17 feet.

In the areas where Cretaceous rocks are found, however, the total yield obtainable from wells penetrating both Cretaceous rocks and the Ogallala formation is generally less than the yield in those areas where the Cretaceous is absent, because the limestones and shales interbedded with the Cretaceous sands occupy space that might have been filled with sands of the Ogallala formation. In some areas, however, particularly in Hale and Lubbock Counties, limestones contain crevices and solution cavities which yield considerable volumes of water. These limestones are believed to be of Cretaceous age but positive identification is lacking.

Tertiary system

Igneous rocks.- The igneous rocks shown in New Mexico in figure 1 are not exposed or known to be penetrated by wells in Texas and will not be discussed further.

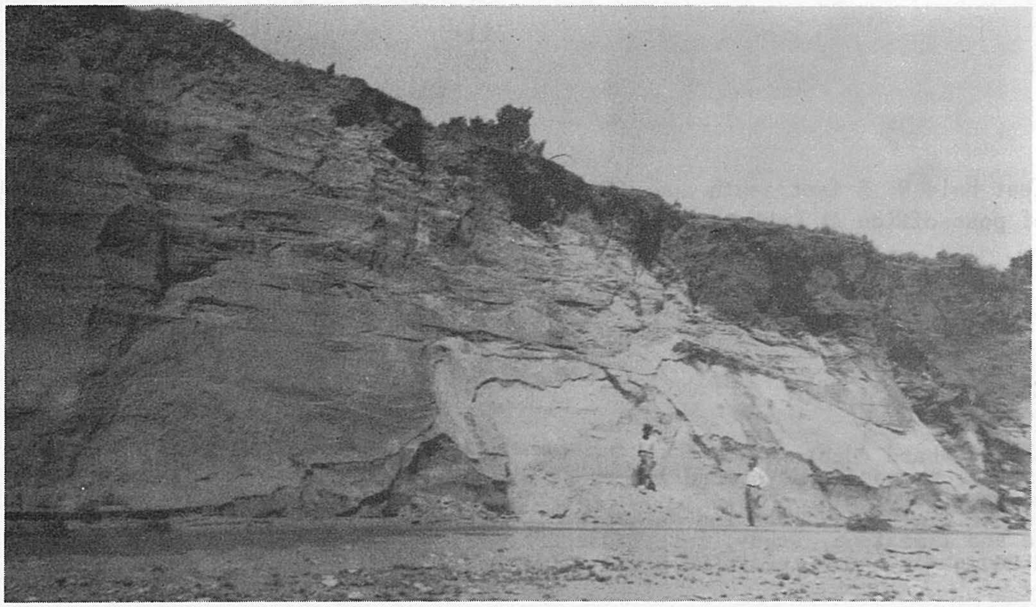
Pliocene series.- The Pliocene series is represented in the South Plains by the Ogallala formation. It lies unconformably on the eroded surfaces of Cretaceous, Triassic, and Permian rocks, and was deposited by streams that had their headwaters in the Rocky Mountains.

Locally, the Pliocene sediments have been subdivided by some authors into units such as the "Clarendon beds" (lower Pliocene), 5/ the "Potter formation", 6/ and the "Coetas formation". 7/ Most of these units have been identified only in local areas and cannot be used to separate the Pliocene deposits of the High Plains into stratigraphic divisions outside those areas.

5/ Gidley, J. W., Am. Mus. Nat. Hist. Bull., vol. 19, pp. 632-635, 1903.

6/ Patton, L. T., Univ. Tex. Bull. 2330, pp. 78-80, 1923.

7/ Patton, L. T., op. cit., pp. 80-86.

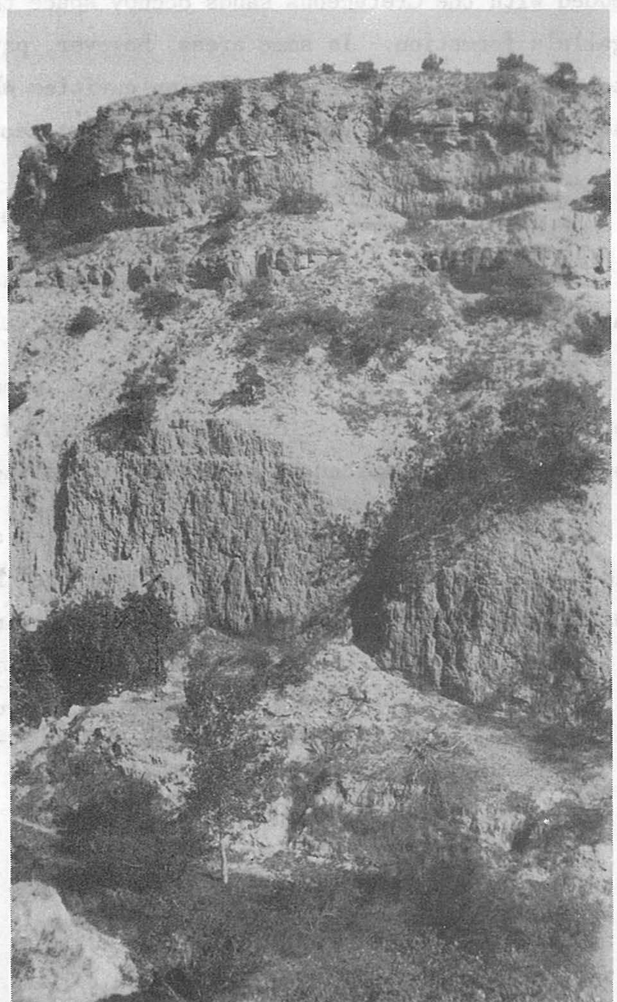


A. WHITE SANDS IN THE LOWER PART OF THE OGALLALA FORMATION ON THE L. H. LEWIS RANCH AT FOOT OF THE ESCARPMENT, 18 MILES NORTHEAST OF FLOYDADA, FLOYD COUNTY, TEXAS.

Photograph by W. N. White.

B. CLAY AND SILT NEAR THE BASE OF THE OGALLALA FORMATION IN SOUTHERN BRISCOE COUNTY, TEXAS.

Photograph by W. L. Broadhurst.



The beds of the Ogallala formation once extended from the mountains of New Mexico eastward far into Texas, but they have been removed by erosion from much of the area they once occupied. According to White, Broadhurst, and Lang 8/.

> "The Ogallala formation has been completely eroded away west of the western escarpment and east of the eastern one and from the canyon-like valley of the Canadian River. The water-bearing sands and gravels of the Ogallala in the South Plains in Texas, therefore, are cut off in all directions from any underground connection except through the underlying older rocks which contain highly mineralized water entirely unlike the fresh water in the Ogallala".

Water cannot enter the Ogallala formation in the South Plains from the Rocky Mountains, the Pecos River, or the Canadian River. (See pls. 2 and 3.)

The Ogallala formation is composed of red and yellow clay, silt, gray and buff-colored sand, conglomerate, and caliche. The character of the material varies both vertically and laterally. Plate 6 shows two pictures of the basal part of the formation. One picture shows the base to be composed almost entirely of sand and the other shows the base to be composed almost entirely of silt and clay.

Much of the Ogallala is partially cemented with calcareous material, but some sands are uncemented and sand is generally pumped out with the water when wells are first installed. A mechanical analysis of sand obtained at a depth of 230 feet in the Hinton well No. 2, in the northeast corner of Crosby County, shows that 54.4 percent of the sand grains are between 0.25 and 0.84 mm. in diameter. Additional mechanical analyses are given on page 40.

A classification of materials reported in 537 drillers' logs of wells in Deaf Smith. Hale, Floyd, Swisher, and Lubbock Counties (fig. 32), shows that about 68 percent of the saturated material in the Ogallala formation between 72 and 350 feet below the surface is sand. In general, drillers' logs do not show in accurate detail the character of the material encountered, but the value of the analysis is enhanced by using a large number of logs from different sources. The analysis of the materials was made by grouping 50-foot intervals of the formation and calculating the percentage of sand within each group. Although few wells reach the lower sands, in general the formation becomes increasingly sandy toward the base. The lower beds, therefore, may have greater permeability and storage capacity. Very little gravel has been found in samples from wells, possibly because few wells penetrate the entire thickness of the formation.

8/ White, W. N., Broadhurst, W. L., and Lang, J. W., U. S. Geol. Survey Water-Supply Paper 889-F, pp. 385-386, 1946.

Increasingly coarser material toward the bottom of the Ogallala formation should be expected if the present interpretation of the origin of the formation is correct. During the early part of the period of deposition, the streams from the Rocky Mountains should have had rather high velocities, and so should have been capable of bearing coarse materials. As the mountains were reduced and the Plains were built up, the velocities would naturally decrease and materials carried by the streams would be proportionately finer.

In addition to the effect of changing stream velocities, it is believed that in much of the area the variation in the character and thickness of the sediments is related to the proximity of the material to the main channels of the early distributive streams that cut deeper channels and deposited coarser material. For example, the most productive and thickest sands are found along a wide strip more or less parallel to the present course of the White River. Outside this strip, buried ridges and hills of older material still remain. East of Lockney wells reach Triassic beds at depths of approximately 50 feet. South of Lockney, nearer the White River, some irrigation wells are approximately 400 feet deep, and did not reach the Triassic.

The Ogallala formation in the South Plains ranges in thickness from a feather edge to 400 feet or more. In the irrigated area the average thickness is probably 300 feet. The average thickness of the saturated material is probably 200 feet. Yields as high as 2,000 gallons a minute have been measured for some wells.

Quaternary system

Pleistocene series.- Rocks of Pleistocene age at 28 widely distributed fossil localities in the Southern High Plains of Texas have been reported by Evans and Meade, 9/ who also describe the surface features of the High Plains and present evidence that some of the depressions were formed by wind erosion. Pleistocene deposits, in some places more than 100 feet thick, include sands, clays, diatomaceous earth, bentonitic clays, volcanic ash, and fresh-water limestone. They are found in playa basins and stream terraces and as lake deposits. Although these deposits are hydrologically continuous with the Ogallala formation, they are not known to yield large quantities of water to wells.

Recent series.- Recent geologic time began with the retreat of the continental glaciers from the northern part of North America about 20,000 years ago and is the geologic age in which we are now living. Deposits of Recent age in the South Plains consist mainly of sand dunes, sheets of wind-blown material, and valley fill. The sheets of wind-blown material cover wide areas to a depth of 20-40 feet. 10/ They are composed of dust-sized particles and fine-grained sand cemented with calcareous material.

9/ Evans, Glen L., and Meade, Grayson E., Quaternary of the Texas High Plains: Univ.Texas Pub. 4401, pp. 486-507, 1944.

10/ Evans, Glen. L., and Meade, Grayson, E., op. cit., p. 502.

Caliche, the evaporated residue of minerals in surface and ground waters, is found near the surface in nearly all parts of the South Plains and mainly in the upper 50 feet of strata. In some places it occurs as an intimate mixture with sand or clay; in other places it is a pure evaporite. Some of it is a soft, white chalky or powdery material and some of it is as hard as well-indurated limestone. Because caliche is more resistant to erosion than the underlying beds, it is the "cap rock" of the Southern High Plains of Texas and forms the top of the escarpments at the edge of the Plains. The age of the caliche probably ranges from Pliocene to Recent.

Nearly all the Recent materials are above the water table and, therefore, do not yield water to wells.

HYDROLOGIC CYCLE

Practically all usable water on the earth comes from the oceans. This liquid water is vaporized by the sun's energy and is transported inland by air currents where it is deposited as rain, snow, hail, sleet, and other form of precipitation. Immediately upon reaching the surface of the earth and, if it was deposited in frozen form, after melting, each particle of water is acted upon by gravity which tends to pull the water back to the oceans from which it came. When sufficient water has accumulated to exceed the capillary requirements of the adjacent surface, some water will move over the surface into drainage channels and return directly to the oceans. In an arid region evaporation may be so great that only a very small percentage of the particles complete the cycle in that manner. A part of the precipitation is absorbed by the soil, which in turn surrenders a portion to the atmosphere in the processes of evaporation and transpiration by vegetation. The moisture lost in this way is eventually precipitated upon the earth again. Where the soil is underlain by permeable material, excess moisture that is not evaporated, transpired, or held in storage by capillary forces, infiltrates into the earth until it reaches the water table. Thereupon it percolates down gradient in a manner similar to those particles that travel entirely on the surface, except that owing to the greater frictional loss of energy in percolating through the rocks, the rate of movement is generally much slower. This ground water, as it is now called, may emerge from the earth in springs or seeps at low points down gradient and continue its journey to the seas. It is evident, therefore, that water beneath the surface is acted upon by the same physical forces that cause water upon the surface to seek a lower level. The circuitous routes taken by these particles of water from the time they leave the ocean source until they return constitute what is called the hydrologic cycle.

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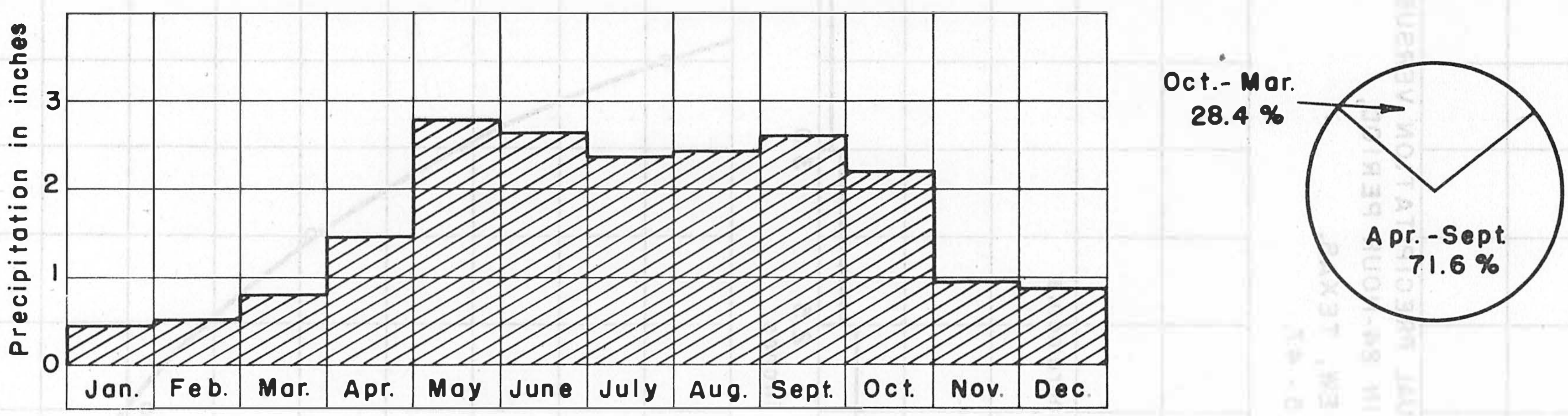
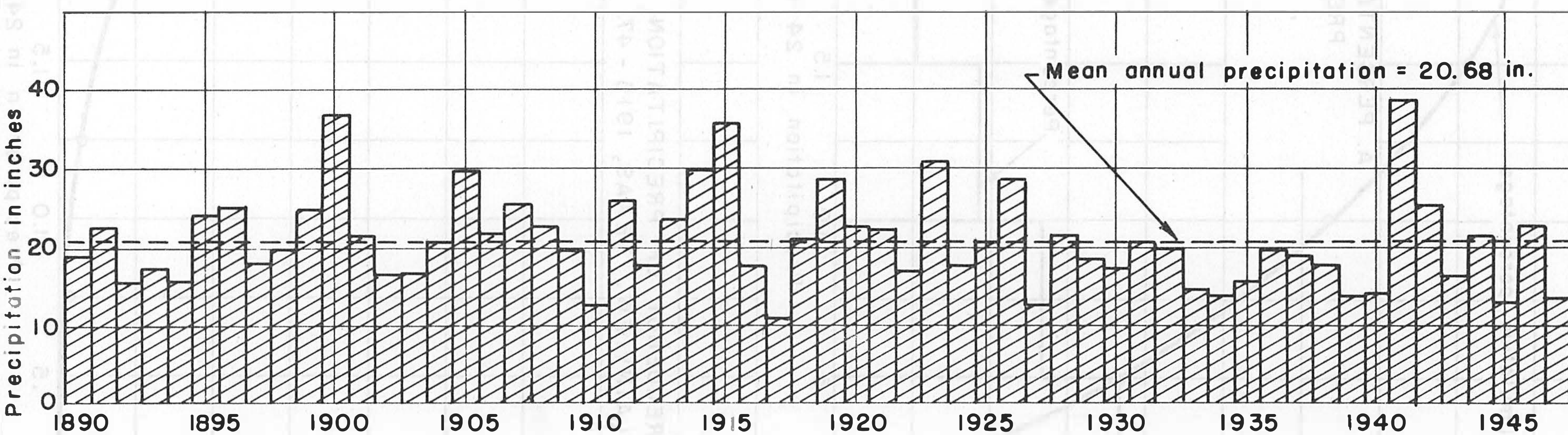


A. AVERAGE MONTHLY DISTRIBUTION OF ANNUAL PRECIPITATION.
(Average of 5 stations).



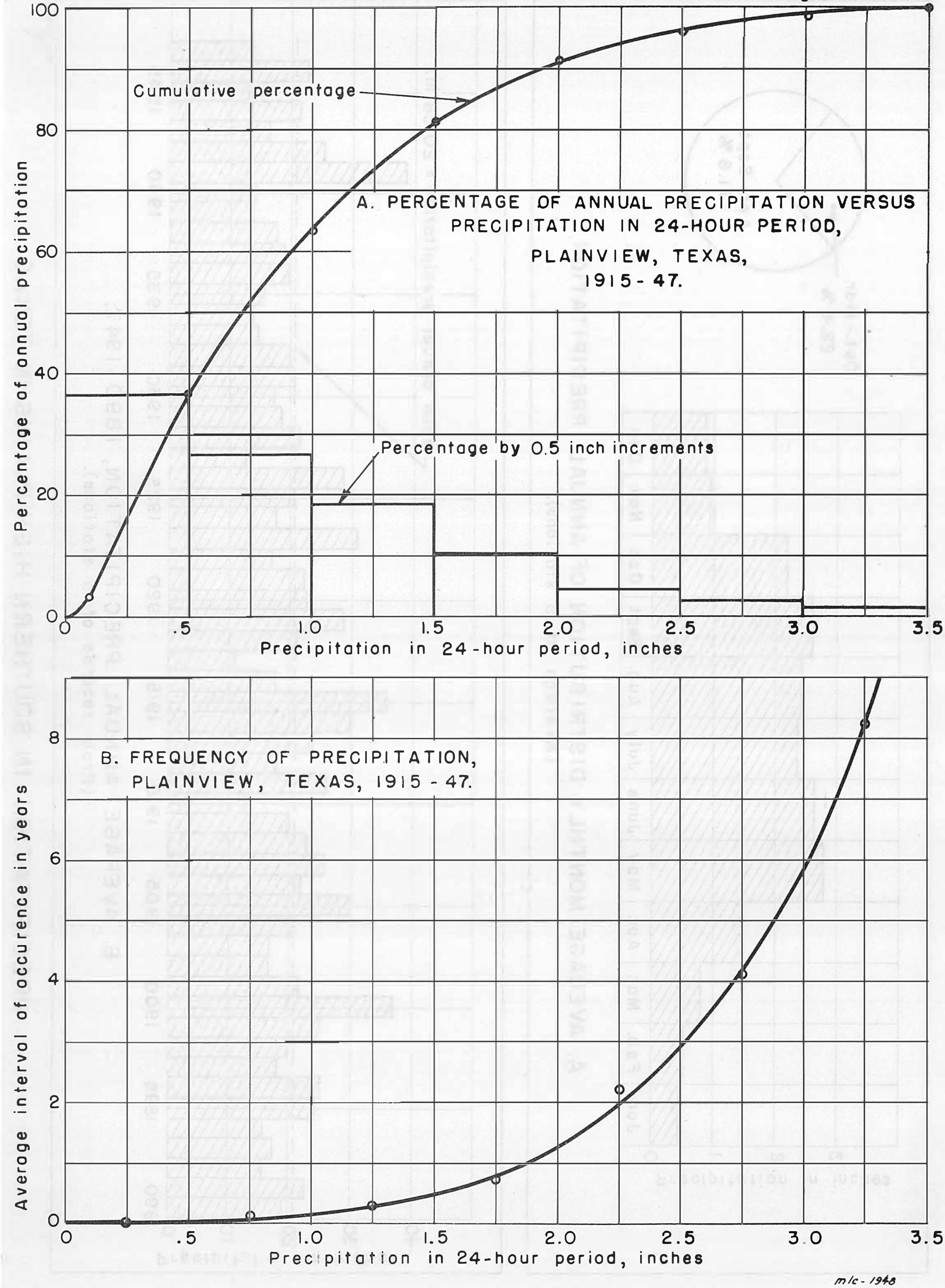
B. AVERAGE ANNUAL PRECIPITATION, 1890-1947.
(From records of 5 stations).

Figure 3

mic - 1948

PRECIPITATION IN SOUTHERN HIGH PLAINS IN TEXAS.

Figure 4


Cumulative percentage
Percentage by 0.5 inch increments
A. PERCENTAGE OF ANNUAL PRECIPITATION VERSUS PRECIPITATION IN 24-HOUR PERIOD, PLAINVIEW, TEXAS, 1915-47.
Percentage of annual precipitation
0
20
40
60
80
100
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
Precipitation in 24-hour period, inches
B. FREQUENCY OF PRECIPITATION, PLAINVIEW, TEXAS, 1915-47.
Average interval of accurence in years
0
2
4
6
8
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
Precipitation in 24-hour period, inches
mlc-1948

Precipitation

Precipitation records of the United States Weather Bureau from stations at Lubbock, Plainview, Muleshoe, Dimmit, and Tulia, for periods ranging from 25 to 51 years, are given on pages 16 to 20 . These records are supplemented in figure 3,B, by earlier records from stations at Epworth near Abernathy, Amarillo, Hale Center, Nazareth, Happy, and Hereford in order to study the distribution of precipitation over a longer period of time. These records show that the precipitation is slightly greater in the eastern part of the South Plains than in the western part, but that the average annual precipitation on the South Plains is approximately 20 inches. Although the mean precipitation for the South Plains was calculated to be 20.68 inches, the most frequent average annual precipitation over the 58-year period from 1890 to 1947, inclusive, was approximately 19 inches. This is explained by the greater departure above normal in years of exceptionally high precipitation as compared with the departure below normal in years of drought. For example, the wettest year on record was 1941, when the average precipitation for the five stations mentioned above was 38.40 inches (departure from normal, 17.72 inches); the precipitation in 1917, the driest year, was 10.50 inches (departure from normal, -10.18 inches). On the average more than 70 percent of the annual moisture is precipitated during the 6-month period from April to September, inclusive, which comprises the principal growing season. (See fig. 3, A.) The analysis of these data shows the predominance of above-normal precipitation for the 32-year period from 1894 to 1926, inclusive, in which the average annual precipitation was 22.56 inches, and the below-normal precipitation in the 14-year period 1927-40, inclusive, in which the average annual precipitation was only 16.97 inches. (See fig. 3, B.) The difference in the average annual precipitation for these two periods amounts to 5.59 inches, or 27 percent of the long-time average annual precipitation.

Records of the daily precipitation at Plainview, Texas, from 1915 to 1947, inclusive, which were supplied by W. J. Klinger, the official Weather Bureau observer, indicate that on the average some moisture falls during 54.6 days of the year. Of this precipitation 37 percent falls in amounts of less than 0.5 inch per day, and about 90 percent falls in amounts less than 2.0 inches per day. (See fig. 4, A.) In figure, 4, B, the frequency of occurrence is plotted for various rates of daily precipitation. Over a long period of time a 3-inch rain in 24 hours may be expected about every 6 years; a 2-inch rain may be expected almost every year.

The annual precipitation by months, departure from the annual average, and the monthly and annual averages for each of the five principal stations previously named, from the time each station was established to January 1, 1948 are tabulated on the following pages.

Table 2. Monthly and annual precipitation, in inches, and departure (+ or -) from the long-term average at Lubbock, Texas

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	Departure from average
1911	--	--	--	2.36	0.72	0.28	6.75	0.21	1.33	1.08	0.22	1.55	14.50 1/	--
12	.02	1.28	.61	.50	1.58	.96	3.35	2.37	.73	2.81	.01	.38	14.60	- 4.41
13	.04	.20	1.18	1.82	.24	5.88	.40	.32	4.19	1.53	1.54	2.12	19.46	+ .45
14	.15	.10	.31	1.46	4.04	3.86	6.17	5.95	.46	7.12	.35	1.47	31.44	+12.43
1915	.09	3.00	2.52	6.18	1.52	4.01	1.42	2.96	7.86	1.52	.04	.76	31.88	+12.87
16	.17	T	1.15	2.63	.39	1.52	.36	2.45	2.79	2.91	.55	.11	15.03	- 3.98
17	.35	.05	.21	.58	1.07	.64	1.42	1.16	3.03	.14	.08	T	8.73	-10.28
18	.84	.58	.05	.72	1.67	2.95	.53	.79	.79	.51	.69	2.33	12.45	- 6.56
19	.12	.25	3.39	3.53	2.10	3.52	2.28	2.83	5.70	7.34	.36	.19	31.61	+12.60
1920	1.27	.11	.24	.15	2.91	3.66	2.19	2.64	1.63	1.43	2.22	.09	18.54	- .47
21	.22	.45	1.47	.24	.43	7.71	.84	.92	4.50	.02	T	T	16.80	- 2.21
22	.34	.20	.55	3.59	3.50	2.43	1.36	.28	.17	.56	1.50	.07	14.55	- 4.46
23	.24	.86	1.04	3.18	2.77	3.98	1.65	1.59	2.67	6.80	.85	.64	26.27	+ 7.26
24	T	.17	.96	.86	.90	1.79	1.20	1.76	1.25	.47	.03	.15	9.54	- 9.47
1925	.65	.02	T	1.12	2.31	.86	3.38	3.32	9.44	1.33	.11	.21	22.75	+ 3.74
26	.56	.04	1.64	1.81	5.14	1.10	1.03	2.75	4.15	8.40	.67	1.63	28.92	+ 9.91
27	.79	.37	T	.40	T	2.91	2.16	.59	1.16	.40	T	.81	9.59	- 9.42
28	.31	1.18	T	.15	3.08	1.06	6.78	4.04	.08	2.10	.74	.28	19.80	+ .79
29	.43	.34	2.03	.15	6.91	.90	.20	1.68	1.36	3.56	1.00	.07	18.63	- .38
1930	.61	.03	.45	1.04	1.71	1.70	.12	1.34	.11	3.91	.94	1.44	13.40	- 5.61
31	.32	1.98	1.34	1.82	1.32	.95	2.17	2.44	.72	3.47	1.39	1.44	19.36	+ .35
32	.93	1.09	.04	1.84	2.37	5.66	1.90	3.15	3.41	1.29	T	2.48	24.16	+ 5.15
33	.37	.95	.02	.06	2.97	.21	1.36	2.19	.71	.42	.99	.06	10.31	- 8.70
34	.06	.06	1.98	1.08	1.26	.28	.65	1.66	1.86	.28	.55	T	9.72	- 9.29
1935	.15	.60	.89	.04	3.49	2.57	1.25	1.69	3.02	1.22	2.04	.33	17.29	- 1.72
36	1.08	.02	.59	.92	5.86	.92	1.05	.13	13.93	1.52	.74	.21	26.97	+ 7.96
37	.26	.01	1.81	2.01	4.00	3.12	1.32	2.06	3.85	3.22	.07	.52	22.25	+ 3.24
38	.91	1.18	.49	.14	1.99	5.89	4.01	.47	.63	.51	.27	.03	16.52	- 2.49
39	2.45	.19	.09	.28	1.82	.67	1.73	2.75	.01	.94	.18	.60	11.71	- 7.30
1940	.23	1.97	T	1.84	1.74	2.06	T	1.57	.73	1.07	2.35	.20	13.76	- 5.25
41	.55	.61	3.56	2.23	12.69	4.13	3.68	1.85	4.47	5.89	.17	.72	40.55	+21.54
42	.04	.18	.51	3.25	.35	1.74	2.58	4.97	7.61	3.39	.01	2.80	27.43	+ 8.42
43	.04	.02	.25	.53	2.71	2.37	3.17	T	1.16	.10	.62	1.87	12.84	- 6.17
44	1.28	1.36	1.09	.84	3.03	1.75	2.93	2.37	3.73	.80	1.72	1.64	22.54	+ 3.53
1945	.69	.39	.10	.46	.46	.36	3.08	2.17	2.22	2.26	.27	.32	12.78	- 6.23
46	1.18	.15	.76	.07	1.49	2.72	.58	3.55	3.59	4.67	.44	1.04	20.24	+ 1.23
47	.73	.02	.69	1.06	6.35	1.56	1.06	.06	.08	.37	1.43	.52	13.93	- 5.08
Average	.51	.56	.89	1.38	2.62	2.40	2.06	1.97	2.84	2.31	.68	.79	19.01	

1/ Incomplete.

Table 3.- Monthly and annual precipitation, in inches, and departure (+ or -) from the long-term average at Plainview, Texas

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	Departure from average
1908	0.72	0.72	0.16	1.96	4.70	1.70	3.19	4.32	0.70	1.00	1.39	T	20.56	+ .79
09	T	T	.97	T	2.18	5 09	3.37	1.15	.37	.98	4.52	.27	18.90	-2.45
1910	.30	T	.23	1.09	1.93	.61	3.16	2.67	.06	.77	.35	.18	11.35	-10.00
11	.38	5.83	.43	4.80	1.92	.03	10.06	1.03	2.40	2.47	.36	1.34	31.05	+ 9.70
12	T	1.35	.63	1.38	1.56	.74	3.60	2.94	5.75	.53	0	.40	18.88	- 2.47
13	.16	.40	.52	1.67	.50	4 39	2.89	2.03	3.33	1.24	1.84	1.76	20.73	- .67
14	30	T	.34	1.76	5.42	2.24	6.12	5.22	.60	6.18	.32	.57	29.07	+ 7.72
1915	.10	2.66	1.15	6 46	1.40	6.08	2.80	6.16	6.93	2.38	T	1.29	37.41	+16.06
16	08	T	.97	2.53	.92	1.08	1.24	2.80	1.10	3.90	1.44	.30	16.36	- 4.99
17	.25	.05	.10	.78	1.10	47	2.41	3.16	1.17	.29	.42	T	10.20	-11.15
18	1.07	.61	.14	.48	1 91	4.60	1.51	2.32	1.50	1.19	.98	2.28	18.59	- 2.76
19	17	.36	2 93	5.41	5.96	2 13	4.20	1.67	5.40	3.37	.64	.05	32.29	+10.94
1920	1.06	.56	.29	.39	4.06	3 37	2.45	4.01	2.48	3.65	2.23	1.43	25.98	+ 4.37
21	1.02	.87	.49	11	2.35	10.42	4.56	2.09	1.89	.10	.08	.06	24.04	+ 2.69
22	68	.39	1.79	4.12	3.53	2.52	2.82	.42	.85	.33	1.93	0	19.38	- 1.97
23	.21	.91	2.41	2 60	1.26	5 42	1.85	2.80	3.14	6.84	1.33	.88	29.65	+ 8.30
24	T	.34	1.33	1.23	1.54	4.08	4.81	4.39	1.38	1.99	.39	.60	22.08	+ .73
1925	.20	T	.04	.76	5.65	3.02	1.47	3.74	4.55	1.26	.60	T	21.29	- .06
26	70	0	2.81	3.45	3.89	2.73	2.36	4.13	8.17	6.58	.77	2.51	38.10	+16.75
27	.56	.26	T	.62	.98	2.89	3.20	2.06	3.01	.06	T	1.07	14.71	- 6.64
28	.20	1.73	.15	12	6.05	1.26	4.12	2.36	.75	3.06	1.28	.30	21.38	+ .03
29	.40	.55	3.32	.10	2.69	1.87	.87	1.34	1.41	2.49	1.40	.20	16.64	- 4.71
1930	1.63	.08	1.04	1.83	3.16	3.89	.20	1.48	1.24	5.84	.40	1.61	22.40	+ 1.05
31	.35	1.40	1.03	2.37	1.03	1.30	1.82	2.98	T	1.92	1.70	1.71	17.61	- 3.74
32	1.28	.46	.02	2 16	.75	5.11	1.19	3.70	3.66	.96	T	2.23	21.52	+ .17
33	.40	.81	1.05	38	3.03	.22	1.91	6.40	2.60	.62	1.71	.03	19.16	- 2.19
34	10	.08	2.02	2.94	4.32	.40	.07	1.72	1.16	T	.94	0	13.75	- 7.60
1935	.18	.53	.43	.05	5.56	4.55	2.09	2.63	.91	1.18	1.90	.31	20.32	- 1.03
36	1.35	.15	.10	.59	4.59	.50	2.80	.38	7.08	.61	.10	.51	18.76	- 2.59
37	.27	.09	1.25	.61	5.16	4.64	1.89	2.45	3.34	1.77	.05	.48	22.00	+ .65
38	39	1.18	1.33	.84	1.33	6.42	4.10	1.15	1.11	.87	.10	.07	18.89	- 2.46
39	1.92	.14	.80	82	1.89	3.22	.65	2.75	.02	.85	.08	1.02	14.16	- 7.19
1940	.32	1.91	0	1 68	2.57	.57	1.40	1.51	.82	1.45	3.09	.11	15.43	- 5.92
41	.27	1.00	2.30	1 34	7.07	6.03	4.35	2.28	3.65	5.34	.14	.58	34.35	+13.00
42	.10	.41	.60	4 15	.23	2.01	2.13	4.04	3.29	4.03	.02	2.71	23.72	+ 2.37
43	.05	T	T	1.54	3.66	.28	6.67	.03	2.38	.16	.80	2.32	17.89	- 3.46
44	2.22	.99	.20	.76	2.49	4.88	2.14	1.22	3.34	.65	.97	1.87	21.73	+ .38
1945	.66	.54	.16	1.68	.71	.65	2.06	2.74	1.20	1.94	T	.34	12.68	- 8.67
46	1.71	.35	.95	.39	1.41	1.74	1.30	2.94	3.87	4.60	.71	2.82	22.79	+ 1.44
47	.82	.30	1.39	1.35	7.03	2.23	.64	.22	.05	.14	1.12	.56	15.85	- 5.50
Average	.55	.70	.90	1 68	2.94	2.88	2.76	2.59	2.42	2.16	.90	.87	21.35	

Table 4. **Monthly and annual precipitation, in inches, and departure (+ or -) from the long-term average at Muleshoe, Texas**

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	Departure from average
1921	-	-	-	-	-	-	-	1.05	3.02	0	0	0	4.07 1/	
1922	.11	.10	.31	5.15	1.90	2.17	1.92	.40	1.60	0	.33	0	13.99	- 4.29
1923	.09	1.57	1.51	1.83	.77	10.05	1.70	1.12	2.32	6.27	1.33	.53	29.09	+ 10.81
1924	0	.25	1.07	.37	1.07	1.67	8.13	3.39	.95	.67	.45	0	18.02	- .26
1925	0	0	.09	.08	1.69	3.96	1.46	2.78	4.14	.85	.37	0	15.42	- 2.86
1926	0	0	1.62	2.42	4.33	.97	1.31	1.71	8.49	2.04	.40	.94	24.23	+ 5.95
1927	.54	0	.16	.13	0	1.71	4.61	2.03	5.16	.03	0	.55	14.92	- 3.36
1928	0	.40	.20	0	3.53	1.13	2.39	2.39	1.19	4.70	2.80	.23	18.96	+ .68
1929	.23	0	2.25	.15	5.16	2.59	.67	2.27	3.82	1.36	.57	0	19.07	+ .79
1930	0	0	0	3.52	1.84	2.93	1.27	1.65	2.43	2.04	.69	.47	16.84	- 1.44
1931	1.11	1.32	.45	3.46	2.41	.68	2.88	4.63	.52	.72	1.41	1.46	21.05	+ 2.77
1932	.51	.52	.05	1.05	.85	4.25	.30	2.70	4.58	.63	0	1.89	17.33	- .95
1933	.48	.52	.69	.20	1.41	.69	.95	6.27	.91	.57	.86	0	13.55	- 4.73
1934	.12	.14	1.96	1.31	1.64	2.39	1.28	1.34	1.77	.98	2.14	.14	15.21	- 3.07
1935	.35	.28	.95	.07	1.85	4.48	2.96	1.04	.89	.11	1.70	.22	14.90	- 3.38
1936	1.82	.14	.12	.19	5.66	1.36	1.80	.41	2.55	.88	.12	.67	15.72	- 2.56
1937	.08	.18	1.66	.95	5.66	2.56	1.24	.60	4.71	1.28	0	.56	19.48	+ 1.20
1938	.64	1.24	1.45	.73	1.63	7.74	1.78	.54	1.39	2.93	.34	.08	20.49	+ 2.21
1939	1.96	.06	.40	.57	2.06	1.82	.94	3.42	.05	1.28	.18	1.34	14.08	- 4.20
1940	.27	.65	0	1.53	2.63	1.89	.33	3.97	.37	.22	2.04	.07	13.97	- 4.31
1941	.24	.38	3.14	1.99	11.86	5.77	6.92	2.09	3.46	6.37	.47	.83	43.52	+ 25.24
1942	.02	0	1.15	2.96	.60	2.21	.98	4.50	2.29	4.94	0	1.45	21.10	+ 2.82
1943	0	.50	0	.28	1.67	1.74	3.13	.21	1.12	1.06	1.10	3.45	14.26	- 4.02
1944	.57	.78	.01	1.14	2.07	4.00	2.21	3.44	4.77	.12	.47	.93	20.51	+ 2.23
1945	.57	.13	.17	.35	.64	.00	1.68	2.50	3.79	1.17	.00	.21	11.21	- 7.07
1946	1.18	.05	.19	.14	.80	2.82	1.00	2.20	4.21	5.48	.64	1.17	19.88	+ 1.60
1947	.58	.20	.67	1.36	4.32	.35	2.50	.33	.22	.22	.76	.58	12.09	- 6.19
Average	.44	.36	.78	1.23	2.62	2.77	2.17	2.18	2.62	1.74	.71	.66	18.28	

1/ Incomplete.

Table 5. Monthly and annual precipitation, in inches, and departure (+ or -) from the long term average at Dimmitt, Texas

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	Departure from average
1923	.00	1.25	2.25	5.23	1.32	5.35	0.95	3.04	7.22	9.51	1.72	0.74	38.58	+19.79
24	.00	.22	.38	.47	.82	2.39	3.53	4.63	1.09	1.03	.75	.14	15.45	- 2.34
1925	.00	.00	.05	.26	2.43	3.27	3.55	2.96	7.29	.95	.43	.06	21.25	+ 2 46
26	.10	.00	1.77	2.27	4.48	2.01	.75	2.38	5.90	3.08	.43	.85	24.02	+ 5.23
27	.29	.10	.11	.39	.16	3.06	3.07	2.59	2.07	.44	.00	.55	12.83	- 5.96
28	.00	.77	.24	.25	4.02	1.52	3.95	5.67	.33	2.91	2.01	.27	21.94	+ 3.15
29	.17	.16	2.21	.20	4.99	1.38	.93	5.06	2.16	3.20	.81	.09	21.36	+ 2.57
1930	.60	.00	.50	1.31	1.30	4.67	1.69	2.07	.49	3.89	.57	.87	17.96	- .83
31	.46	.76	.26	2.13	3.60	.40	1.31	2.53	.71	1.27	1.38	.93	15.74	- 3.05
32	.44	.43	.15	1.89	.37	6.10	.32	1.23	4.60	.46	0	1.28	17.27	- 1.52
33	.58	.14	.80	.35	3.14	.29	2.01	4.07	1.20	1.47	.71	0	14.76	- 4.03
34	0	0	1.52	.84	4.99	1.58	.49	2.10	1.31	.90	1.31	0	15.04	- 3.75
1935	.50	.43	.39	0	1.72	1.43	1.77	2.12	1.73	.08	1.30	.20	11.67	- .53
36	.69	.04	0	.25	7.64	1.10	1.53	.27	4.98	1.04	0	.49	18.03	- .76
37	.03	.05	1.03	.40	6.49	1.98	2.25	.18	2.42	.46	.11	.10	15.50	- 3.29
38	.47	1.61	1.10	.41	2.54	2.66	2.92	1.79	.96	2.67	.20	.10	17.43	- 1.36
39	2.21	.04	.49	.70	1.12	4.27	.86	1.58	.15	1.15	.11	.94	13.62	- 5.17
1940	.12	.34	.18	1.35	2.05	.21	.45	1.67	.16	1.33	3.90	.23	11.99	- 6.80
41	.07	.53	1.96	1.55	8.00	7.78	2.46	3.63	4.74	7.79	.42	.63	39.56	+20.77
42	0	.10	.47	4.35	.47	2.57	2.32	3.64	4.34	5.79	0	1.86	25.91	+ 7.12
43	0	0	0	.78	2.01	3.26	4.72	.93	.85	.66	.54	3.08	16.83	- 1.96
44	.77	.66	0	.69	2.00	3.53	3.22	1.09	2.91	.88	.66	1.66	18.07	- .72
1945	.40	.11	.52	.31	.28	.63	2.24	2.76	3.94	.86	0	.14	12.19	- 6.60
46	.91	.11	.46	.84	.96	1.94	.86	1.89	4.53	6.75	.25	.80	20.30	+ 1.36
47	.22	0	.45	1.51	3.27	2.23	1.76	1.25	.21	0	.80	.51	12.21	- 6.58
Average	.36	.31	.69	1.15	2.83	2.62	2.00	2.44	2.65	2.34	.74	.66	18.79	

Table 6.- Monthly and annual precipitation, in inches, and departure (+ or -) from the long-term average at Tulia, Texas

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	Departure from average
1896	-	-	-	-	-	-	4.36	0.76	2.24	4.01	0.55	1.93	13.85 1/	
97	1.76	+	.75	1.08	2.78	-	-	-	-	-	0	-	6.37 1/	
98	.50	.18	T	.95	3.36	5.55	4.67	3.07	1.31	.10	.75	1.70	22.14	- .06
99	.55	.10	.30	.25	3.17	4.44	10.84	0.00	2.96	.65	2.40	-	24.66	+ 3.46
1900	.10	.52	.80	6.60	3.77	3.25	4.40	2.30	6.83	7.80	2.25	T	38.62	+16.42
01	.10	-	-	-	-	-	-	.70	2.50	1.05	2.80	.20	7.35 1/	
02	.20	T	.65	1.35	7.47	.87	2.20	.00	2.05	1.35	1.85	.70	18.69	- 3.51
03	.40	1.60	T	2.35	.35	3.58	.84	3.88	4.25	1.92	.00	.00	19.17	- 3.03
04	.00	.00	.00	.95	2.86	3.42	3.78	3.07	3.35	1.18	.15	.55	19.31	- 2.89
1905	.68	1.95	1.65	7.60	2.48	.11	-	-	-	-	-	-	14.47 1/	
07	1.98	T	.05	.93	2.34	2.15	4.30	8.85	1.25	5.25	1.00	1.25	29.35	+ 7.15
08	.95	1.20	.32	.85	4.08	1.80	4.09	6.67	1.85	1.85	1.50	T	25.16	+ 2.96
09	.10	.07	1.83	T	1.55	8.02	3.17	.64	.60	1.65	4.39	.58	22.60	+ .40
1910	.33	T	1.06	1.91	2.65	1.25	2.55	3.75	T	.70	.51	.36	15.07	- 7.13
11	.32	5.43	.77	3.81	1.75	T	6.60	1.32	3.05	3.24	1.36	2.12	29.77	+ 7.57
12	T	3.19	1.15	1.06	1.95	1.03	1.58	3.97	4.10	.65	T	1.07	19.75	- 2.45
13	.40	.91	.64	2.82	.84	4.18	3.85	1.95	6.53	1.16	2.15	4.12	29.55	+ 7.35
14	.35	.00	.37	2.06	6.80	.62	6.06	4.50	.74	5.25	.15	2.00	28.90	+ 6.70
1915	.50	3.24	1.89	5.08	1.29	2.17	5.06	7.56	6.27	3.67	.33	.56	37.62	+15.42
16	.68	.00	T	3.00	.29	4.11	.12	5.58	1.30	4.86	.55	.43	20.92	- 1.28
17	1.04	.00	.20	1.02	2.30	.10	2.55	3.71	1.46	.05	.15	T	12.58	- 9.62
18	1.05	.62	.00	.90	3.21	2.17	2.15	2.67	2.03	11.58	1.05	3.60	31.03	+ 8.83
19	T	.10	2.85	8.25	6.14	2.51	1.40	2.26	-	-	-	-	23.51 1/	
1923	.01	.79	2.21	1.64	1.09	2.40	2.49	2.09	6.13	8.72	1.31	.65	29.53	+ 7.33
24	.00	.38	.79	.63	4.52	1.13	3.85	4.81	1.15	2.72	1.86	.00	21.84	- .36
1925	.00	.02	.00	.12	2.48	1.78	3.78	4.27	5.27	1.52	.41	.00	19.65	- 2.55
26	.40	.00	1.71	-	-	-	-	-	-	-	-	-	2.11 1/	
27	.18	.00	T	.62	.13	1.18	3.06	3.31	2.54	.00	.00	.75	11.77	-10.43
28	.00	1.35	.24	.53	5.99	1.59	6.00	4.41	.14	1.16	2.23	.25	23.89	+ 1.69
29	.40	.40	2.24	.00	3.06	1.21	.00	2.29	1.58	3.50	1.08	.40	16.16	- 6.04
1930	1.06	.01	1.18	1.82	.79	2.91	.88	2.18	T	2.89	.28	1.00	15.00	- 7.20
31	.50	1.16	1.23	3.59	3.64	1.34	3.33	5.53	1.89	1.27	3.89	1.99	29.36	+ 7.16
32	.90	1.12	.00	2.13	.78	3.05	.77	4.20	3.40	.90	.00	1.67	18.92	- 3.28
33	.71	-	-	-	-	-	1.93	4.91	.65	.12	2.10	.00	10.42 1/	
34	.02	.00	2.60	.33	5.72	1.43	.56	1.55	.69	.94	1.33	.15	15.32	- 6.88
1935	.46	.51	.33	.02	2.63	2.62	.77	2.73	1.10	.46	1.70	.00	13.33	- 8.90
36	1.05	.12	.00	.23	8.79	.78	.22	.20	5.22	1.34	.00	.31	18.26	- 3.94
37	.22	.26	1.31	.65	5.64	1.94	1.40	.77	2.82	.38	.04	.14	15.57	- 6.63
38	.37	1.83	1.45	.30	1.82	2.61	2.57	.44	1.77	1.30	T	.11	14.57	- 7.63
39	1.87	.10	1.11	1.07	.87	4.97	.98	1.92	.30	1.28	.04	1.05	15.56	- 6.64
1940	.26	1.60	.03	2.55	2.42	1.49	.25	1.85	.40	.69	2.83	.23	14.60	- 7.60
41	.18	.82	2.03	1.47	8.02	5.59	3.36	2.05	3.39	6.22	.38	.50	34.01	+11.81
42	.10	.35	1.10	3.67	.36	3.82	1.54	4.11	3.54	5.97	.00	2.88	27.44	+ 5.24
43	.00	.03	.02	1.57	3.57	3.49	4.91	.35	1.08	.62	1.33	2.67	19.64	- 2.56
44	1.88	.80	T	1.48	2.87	3.82	3.16	.39	3.42	1.23	.97	2.79	22.81	+ .61
1945	.57	.52	.62	2.32	.21	.69	2.91	3.70	2.50	1.36	.00	.01	15.41	- 6.79
46	1.11	.33	1.09	.93	.74	5.43	1.22	6.54	4.16	6.02	.79	2.41	30.77	+ 8.57
47	.27	.25	.83	1.91	4.24	2.68	.75	T	.24	T	.94	.60	12.71	- 9.49
Average	.52	.71	.83	1.87	3.00	2.54	2.85	2.93	2.46	2.47	1.05	.97	22.20	

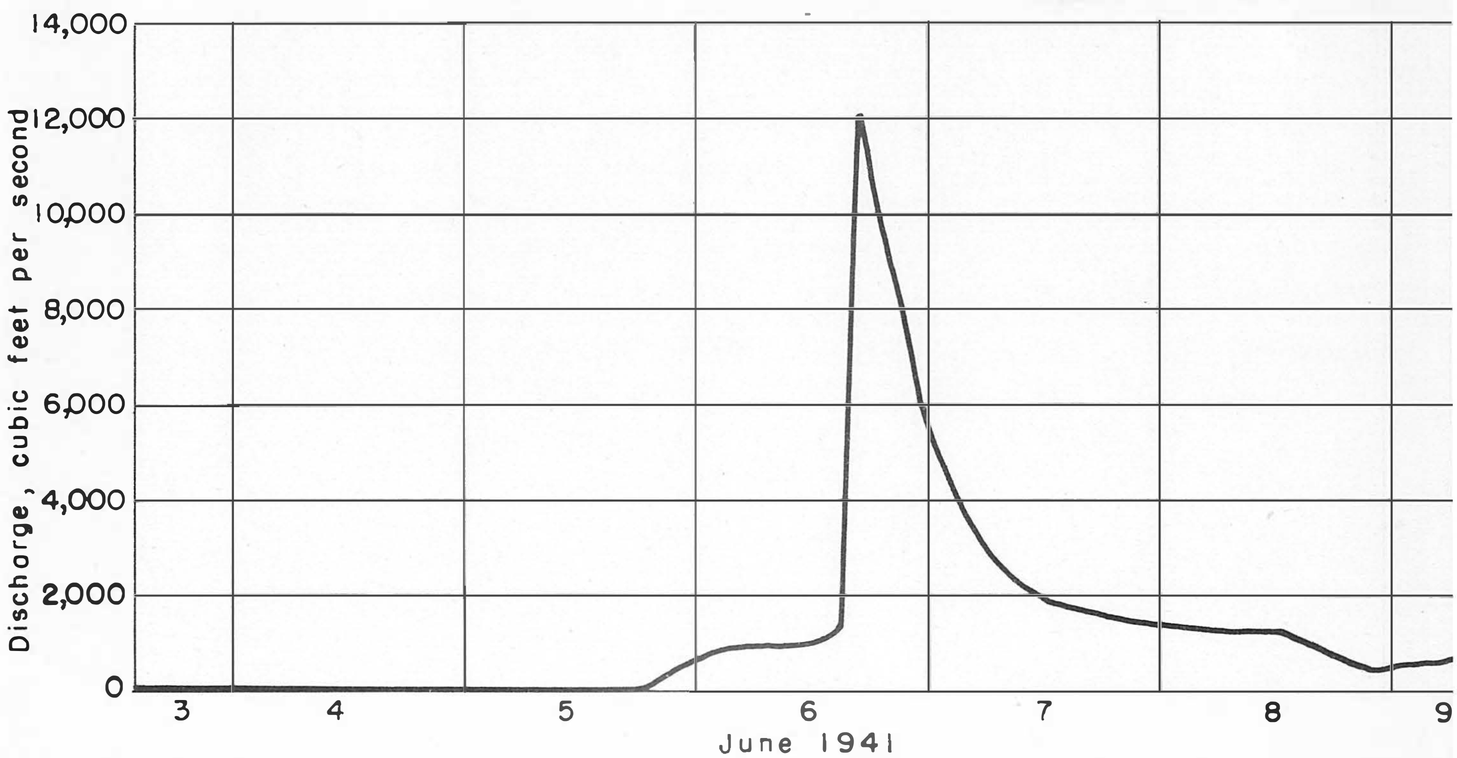
1/ Incomplete.

PLATE 7

A. AIR VIEW OF WHITE RIVER (RUNNING WATER DRAW) AT PLAINVIEW, TEXAS, JUNE 6, 1941.

(Looking south along South Broadway.)

Photograph courtesy Winfield Holbrook.



B. DISCHARGE OF WHITE RIVER AT PLAINVIEW, TEXAS.

mlc 1949

Runoff

Stream runoff.- The characteristics of the soil, precipitation, and slope of the land in the Southern High Plains in Texas are such that loss of water by stream runoff is generally negligible. Gaging stations have been maintained by the Surface Water Branch of the Geological Survey since 1938-39 on the three principal streams that traverse the South Plains. These records, which are given in table 7, page 22, show the monthly and annual runoff from the time the stations were established to January 1, 1948.

This table illustrates the greater runoff from the tight clay soils of Randall and Deaf Smith Counties as compared with that from the sandy loams in the vicinity of Lubbock, Texas. From 75 to 90 percent of the total 8-year runoff occurred in the unusually wet year 1941. A study of rainfall records indicates that the average runoff over a long period of time will be considerably less than the average during the 8-year period of record.

The total amount of precipitation entering a stream on the High Plains cannot be determined from one stream-gaging station. Much water may be absorbed by the channel upstream and downstream from the measuring section. For example, after heavy rains in May 1937, the discharge of White River (Running Water Draw) at Plainview, Texas, reached a peak of about 1,200 second-feet, but the maximum flow 15 miles below Plainview was only about 80 second-feet. Nearly all the water was absorbed by the soil and a large part percolated downward to the water table. The discharge at Plainview reached a peak of 12,000 second-feet on June 6, 1941 (see pl. 7), but it was reported that only a small percentage of the water flowed over the cap rock at the east edge of the Plains.

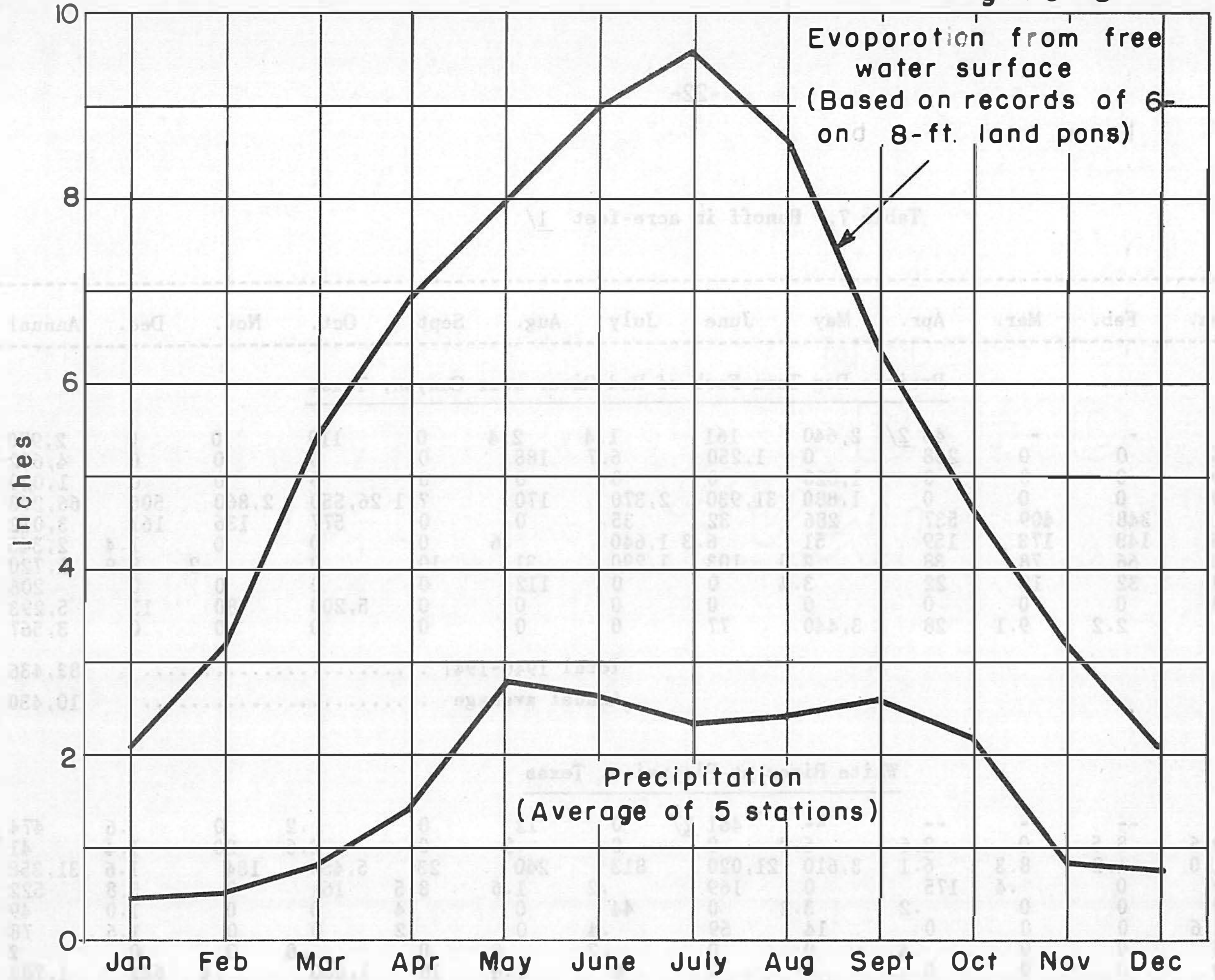
Table 7. Runoff in acre-feet 1/

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
						Prairie Dog Town Fork of Red River near Canyon, Texas							
1938	-	-	-	46 2/	2,640	161	1.4	2.4	0	119	0	0	2,970 2/
1939	65	0	0	258	0	1,250	6.7	188	0	0	0	0	4,672
1940	0	0	0	0	1,020	0	0	0	0	0	0	0	1,020
1941	0	0	0	0	1,880	31,930	2,370	170	7.1	26,550	2,860	506	66,273
1942	491	348	409	537	286	32	35	0	0	577	136	161	3,012
1943	166	148	173	159	51	6.3	1,640	.6	0	0	0	1.4	2,345
1944	93	66	78	38	2.0	103	1,290	31	10	0	.2	8.9	1,720
1945	19	32	18	22	3.4	0	0	112	0	0	0	0	206
1946	0	0	0	0	0	0	0	0	0	5,200	80	13	5,293
1947	11	2.2	9.1	28	3,440	77	0	0	0	0	0	0	3,567
							Total 1940-1947						83,436
							Annual average						10,430
						White River at Plainview, Texas							
1939	--	--	--	--	--	461 2/	0	12	0	.2	0	.6	474 2/
1940	0.6	8.5	0	2.6	5.0	0	0	.2	0	2.6	20	1.4	41
1941	1.0	1.2	8.3	6.1	3,610	21,020	813	240	23	5,450	184	1.6	31,358
1942	0	0	.4	175	0	169	.2	1.6	8.5	161	0	5.8	522
1943	0	0	0	.2	3.2	0	44	0	.4	0	0	1.0	49
1944	2.6	0	0	0	14	59	.4	0	.2	0	0	1.6	78
1945	0	0	0	.4	0	0	.2	.8	0	.8	0	0	2
1946	0	0	0	0	0	0	0	1.6	18	1,080	.4	682	1,782
1947	0	0		.2	1,430	17	15	0	0	0	0	0	1,462
							Total 1940-1947						35,294
							Annual average						4,412
						Double Mountain Fork of Brazos River at Lubbock, Texas							
1939	--	--	--	--	--	--	--	--	0	0	0	0	0 2/
1940	0	0	0	0	0	0	0	0	0	0	0	0	0
1941	0	0	8.7	0	3,730	2,170	302	.4	.6	477	39	.2	6,728
1942	0	0	0	14	0	803	6.3	0	1,040	112	0	34	2,009
1943	0	0	0	0	0	0	0	0	0	0	0	0	0
1944	0	0	0	0	210	68	15	0	0	0	0	0	293
1945	0	0	0	0	0	0	0	0	0	0	0	0	0
1946	0	0	0	0	0	0	0	0	0	6.7	0	0	7
1947	0	0	0	0	4.6	0	0	0	0	0	0	0	5
							Total 1940-1947						9,042
							Annual average						1,118

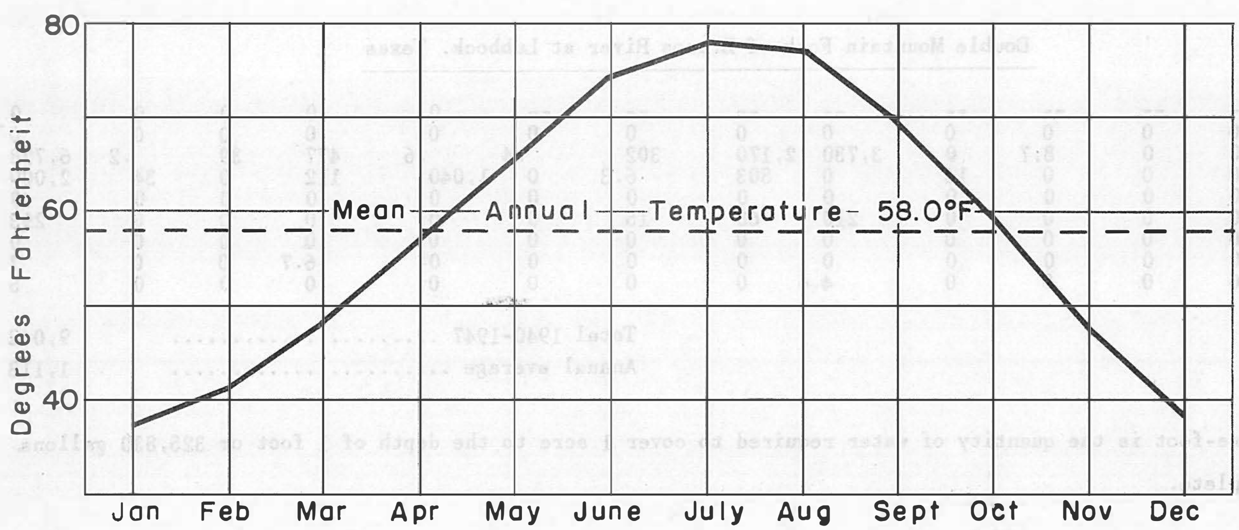
1/ An acre-foot is the quantity of water required to cover 1 acre to the depth of 1 foot or 325,830 gallons.

2/ Incomplete.

Figure 5



A. AVERAGE PRECIPITATION AND EVAPORATION IN THE SOUTHERN HIGH PLAINS IN TEXAS.



B. MEAN TEMPERATURE IN THE SOUTHERN HIGH PLAINS IN TEXAS. (Average of 5 stations).

m/c-1949

Runoff into depressions.- Over most of the High Plains in Texas, saucer-like depressions ranging from a few feet to 50 feet or more in depth and from a few hundred feet to a mile or more in diameter, are of common occurrence. The depressions afford the most prominent relief over the interior of the relatively level plains and are the catchment areas of the runoff from excessive precipitation. The runoff, which is influenced largely by the type of cultivation, the contour of the rows, the slope of the land, the vegetation, and the intensity of the precipitation, varies widely in individual sinks and over larger areas. Basic hydrologic data on which to evaluate the runoff are lacking, but studies of available information indicate that the average annual accumulation in sinks within the irrigated district is probably on the order of 200,000 acre-feet.

Evaporation and transpiration of precipitation

Of the average of 20 inches of moisture that is precipitated annually upon the South Plains, it is estimated that more than 99 percent is lost through evaporation and transpiration and does not reach the water table. Evaporation is the process by which liquid water upon the earth is vaporized and absorbed by the atmosphere. Transpiration is the process by which plants absorb water from the soil and carry it to the leaves, from which it is evaporated. Both evaporation and transpiration are more rapid under conditions of high temperature, high winds, low humidity, and low atmospheric pressure. These conditions are quite common in the High Plains, especially during the summer.

Figure 5 shows the average monthly rate of evaporation from a free-water surface in the South Plains, as interpolated from records of evaporation pans maintained by Texas Agriculture Experiment Stations and field stations of the U. S. Department of Agriculture at Amarillo, Big Spring, Dalhart, Lubbock, and Spur Texas. This interpolation indicates that the average annual evaporation from a free-water surface on the South Plains is approximately 70 inches, of which about 70 percent occurs during the 6-month period from April to September, inclusive. The evaporation from a saturated soil would be somewhat less than this amount, depending upon the texture, cover, method of cultivation, and other factors. It can be seen that the month of July is the most critical period for plant growth because of the predominantly high evaporation and temperature and the relatively low precipitation. Because the potential annual evaporation is, on the average, 3.5 times greater than the annual precipitation, a rainfall of light intensity will be largely or entirely evaporated and thus will have little opportunity to aid plant growth or to recharge the ground-water reservoir. In general the winter is much more favorable for the storage of soil moisture, but it is also usually deficient in precipitation.

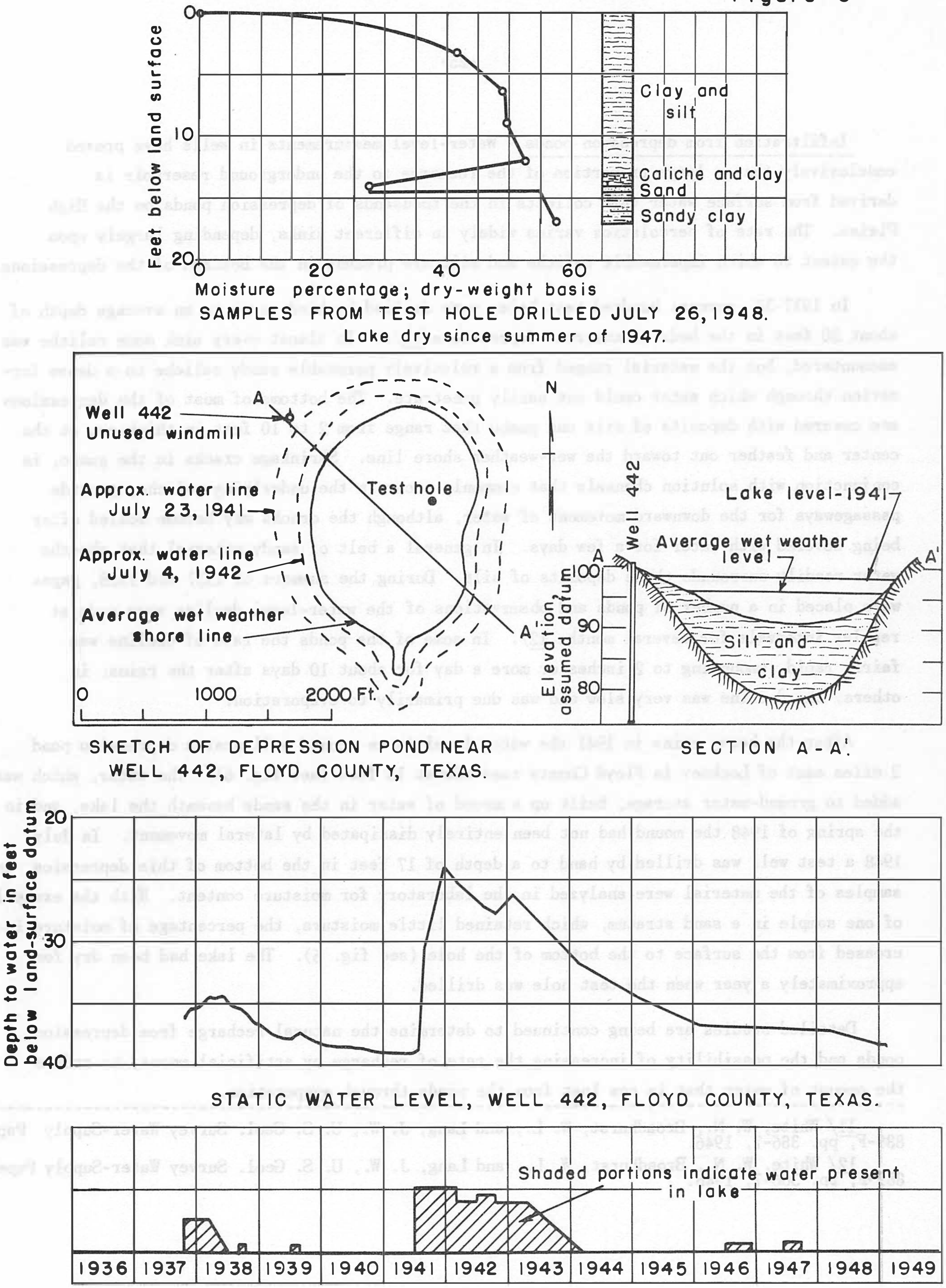
If the rainfall is greater than can be evaporated from the top soil in a short time, the remainder wets the underlying soil to a depth ranging from a few inches to a few feet. Part of the soil moisture may be lost by direct evaporation at the surface, and subsequently may be replaced by upward movement of capillary moisture, and the remainder may be held in suspension by capillary attraction until it is absorbed by plants and is transpired.

Infiltration of rainfall

Most of the surface of the High Plains is underlain by sediments that are cemented with calcium carbonate and usually are called caliche. In some localities the caliche probably prevents penetration of surface water, but more generally, throughout much of the "tightlands" commonly found in Deaf Smith, Castro, Randall, Swisher, Hale, and Floyd Counties, downward percolation is retarded by the clayey subsoil. The principal areas in which direct infiltration can occur are the sandy zones in Bailey, Lamb, Lubbock, and Hockley Counties. Water levels in these areas showed much greater rises in 1941 and 1942 than these in the "tightlands" referred to above (see figs. 10 to 21). Before rainfall can percolate down to the water table, the moisture deficiencies of the soil and the needs of vegetation must be supplied. If the underlying soils are permeable, the surplus moisture that percolates below the root zone will eventually find its way into the underground reservoir. As the soils on the High Plains are seldom saturated to any great depth, this manner of ground-water recharge is confined to periods of exceptionally great precipitation.

Infiltration from sand-dune areas.- Sand-dune areas of wide extent, which cover parts of the High Plains, play an important part in recharging the ground-water supplies. Among the largest of the sand-dune areas is one that extends eastward from Roosevelt County, New Mexico, across Bailey and Lamb Counties and a small part of Hale County, Texas. Most of the sand hills in this group lie in a large, shallow basin which has a very poorly developed drainage system. In general, these sand hills are underlain by deposits similar to the remainder of the High Plains, which might be classified as semipermeable; however, solution channels are present in the caliche deposits, which probably offer little resistance to percolation. The effectiveness of the sand dunes in facilitating recharge lies in the rapid absorption of rainfall and reduction of evaporation and surface runoff. Their importance in contributing to ground-water recharge can be seen in the hydrographs of wells in Bailey County, figure 10.

Figure 6



NATURAL RECHARGE FROM A DEPRESSION POND, 2 MILES EAST OF LOCKNEY, FLOYD COUNTY, TEXAS.

mlc-1948

Infiltration from depression ponds.- Water-level measurements in wells have proved conclusively that a large proportion of the recharge to the underground reservoir is derived from surface water that collects in the thousands of depression ponds on the High Plains. The rate of percolation varies widely in different sinks, depending largely upon the extent to which impermeable caliche and silt are present in the bottoms of the depressions.

In 1937-38, several hundred test holes were drilled by hand auger to an average depth of about 30 feet in the beds of numerous depressions 11/. In almost every sink some caliche was encountered, but the material ranged from a relatively permeable sandy caliche to a dense formation through which water could not easily penetrate. The bottoms of most of the depressions are covered with deposits of silt and gumbo that range from 2 to 10 feet in thickness at the center and feather out toward the wet-weather shore line. Shrinkage cracks in the gumbo, in conjunction with solution channels that commonly occur in the underlying caliche, provide passageways for the downward movement of water, although the cracks may become sealed after being covered with water for a few days. In general a belt of sandy material that absorbs water readily surrounds these deposits of silt. During the summers of 1937 and 1938, gages were placed in a number of ponds and observations of the water-level decline were made at regular intervals for several months 12/. In some of the ponds the rate of decline was fairly rapid, amounting to 2 inches or more a day for about 10 days after the rains; in others, the decline was very slow and was due primarily to evaporation.

After the heavy rains in 1941 the water level in an unused well near a depression pond 2 miles east of Lockney in Floyd County rose almost 15 feet (see fig. 6). The water, which was added to ground-water storage, built up a mound of water in the sands beneath the lake, and in the spring of 1948 the mound had not been entirely dissipated by lateral movement. In July 1948 a test well was drilled by hand to a depth of 17 feet in the bottom of this depression, and samples of the material were analyzed in the laboratory for moisture content. With the exception of one sample in a sand stratum, which retained little moisture, the percentage of moisture increased from the surface to the bottom of the hole (see fig. 6). The lake had been dry for approximately a year when the test hole was drilled.

Detailed studies are being continued to determine the natural recharge from depression ponds and the possibility of increasing the rate of recharge by artificial means, to reduce the amount of water that is now lost from the ponds through evaporation.

11/ White, W. N., Broadhurst, W. L., and Lang, J. W., U. S. Geol. Survey Water-Supply Paper 889-F, pp. 386-7, 1946.

12/ White, W. N., Broadhurst, W. L., and Lang, J. W., U. S. Geol. Survey Water-Supply Paper 889-F, pp. 386-7, 1946.

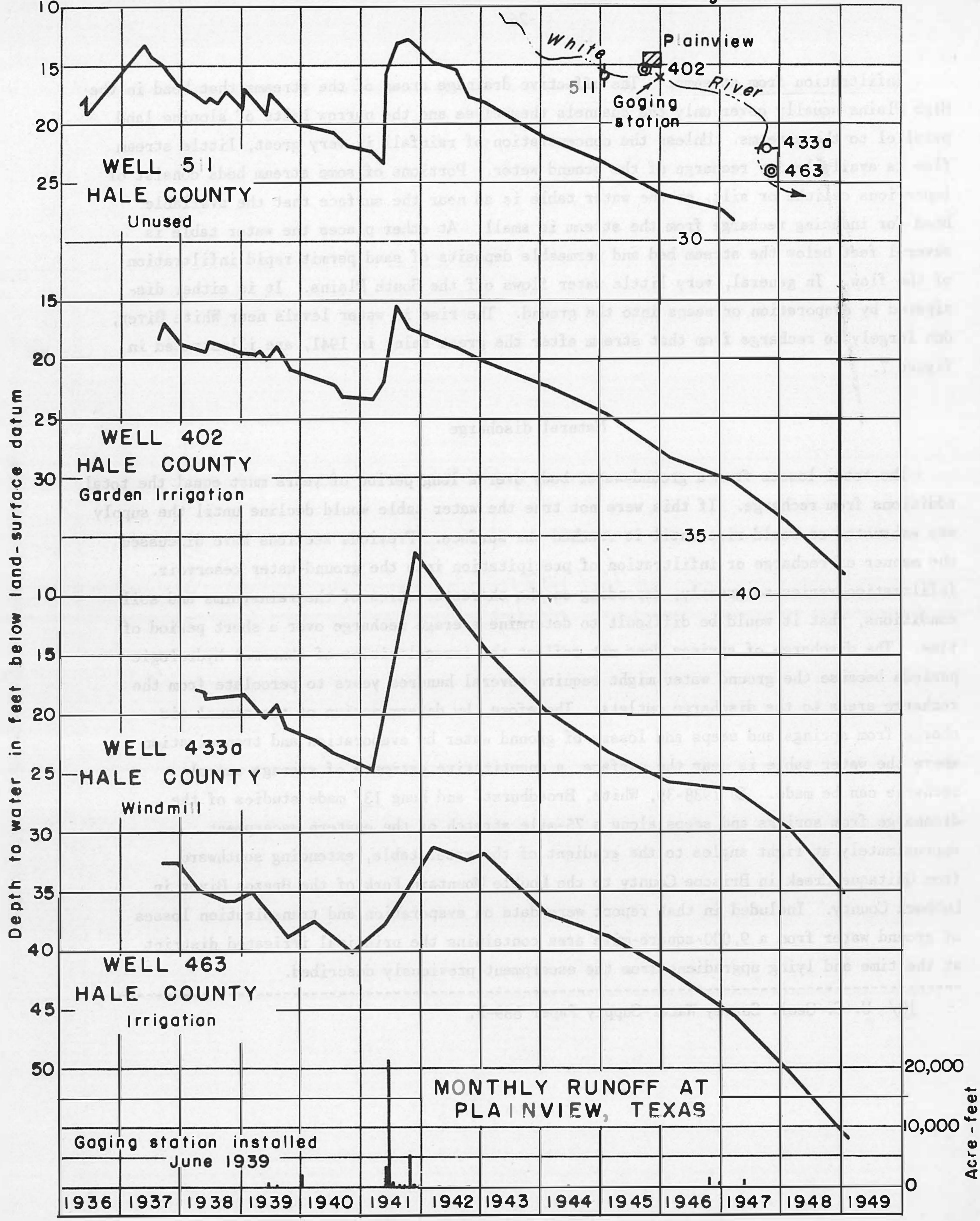
Infiltration from streams.- The effective drainage areas of the streams that head in the High Plains usually cover only the channels themselves and the narrow belts of sloping land parallel to the streams. Unless the concentration of rainfall is very great, little stream flow is available for recharge of the ground water. Portions of some stream beds consist of impervious caliche or silt, or the water table is so near the surface that the available head for inducing recharge from the stream is small. At other places the water table is several feet below the stream bed and permeable deposits of sand permit rapid infiltration of the flow. In general, very little water flows off the South Plains. It is either dissipated by evaporation or seeps into the ground. The rise in water levels near White River, due largely to recharge from that stream after the great rains in 1941, are illustrated in figure 7.

Natural discharge

The total losses from a ground-water body over a long period of years must equal the total additions from recharge. If this were not true the water table would decline until the supply was exhausted or would rise until it reached the surface. Previous sections have discussed the manner of recharge or infiltration of precipitation into the ground-water reservoir. Infiltration varies so greatly, depending on the characteristics of the rainstorms and soil conditions, that it would be difficult to determine average recharge over a short period of time. The discharge of springs does not reflect the irregularities of abnormal hydrologic periods because the ground water might require several hundred years to percolate from the recharge areas to the discharge outlets. Therefore, by determination of the annual discharge from springs and seeps and losses of ground water by evaporation and transpiration where the water table is near the surface, a quantitative estimate of average annual recharge can be made. In 1938-39, White, Broadhurst, and Lang 13/ made studies of the discharge from springs and seeps along a 75-mile stretch of the eastern escarpment approximately at right angles to the gradient of the water table, extending southward from Quitaque Creek in Briscoe County to the Double Mountain Fork of the Brazos River in Lubbock County. Included in that report were data on evaporation and transpiration losses of ground water from a 9,000-square-mile area containing the principal irrigated district at the time and lying upgradient from the escarpment previously described.

13/ U. S. Geol. Survey Water-Supply Paper 889-F.

Figure 7



RECHARGE FROM WHITE RIVER IN 1941.

m/c

Total natural discharge and recharge.- From the measurements and estimates described above, the total natural discharge of ground water from the 9,000 square miles was estimated to be at the rate of 25,000 to 30,000 acre-feet a year. This is estimated to be equivalent to the average annual recharge from rainfall, and represents only a fraction of an inch over the 9,000 square miles. It is estimated that, in 1948, the area that might possibly contribute recharge to the main irrigation district is approximately 13,000 square miles. Natural recharge and discharge in this larger area are, of course, larger than in the included 9,000-square-mile area, though the increase may not be proportional to the increase in size because the areas of greatest recharge and discharge were included in the original survey. Where the shallow water table has declined because of increased pumpage, the natural evapo-transpiration losses from the underground reservoir have been reduced or eliminated.

When the water table is at the surface the ground-water reservoir is full and no water can be added. At such times the rainfall runs off--that is, it is rejected. Prior to 1941 the water table along Blackwater Draw in Bailey County was several feet below the bed of the stream. After the heavy rainfall in 1941, the water table rose above the bed of the stream and a considerable quantity of water in the stream could not enter the ground. That water was rejected and most of it was lost by evaporation. As a result of pumping after 1943, the water table was lowered below the stream bed and storage space was again created to accomodate infiltration from rainfall. This additional storage space is of no great importance to the South Plains as a whole, and only local areas similar to the one along Blackwater Draw may be benefited by increased recharge resulting from a decline of the water table.

Summary of water losses

A tremendous quantity of water is precipitated annually upon the South Plains. According to the records of 5 stations maintained by the U. S. Weather Bureau the average yearly precipitation is about 20 inches. A very small part amounting to only a few hundredths of an inch is lost by stream flow during storm periods, a small part amounting to only a small fraction of an inch recharges the underground reservoir, and the remainder is transpired by vegetation or evaporated before it ever reaches the water table.

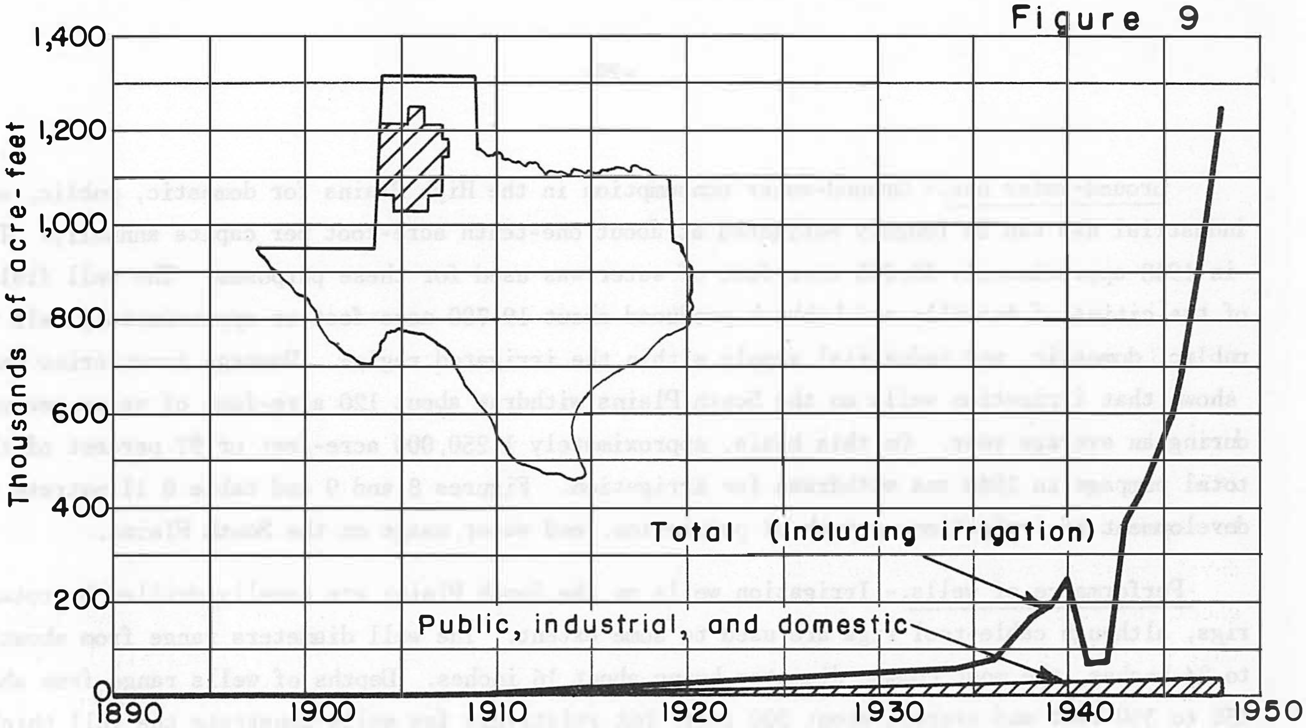
DEVELOPMENT OF GROUND WATER

The first settlers in the High Plains in Texas were supplied water by the springs issuing from the eastern escarpment and from the intermittent and water-table ponds in the interior of the Plains. The first communities sprang up in the vicinity of the larger springs and ponds. Probably the first domestic wells to tap the water-bearing sands were drilled between 1880 and 1890. Irrigation from ground water was first begun at Plainview in 1911. Drilling then spread to the Hereford and Muleshoe districts, and by 1914 about 140 wells had been completed. The development as a whole was only moderately successful, and during the next 20 years, 1914-34, about 160 additional pumping plants were installed, many of the older ones being unused during that period. A part of the lack of success was due to the high cost and relatively low efficiency of the low-speed pumps and oil-burning power units then in use. After the advent of the moderately priced high-speed turbine pumps powered by small automobile engines with direct drive, the efficiency of the pumping plants rose sharply.

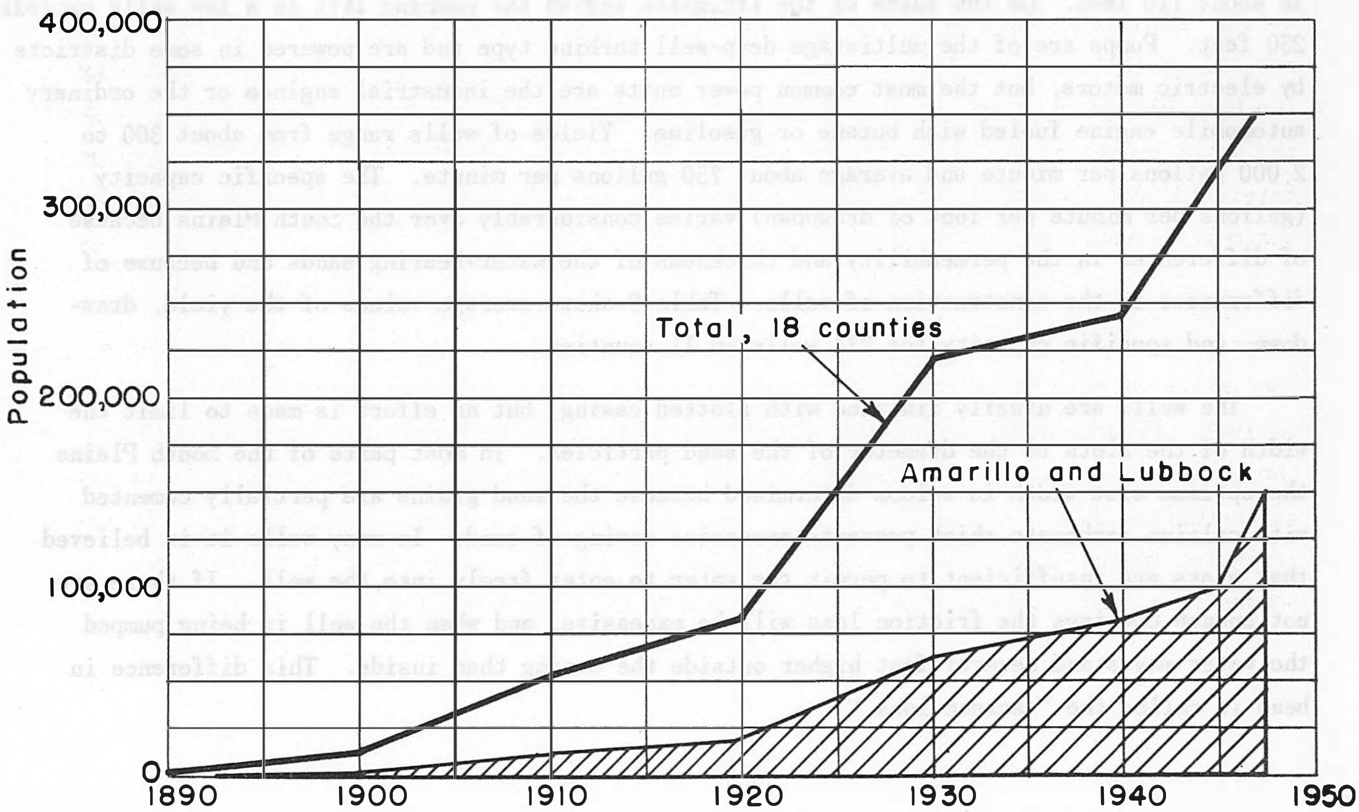
A series of dry years from 1927 to 1934 caused an increase in the drilling of irrigation wells. Beginning about 1935, the development increased steadily except for declines in the rate of installations in 1938-39 and 1941-42; and since 1943 the expansion of irrigation in the High Plains has been spectacular. Approximately 3,000 wells were completed in 1948, and the total number of wells in operation in the South Plains on January 1, 1949, was approximately 10,500. Locations of irrigation wells completed January 1, 1948 and the majority of the public-supply and industrial wells are shown on plate 1.

Population.- Records of the United States Bureau of the Census indicate that the 18 counties now containing the principal irrigation district in the Texas High Plains had a population of only 24 in 1880. The population of the same area was estimated to be 350,000 in 1948. Figures published in the Texas Almanac indicate that during the period 1940-47 the growth in population per square mile was double the average for Texas and 3½ times that of the United States as a whole; however, in 1947 the average density of population in the irrigated region of the High Plains was 20 per square mile, in Texas as a whole 27 per square mile, and in the United States as a whole 45 per square mile.

Figure 9



A. GROUND WATER USED IN 18 COUNTIES IN THE HIGH PLAINS IN TEXAS, 1890-1948.



B. POPULATION IN 18 COUNTIES IN THE HIGH PLAINS IN TEXAS, 1890-1948.

mlc

Ground-water use.- Ground-water consumption in the High Plains for domestic, public, and industrial use can be roughly estimated at about one-tenth acre-foot per capita annually. Thus, in 1948 approximately 35,000 acre-feet of water was used for these purposes. The well fields of the cities of Amarillo and Lubbock produced about 19,700 acre-feet or approximately half the public, domestic, and industrial supply within the irrigated region. Pumpage inventories have shown that irrigation wells on the South Plains withdraw about 120 acre-feet of water per well during an average year. On this basis, approximately 1,250,000 acre-feet or 97 percent of the total pumpage in 1948 was withdrawn for irrigation. Figures 8 and 9 and table 8 illustrate the development of irrigation, growth of population, and water usage on the South Plains.

Performance of wells.- Irrigation wells on the South Plains are usually drilled by rotary rigs, although cable-tool rigs are used to some extent. The well diameters range from about 12 to 24 inches, the most common diameter being about 16 inches. Depths of wells range from about 150 to 350 feet and average about 200 feet; but relatively few wells penetrate the full thickness of the water-bearing sands.

The average depth to the static water level is about 75 feet, and the average pumping lift is about 110 feet. On the edges of the irrigated region the pumping lift in a few wells exceeds 250 feet. Pumps are of the multistage deep-well turbine type and are powered in some districts by electric motors, but the most common power units are the industrial engines or the ordinary automobile engine fueled with butane or gasoline. Yields of wells range from about 300 to 2,000 gallons per minute and average about 750 gallons per minute. The specific capacity (gallons per minute per foot of drawdown) varies considerably over the South Plains because of differences in the permeability and thickness of the water-bearing sands and because of differences in the construction of wells. Table 9 shows average values of the yield, drawdown, and specific capacity for 234 wells in 11 counties.

The wells are usually finished with slotted casing, but no effort is made to limit the width of the slots to the diameter of the sand particles. In most parts of the South Plains the optimum slot width is seldom determined because the sand grains are partially cemented with calcium carbonate which prevents excessive caving of sand. In many wells it is believed that slots are insufficient to permit the water to enter freely into the well. If there are not enough openings the friction loss will be excessive, and when the well is being pumped the water may stand several feet higher outside the casing than inside. This difference in head is called the "screen loss."

In June 1948 a test was made to determine the screen loss in Lubbock City Well No. 32, which is 3 miles northeast from Lubbock. The well was drilled to a depth of 144 feet in October 1947, and it was cased with 18-inch steel pipe perforated from 54 to 144 feet with six 8-inch by 1/4-inch slots per foot. An observation well was drilled to a depth of 144 feet at a distance of 3 feet from the production well, and 6-1/4-inch casing was perforated with 2 slots per foot from 54 to 144 feet. The larger well was then pumped and depths to water in both the production well and the observation well were made over a 5-hour pumping period. The static level was 65 feet and at the end of 5 hours the pumping level was 82 feet. The yield of the well averaged 840 gallons a minute during the test period, and the water level in the observation well was, on the average, only 0.17 foot above the pumping level in well 32. Inasmuch as most or all of this difference could be due to the slope of the cone of depression near the well, the screen loss was negligible. If the production well had been less adequately screened the loss could have amounted to several feet.

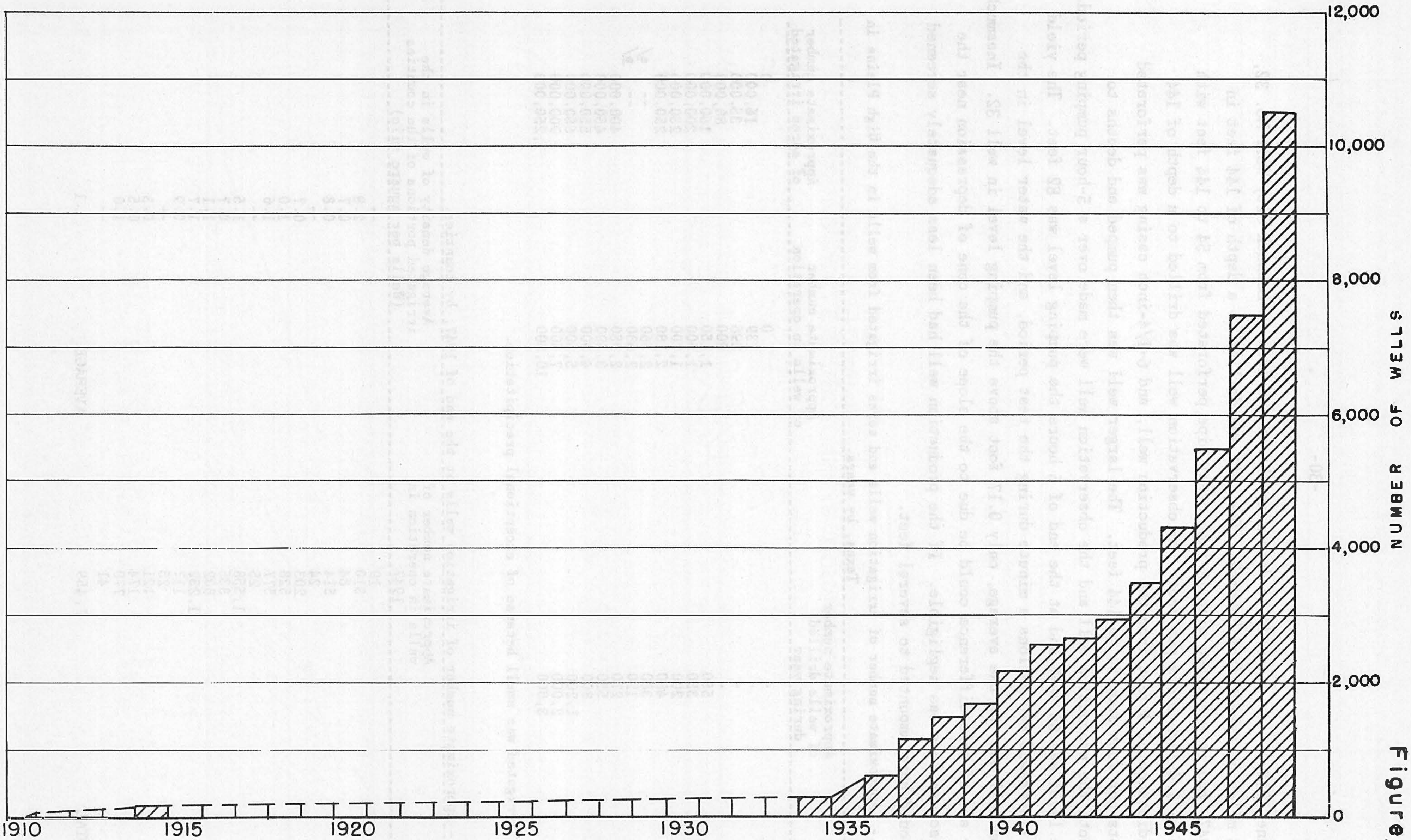
Table 8, A.- Approximate number of irrigation wells and acres irrigated from wells in the High Plains in Texas, by years.

Year	Approximate nu ber of wells drilled during year	Approximate number of wells in operation	Approximate number of acres irrigated
1910	-	0	0
1914	-	139	16,000
1934	-	296	35,000
1936	-	600	80,000
1937	550	1,150	160,000
1938	350	1,500	200,000
1939	200	1,700	230,000
1940	480	2,180	250,000
1941	380	2,560	-- a/
1942	120	2,680	-- a/
1943	270	2,950	400,000
1944	550	3,500	450,000
1945	800	4,300	550,000
1946	1,200	5,500	650,000
1947	2,000	7,500	900,000
1948	3,000	10,500	1,250,000

a/ Acreage irrigated was small because of exceptional precipitation.

Table 8, B.- Approximate number of irrigation wells at the end of 1947, by counties.

County	Approximate number of wells in operation in 1947		Average density of wells in the irrigated portions of the counties (Wells per square mile)
Armstrong	19		--
Bailey	310		2.8
Briscoe	84		0.7
Castro	514		0.8
Cochran	24		--
Crosby	203		0.7
Deaf Smith	528		1.0
Floyd	577		1.6
Gaines	25		--
Hale	1,558		1.5
Hockley	335		0.7
Lamb	802		1.1
Lubbock	1,232		1.7
Lynn	117		0.9
Martin	25		--
Parmer	121		0.3
Randall	174		0.5
Swisher	770		1.0
Terry	41		--
TOTAL	7,459	AVERAGE	1.1



NUMBER OF IRRIGATION WELLS IN OPERATION IN THE HIGH PLAINS IN TEXAS, 1910 - 48.

Figure 8

Table 9

Average yield and drawdown of irrigation wells, by counties

County	Number of wells measured	Average static level (ft.)	Average pumping level (ft.)	Average drawdown (ft.)	Average yield (gpm)	Average yield divided by average drawdown
Bailey	3	28	50	22	798	36
Briscoe	21	89	136	47	695	15
Castro	3	75	97	22	674	31
Crosby	4	86	119	33	650	20
Deaf Smith	32	69	94	25	821	33
Floyd	28	81	133	52	727	14
Hale	29	64	98	34	855	25
Hockley	22	77	103	26	717	28
Lamb	5	40	67	27	972	36
Lubbock	62	67	101	34	648	19
Parmer	8	145	-	-	-	-
Randall	19	82	-	-	-	-
Swisher	28	72	106	34	722	21

* All averages were compiled from 1947-48 measurements

FLUCTUATIONS OF WATER LEVELS AND THEIR SIGNIFICANCE

Before pumping began on the High Plains, the underground reservoirs were in a state of approximate equilibrium--the additions from infiltration were balanced by the flow of springs and the evaporation and transpiration from the underground reservoir in areas where the water table was shallow. This means that any artificial discharge, such as pumping from an irrigation well, must decrease the natural discharge, increase the recharge, or remove water from storage with corresponding lowering of the water table. The decline of the water table in the High Plains has not been widespread enough to materially decrease the natural spring flow; however, there have been slight reductions in transpiration and evaporation losses where the water table has declined in shallow-water areas. The average recharge probably has not increased appreciably as a result of the pumping. Therefore, the decline of the water table during the 4 decades from 1910 to 1949 has been roughly proportional to the quantity of water pumped, except during and shortly after 1941 when the recharge from rainfall was abnormally high.

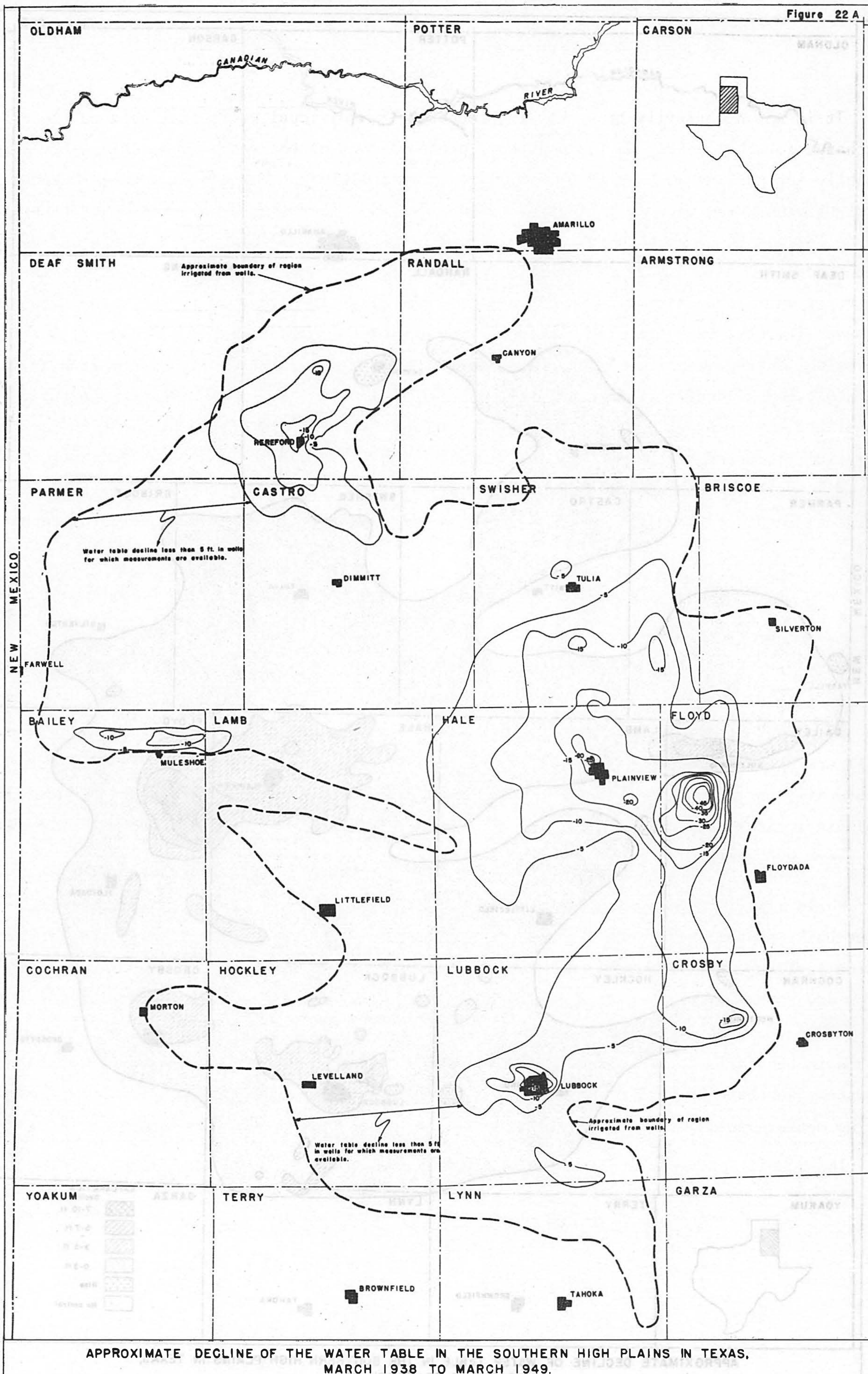
It is not necessarily true that the recharge in individual years will balance the natural discharge for that year. On the contrary, probably most of the recharge occurs in the exceptionally wet periods such as 1899-1900, 1914-15, and 1941-42. Periods of several decades are likely to intervene between periods as wet as 1941-42. (See fig. 3 B.) Where the water table is shallow and the concentration of surface water is great, as in stream channels and depression ponds, the water table may quickly reflect the effects of precipitation; but in areas where the water must percolate through many feet of only slightly permeable deposits the time lag may be several months or years. The United States Geological Survey, in cooperation with the Oklahoma Geological Survey, reported in June 1948 that water levels in the Ogallala formation in the Oklahoma Panhandle had gradually risen since the rains in 1941, and that in May 1948 they were at a higher stage than any recorded in the preceding 10 years. 14/ Pumpage in the Oklahoma Panhandle is negligible compared to the pumpage in the Southern High Plains in Texas. Hydrographs in figures 12, 19, and 21 suggest that similar rises might have occurred in parts of the Southern High Plains in Texas, although interference from pumping has made accurate evaluation of recharge difficult.

Fluctuations resulting from pumpage

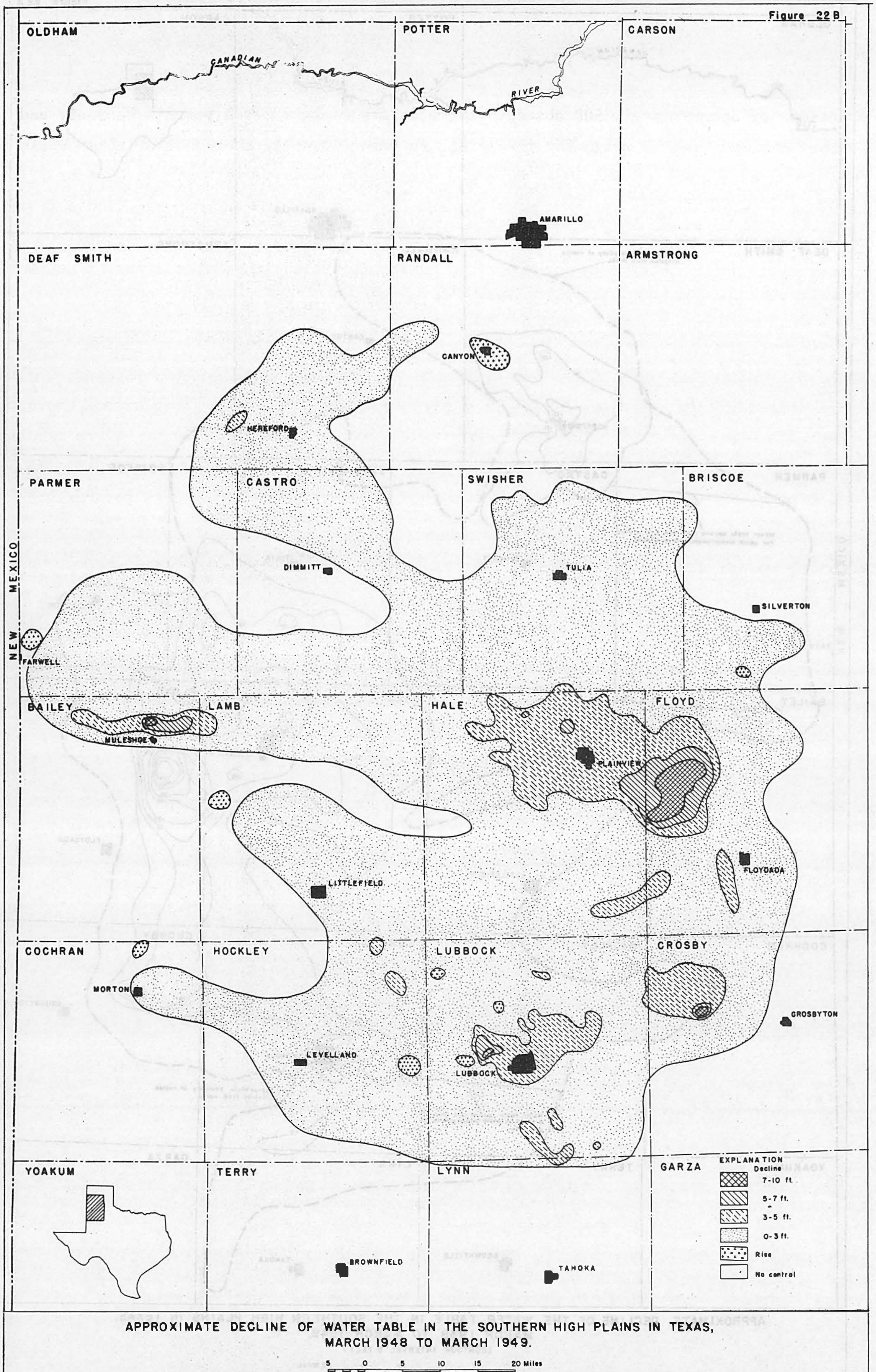
Until about 1940 most of the irrigation wells were confined to relatively small districts, and the declines of the water levels were also concentrated in those districts. Recently the drilling has spread out to cover one great district which embraces parts of 17 counties and in which the wells are steadily becoming more closely spaced. In 1947 there was an average of 1.1 wells per square mile, or 1 well for every 580 acres in the 6,700-square-mile area within the boundaries of the main irrigation district. In 1948 the average was about 1.6 wells per square mile or 1 well for every 400 acres.

While a well is being pumped, a cone of depression is formed in the water table, the lowest point being at the well; however, under the conditions generally prevailing in the Ogallala formation in Texas, the radius of influence may extend out a distance of half a mile or more within a few days. (See figs. 27 and 28.) Continued pumping gradually lowers the water level, and the effects of the pumping can be observed at increasingly greater distances. After heavy pumping ceases in the fall, these depressions in the water table are partially filled by lateral movement of water, so that net yearly declines in the water table in adjacent unpumped wells, based on spring measurements, are very nearly as great as in the pumped wells themselves.

14/ Schoff, Stuart L., The Hopper, Oklahoma Geol. Survey vol. 8, no. 8, pp. 74-76, Aug. 1948.



APPROXIMATE DECLINE OF THE WATER TABLE IN THE SOUTHERN HIGH PLAINS IN TEXAS, MARCH 1938 TO MARCH 1949.
(CONTOUR INTERVAL 5 FEET)



APPROXIMATE DECLINE OF WATER TABLE IN THE SOUTHERN HIGH PLAINS IN TEXAS, MARCH 1948 TO MARCH 1949.

A network of approximately 500 observation wells are measured each year in February and March, after maximum time is given for the levels to become stabilized. Most of these wells have been measured annually since 1936; however, a few were measured as early as 1934 or 1914. The observation wells include irrigation wells, unused wells, and domestic wells, and a few wells that were put down strictly for observation purpose. Records indicate that the type of well makes little difference in the amount of yearly decline, the important factor is the proximity of the observation wells to the heavily pumped areas.

Typical hydrographs of individual wells in the counties with greatest irrigation development are shown in figures 10 to 20. These wells were chosen to show the effects of pumping in their particular locality. In contrast, figure 21 shows hydrographs of 5 wells remote from areas of heavy pumping. Depths to water in representative observation wells in 10 counties are tabulated on pages 47 to 51 . Water-level fluctuations in all observation wells are summarized in table 19 on page 51 . The locations of the individual observation wells whose records are given in the tables or graphs are shown on plate 1.

Contours of water-level declines in the High Plains area from the spring of 1938 to the spring of 1949 are shown in figure 22A. The contour lines connect points of equal declines and are drawn at 5-foot intervals. By measuring the areas enclosed by each contour, the total net amount and approximate extent of the water-table decline in the South Plains was determined as follows:

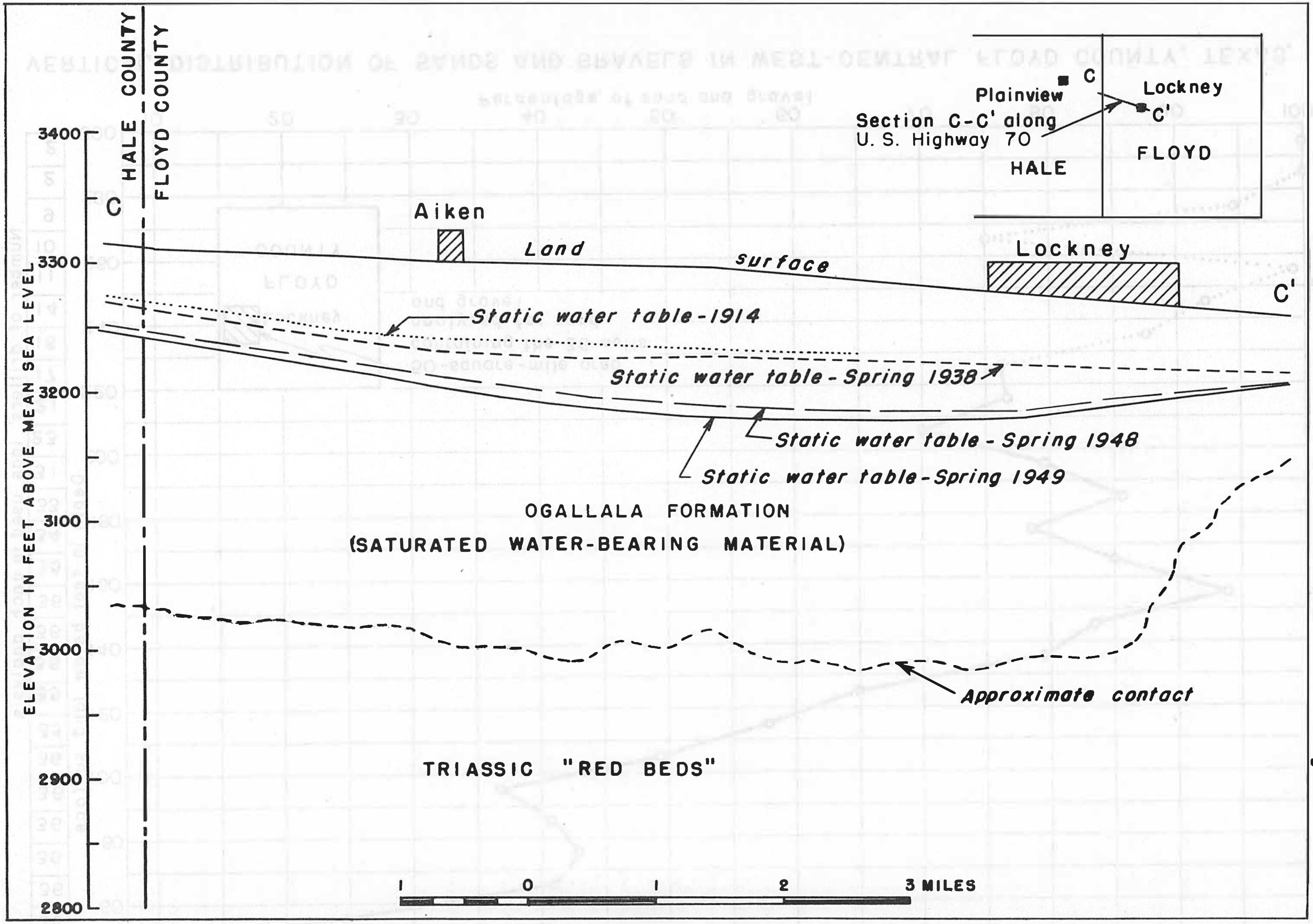
Area affected, in acres	Decline in feet 1938-49
1,100,000	0 - 5
700,000	5 - 10
500,000	10 - 15
118,000	15 - 20
29,000	20 - 25
11,400	25 - 30
7,400	30 - 35
3,700	35 - 40
3,400	40 - 45
2,800	45 - 50

Decline of the water table during a one year period from March 1948 to March 1949 are shown in figure 22B.

Notwithstanding the heavy recharge in 1941, approximately 18 million acre-feet of saturated material was unwatered during the 11-year period. Declines had occurred in some districts before 1938; however, in most places these early declines were relatively small. For example in the heavily pumped district of west-central Floyd County, the net decline from 1914 to 1938 averaged about 7 feet. The greatest recent declines are also centered in this district. In a few localities where pumping was light and the recharge in 1941-42 was exceptionally heavy the water levels were at a higher stage in 1948 than in 1938.

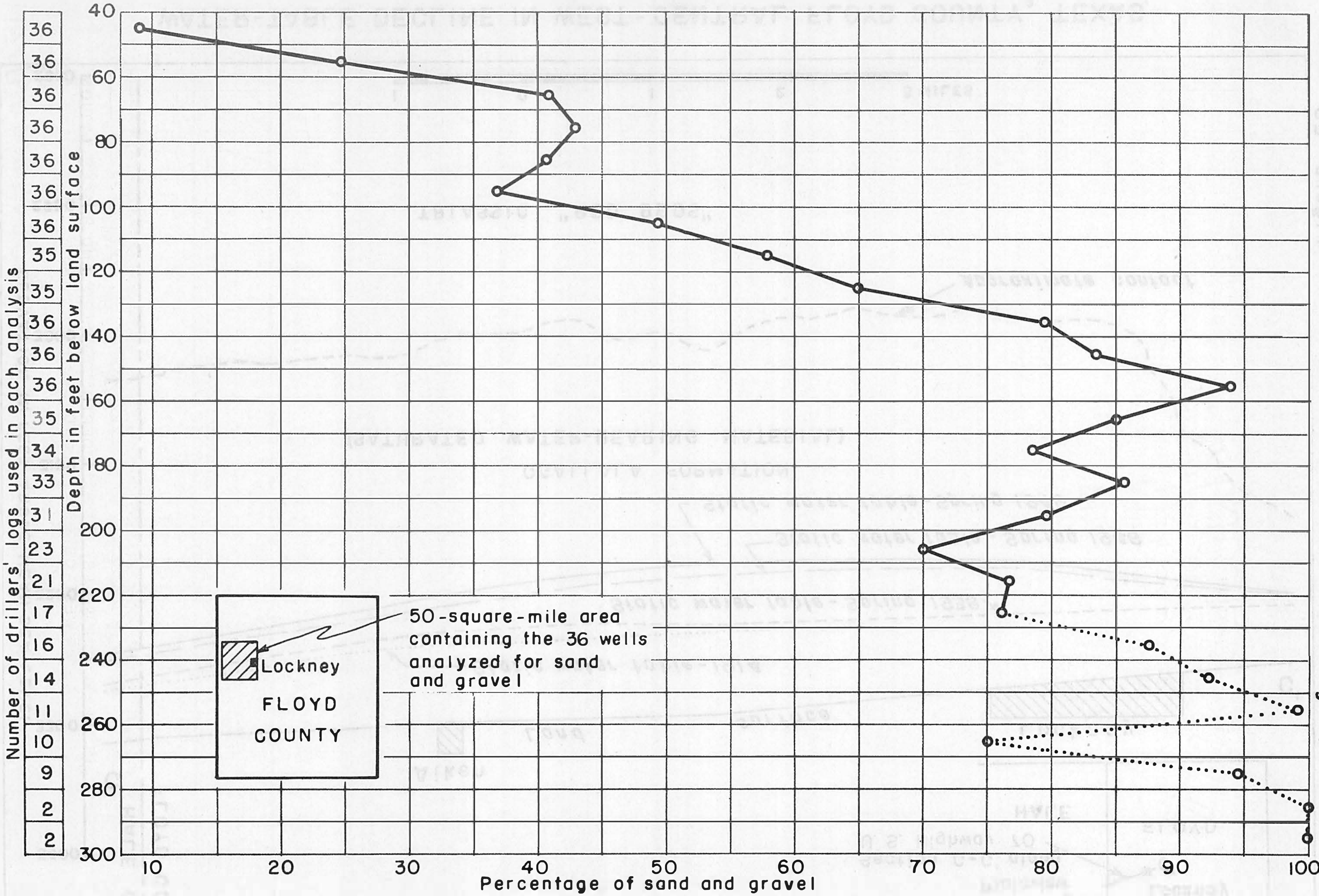
Study of the fluctuations of the water levels is the most accurate method of determining additions to the water sands from recharge and also depletion as a result of pumping. The ability of the underground deposits to yield water from storage (their specific yield or effective porosity) depends greatly upon the grading of the sands and the presence of clays and shales. In granular materials the maximum porosity exists where the individual grains are about the same size and the porosity of several samples of even-grained sands of different grain size is about the same. The size of the grains has no direct relation to the capacity of a material to store water, but it has an important effect on the ability of the material to yield water from storage. Because of the increased molecular attraction, a fine-grained material is lower both in specific yield and in permeability than a coarse-grained sand or gravel, and consequently will yield less water to a well. For example, a coarse sand with a total storage capacity (porosity) of 25 percent of its volume may yield nearly all the water to wells, but a clay with a porosity or storage capacity of 50 percent of its volume may not release enough water to be of economic value. Thus in the High Plains the decline of the water-table after the removal of a given amount of water varies considerably at different depths and from county to county. As there is generally a greater percentage of clays near the surface of the High Plains sediments, the rate of water-level decline for a given rate of pumpage should decrease slightly as the water table is lowered into the sandier zones. Also, the declines in many districts are materially lessened during periods of unusually heavy recharge from surface infiltration and are accelerated during periods of unusually light recharge. These variations are shown by the following detailed analysis of four specific districts which cover fairly well the range of conditions most common to the High Plains.

West-central Floyd County.- In this area, which covers about 50 square miles, irrigation was first started in 1913. The increase in the number of irrigation wells from 1912 to 1947, which, except in periods of heavy rainfall, is roughly proportional to the increase in pumpage, is shown in figure 25, B, and the resultant water-table decline is shown in the composite hydrograph of 17 wells dispersed over the same area. From 1914 to 1949 the average decline was about 37 feet.



WATER-TABLE DECLINE IN WEST-CENTRAL FLOYD COUNTY, TEXAS.

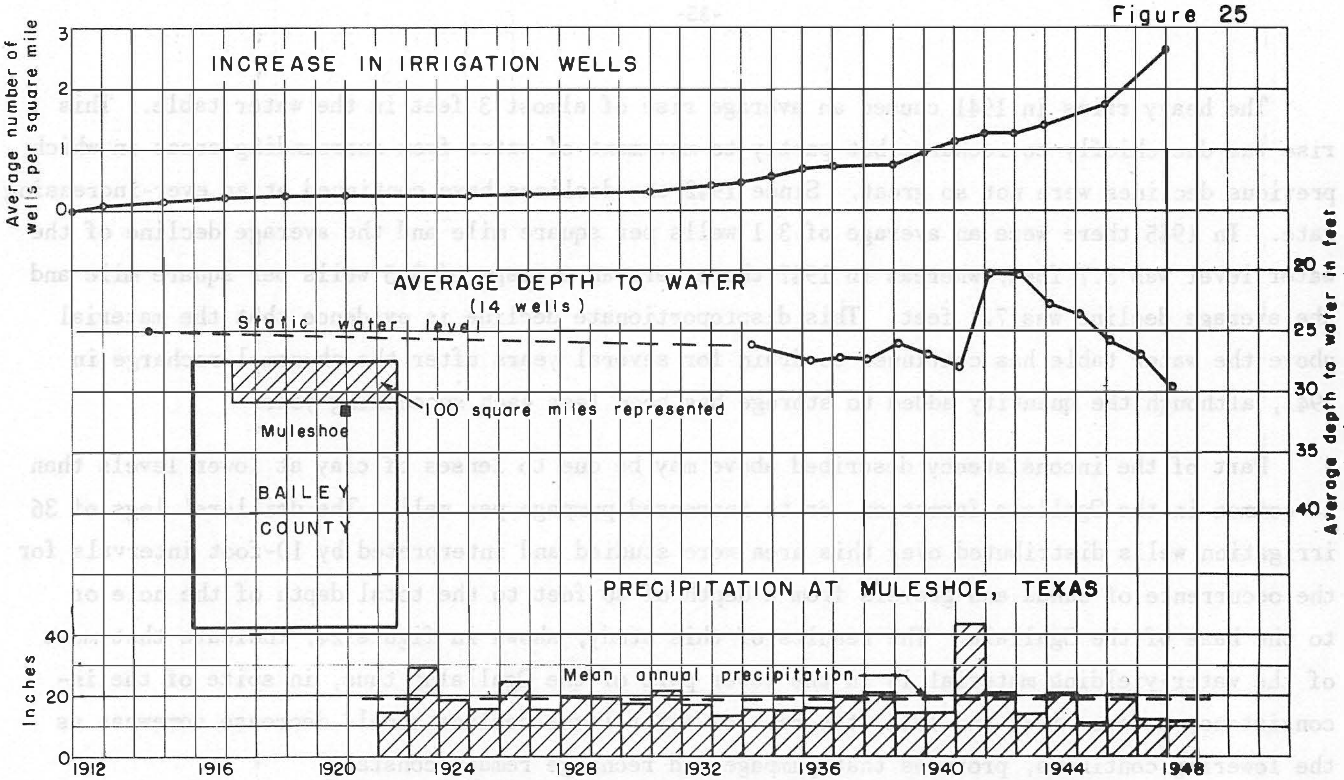
Figure 23



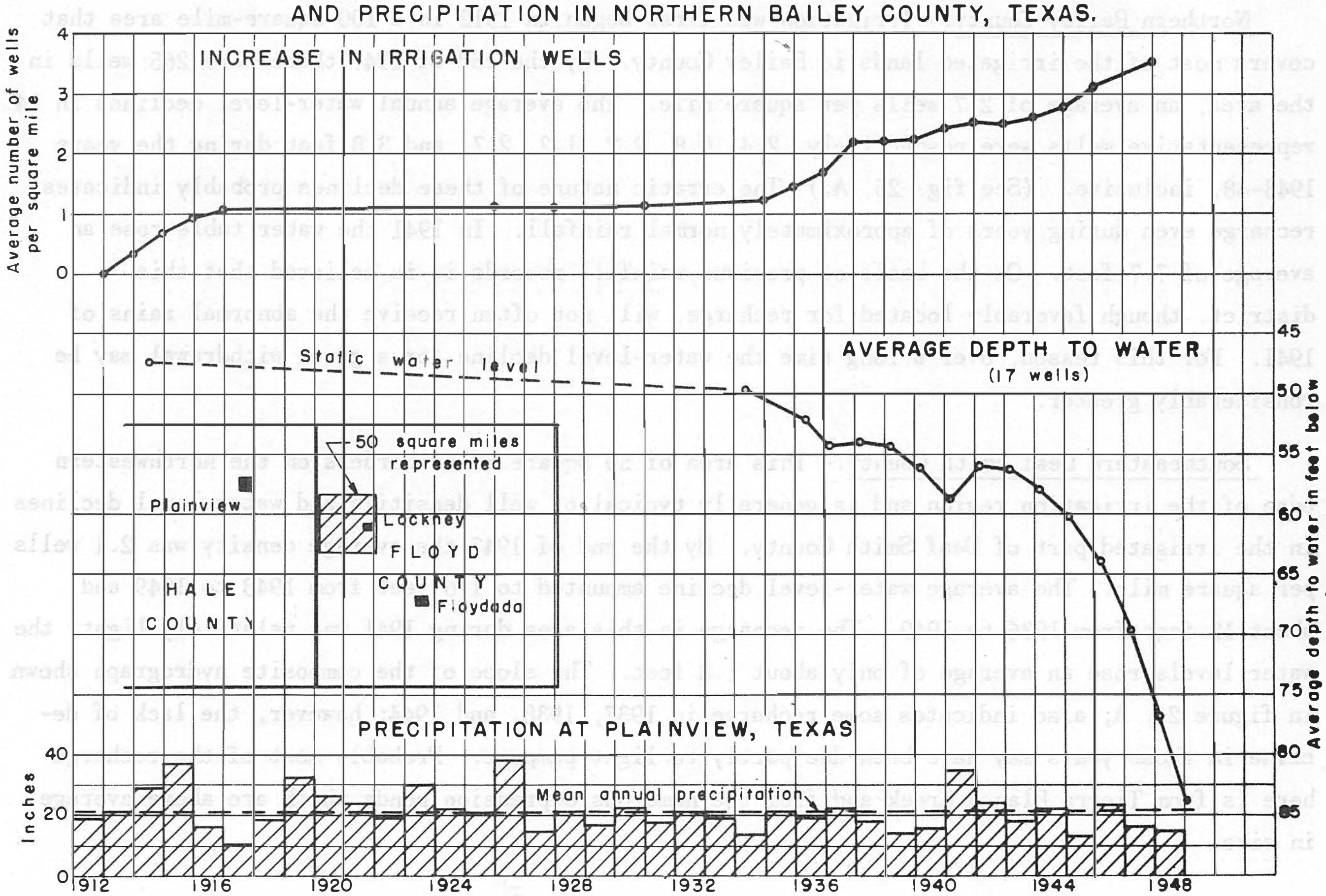
VERTICAL DISTRIBUTION OF SANDS AND GRAVELS IN WEST-CENTRAL FLOYD COUNTY, TEXAS.

Figure 24

Figure 25



A. INCREASE IN IRRIGATION WELLS; AVERAGE DEPTH TO WATER; AND PRECIPITATION IN NORTHERN BAILEY COUNTY, TEXAS.



B. INCREASE IN IRRIGATION WELLS; AVERAGE DEPTH TO WATER; AND PRECIPITATION IN WEST-CENTRAL FLOYD COUNTY, TEXAS.

m/c 1949

The heavy rains in 1941 caused an average rise of almost 3 feet in the water table. This rise was due chiefly to recharge but partly to movement of water from surrounding areas in which previous declines were not so great. Since 1942 the declines have continued at an ever-increasing rate. In 1945 there were an average of 3.1 wells per square mile and the average decline of the water level was 3.7 feet, whereas in 1947 there were an average of 3.5 wells per square mile and the average decline was 7.1 feet. This disproportionate decline is evidence that the material above the water table has continued to drain for several years after the abnormal recharge in 1941, although the quantity added to storage has been less each succeeding year.

Part of the inconsistency described above may be due to lenses of clay at lower levels than is common in the Ogallala formation, or to increased pumpage per well. The drillers' logs of 36 irrigation wells distributed over this area were studied and interpreted by 10-foot intervals for the occurrence of sands and gravels from a depth of 40 feet to the total depth of the hole or to the base of the Ogallala. The results of this study, shown in figure 24, indicate that most of the water-yielding material is in the lower part of the Ogallala; thus, in spite of the inconsistency between 1945 and 1947, the rate of water-level decline should decrease somewhat as the lowering continues, provided that pumpage and recharge remain constant.

Northern Bailey County.- Irrigation was first begun in 1912 in a 100-square-mile area that covers most of the irrigated lands in Bailey County. By the end of 1947 there were 265 wells in the area, an average of 2.7 wells per square mile. The average annual water-level declines in 14 representative wells were respectively, 2.4, 0.8, 2.2, 1.2, 2.7, and 3.8 feet during the years 1943-48, inclusive. (See fig. 25, A.) The erratic nature of these declines probably indicates recharge even during years of approximately normal rainfall. In 1941 the water table rose an average of 7.7 feet. On the basis of previous rainfall records it is believed that this district, though favorably located for recharge, will not often receive the abnormal rains of 1941. For this reason, over a long time the water-level decline for a given withdrawal may be considerably greater.

Southeastern Deaf Smith County.- This area of 50 square miles borders on the northwestern edge of the irrigation region and is generally typical of well densities and water-level declines in the irrigated part of Deaf Smith County. By the end of 1947 the average density was 2.1 wells per square mile. The average water-level decline amounted to 1.6 feet from 1948 to 1949 and about 12 feet from 1936 to 1949. The recharge in this area during 1941 was relatively light; the water levels rose an average of only about 1.8 feet. The slope of the composite hydrograph shown in figure 26, A, also indicates some recharge in 1937, 1938, and 1944; however, the lack of decline in those years may have been due partly to light pumpage. Probably most of the recharge here is from Tierra Blanca Creek and from the numerous depression ponds which are above average in size.

West-central Lubbock County.- This area, which covers about 50 square miles, has been developed for irrigation more recently than the areas previously discussed. By the end of 1947 a total of 122 wells were fairly uniformly distributed over the territory, averaging 2.4 per square mile. The sandy-loam soil typical of this section permits some recharge by direct penetration from the surface when the rainfall is intense. Recharge raised the water levels slightly in 1937, and a rise of almost 6 feet was recorded in the period 1941-43. The average net decline was 8.4 feet from 1938 to 1949 and 12.4 feet from 1943 to 1949. (See fig. 26, B.)

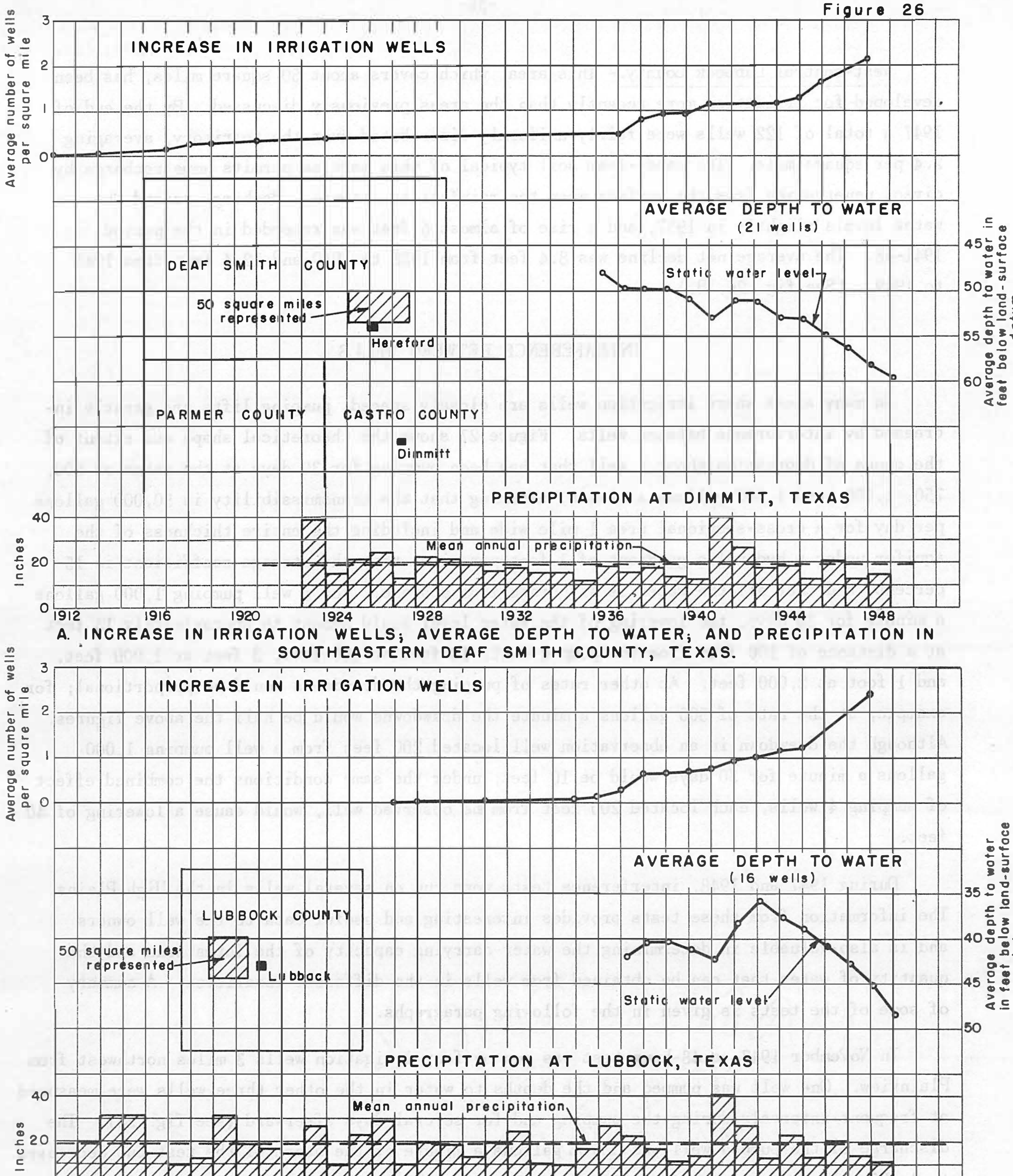
INTERFERENCE BETWEEN WELLS

In many areas where irrigation wells are closely spaced, pumping lifts are greatly increased by interference between wells. Figure 27 shows the theoretical shape and extent of the cones of depression about a well that has been pumping for 30 days at the rates of 500, 750, 1,000, and 1,500 gallons a minute, assuming that the transmissibility is 50,000 gallons per day for a cross-sectional area 1 mile wide and including the entire thickness of the aquifer under a hydraulic gradient of 1 foot per mile, that the storage coefficient is 15 percent, and that all the water is withdrawn from storage. For a well pumping 1,000 gallons a minute for 30 days, the lowering of the water level would amount to approximately 13 feet at a distance of 100 feet from the pumped well, 10 feet at 200 feet, 3 feet at 1,000 feet, and 1 foot at 2,000 feet. At other rates of pumping the drawdowns would be proportional; for example, at the rate of 500 gallons a minute the drawdowns would be half the above figures. Although the drawdown in an observation well located 200 feet from a well pumping 1,000 gallons a minute for 30 days would be 10 feet; under the same conditions the combined effect of pumping 4 wells, each located 200 feet from the observed well, would cause a lowering of 40 feet.

During 1947 and 1948, interference tests were run on several wells in the High Plains. The information from these tests provides interesting and useful data to the well owners and is also valuable in determining the water-carrying capacity of the formations and the quantity of water that can be obtained from wells in the different localities. A summary of some of the tests is given in the following paragraphs.

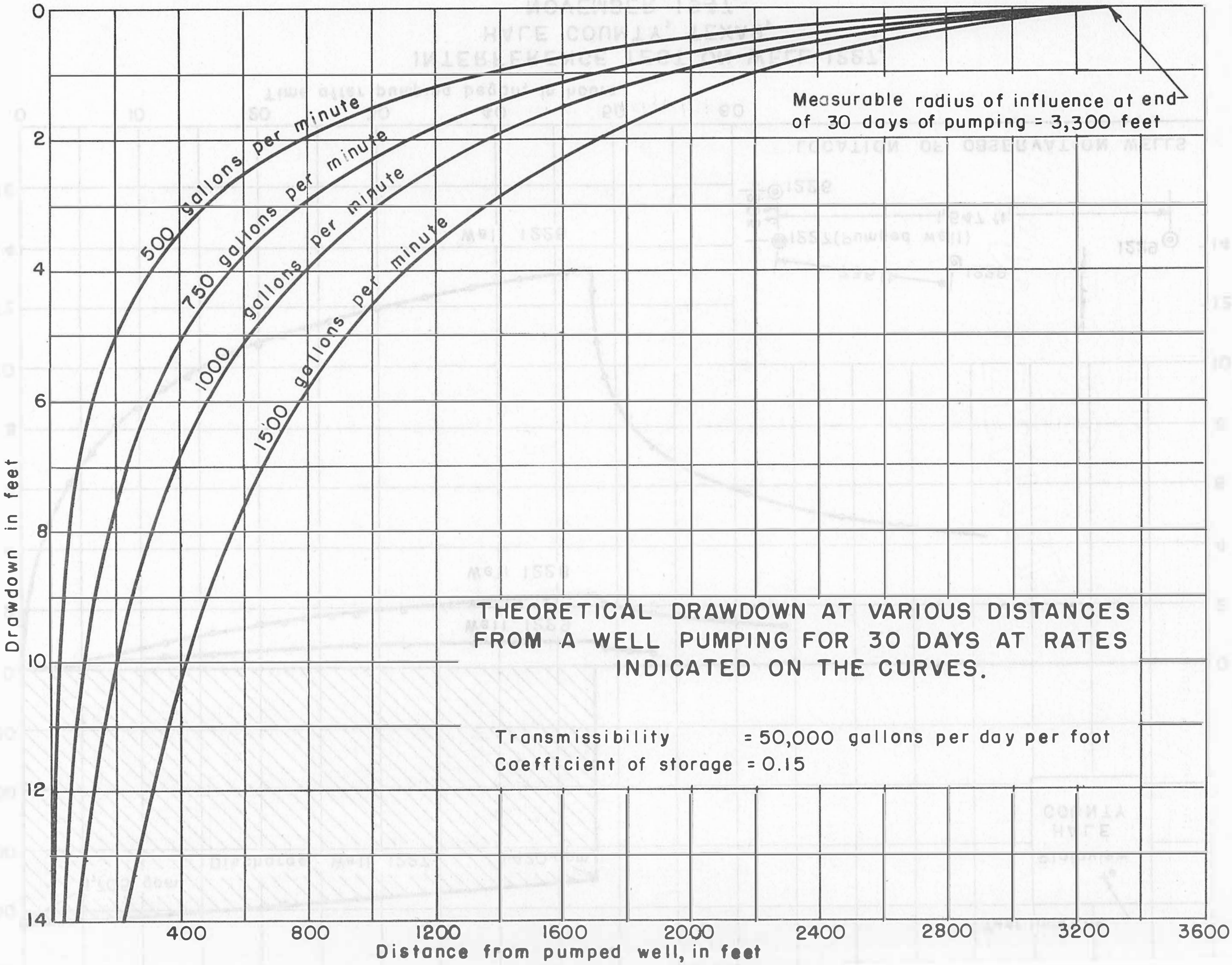
In November 1947, a 48-hour test was run on four irrigation wells 3 miles northwest from Plainview. One well was pumped and the depths to water in the other three wells were measured at frequent intervals during the pumping and for several days afterward (see fig. 28). The discharge of the pumped well was 1,705 gallons a minute at the start of the test but decreased to 1,420 gallons a minute after 48 hours, a decrease of 285 gallons a minute or 17 percent. At the end of 48 hours the drawdown was 13.2 feet in a well 205 feet from the pumped well, 2.4 feet at a distance of 736 feet, and 0.9 foot at a distance of 1,647 feet.

Figure 26



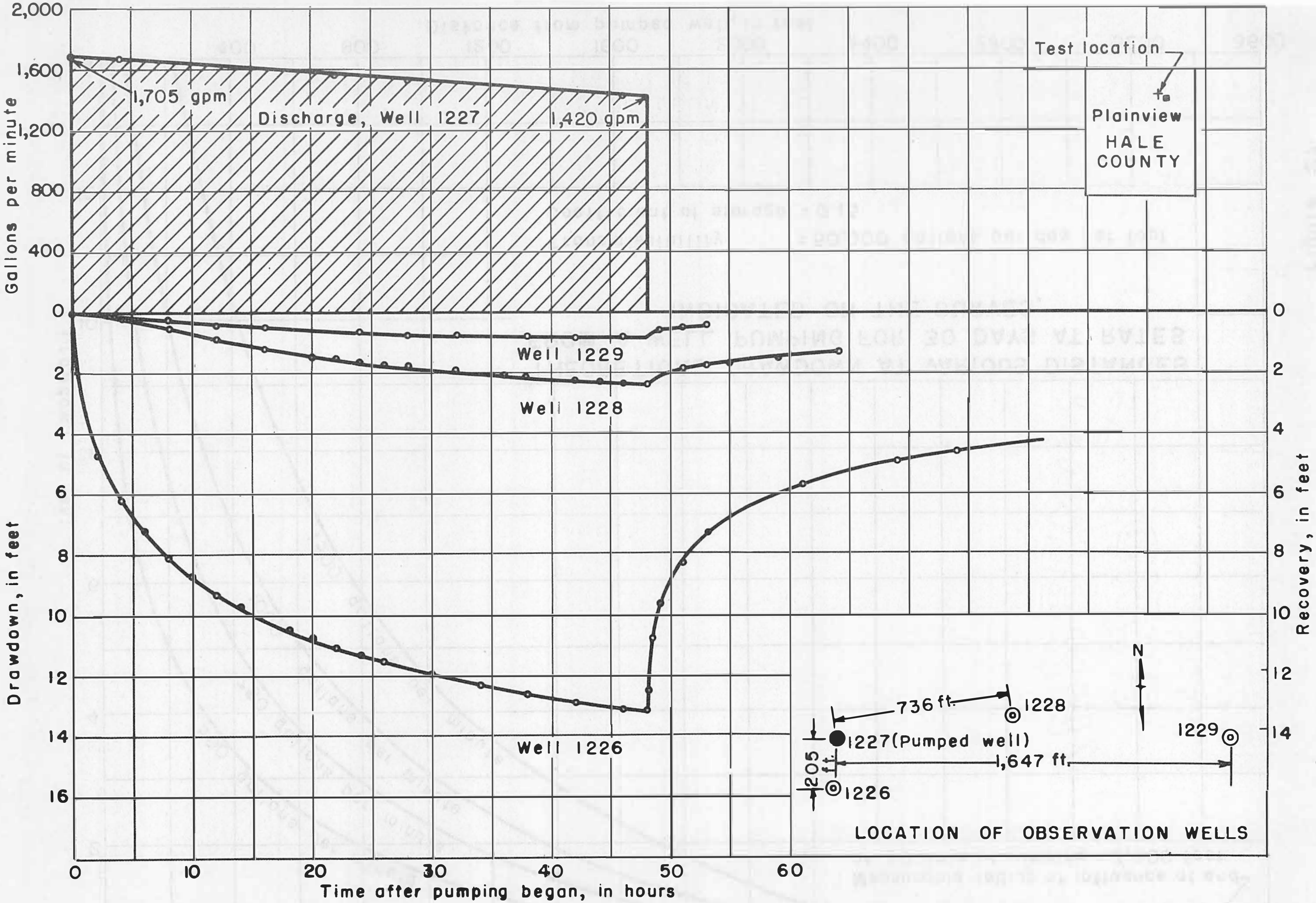
A. INCREASE IN IRRIGATION WELLS; AVERAGE DEPTH TO WATER; AND PRECIPITATION IN SOUTHEASTERN DEAF SMITH COUNTY, TEXAS.

B. INCREASE IN IRRIGATION WELLS; AVERAGE DEPTH TO WATER; AND PRECIPITATION IN WEST-CENTRAL LUBBOCK COUNTY, TEXAS.



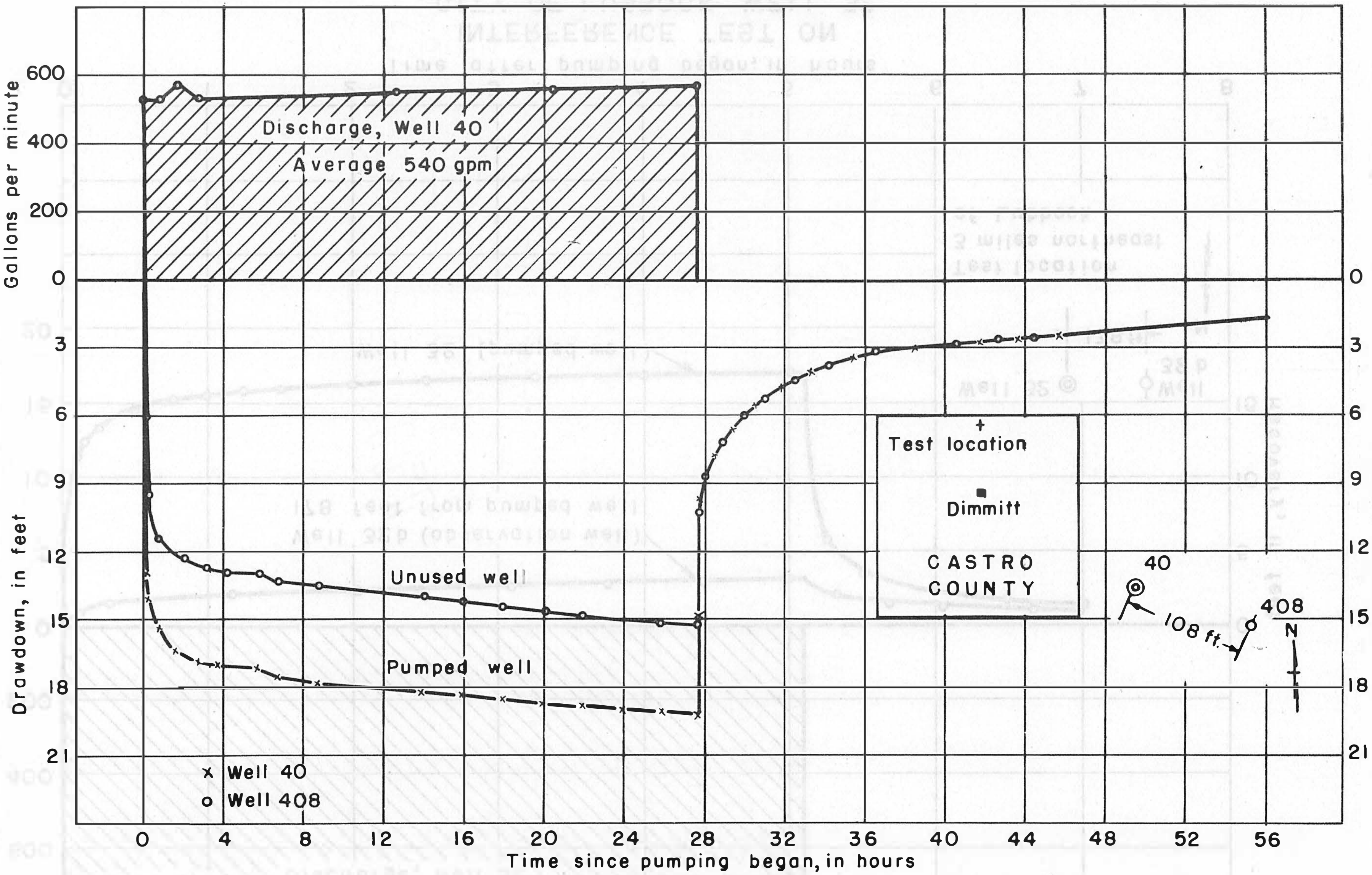
Measurable radius of influence at end of 30 days of pumping = 3,300 feet
500 gallons per minute
750 gallons per minute
1000 gallons per minute
1500 gallons per minute
THEORETICAL DRAWDOWN AT VARIOUS DISTANCES FROM A WELL PUMPING FOR 30 DAYS AT RATES INDICATED ON THE CURVES.
Transmissibility = 50,000 gallons per day per foot
Coefficient of storage = 0.15
Drawdown in feet
0
2
4
6
8
10
12
14
400
800
1200
1600
2000
2400
2800
3200
3600
Distance from pumped well, in feet

Figure 27



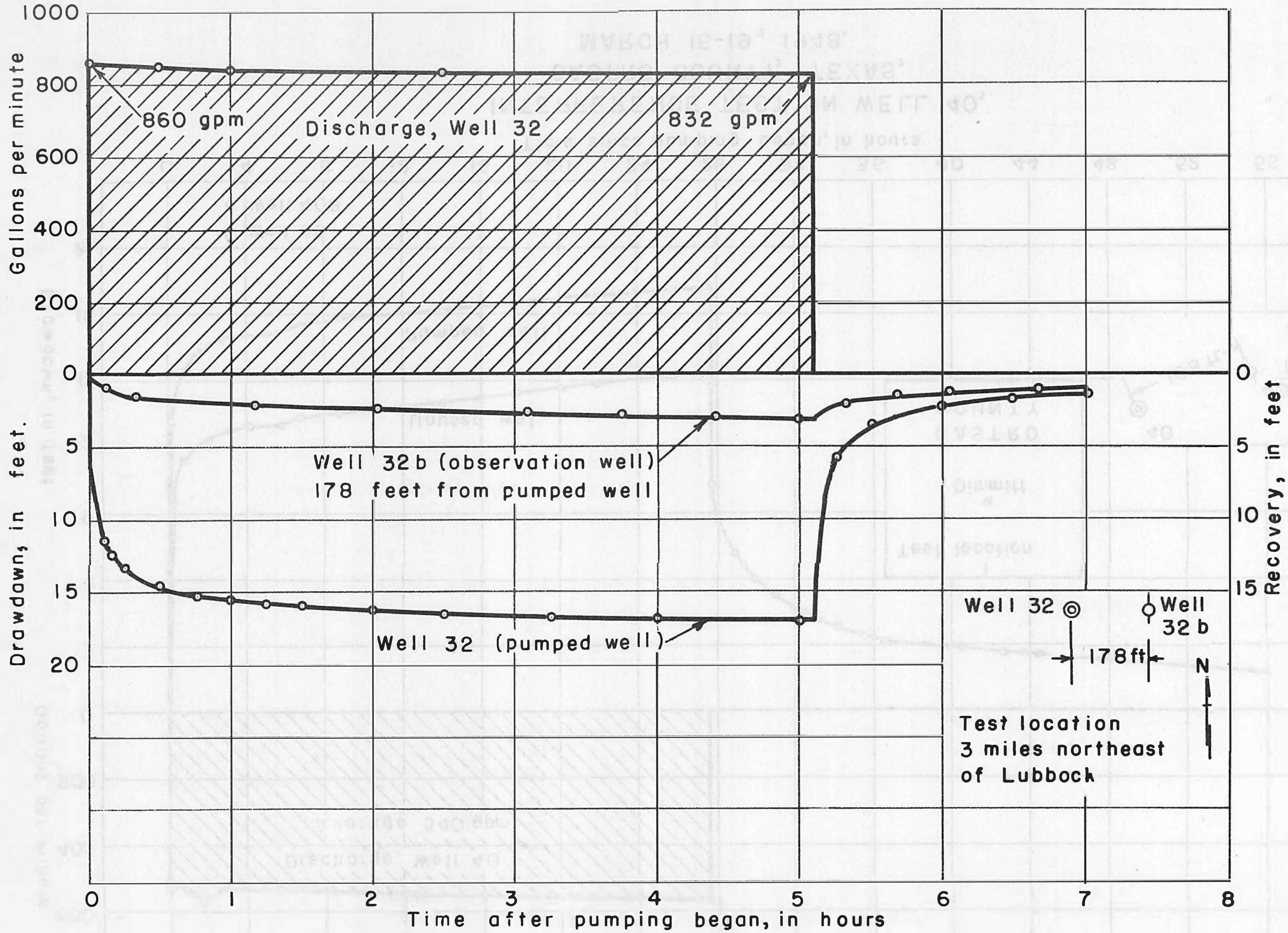
INTERFERENCE TEST ON WELL 1227,
HALE COUNTY, TEXAS,
NOVEMBER 1947.

Figure 28



INTERFERENCE TEST ON WELL 40,
CASTRO COUNTY, TEXAS,
MARCH 16-19, 1948.

Figure 29



INTERFERENCE TEST ON
CITY OF LUBBOCK WELL 32,
JUNE 10, 1948.

Figure 30

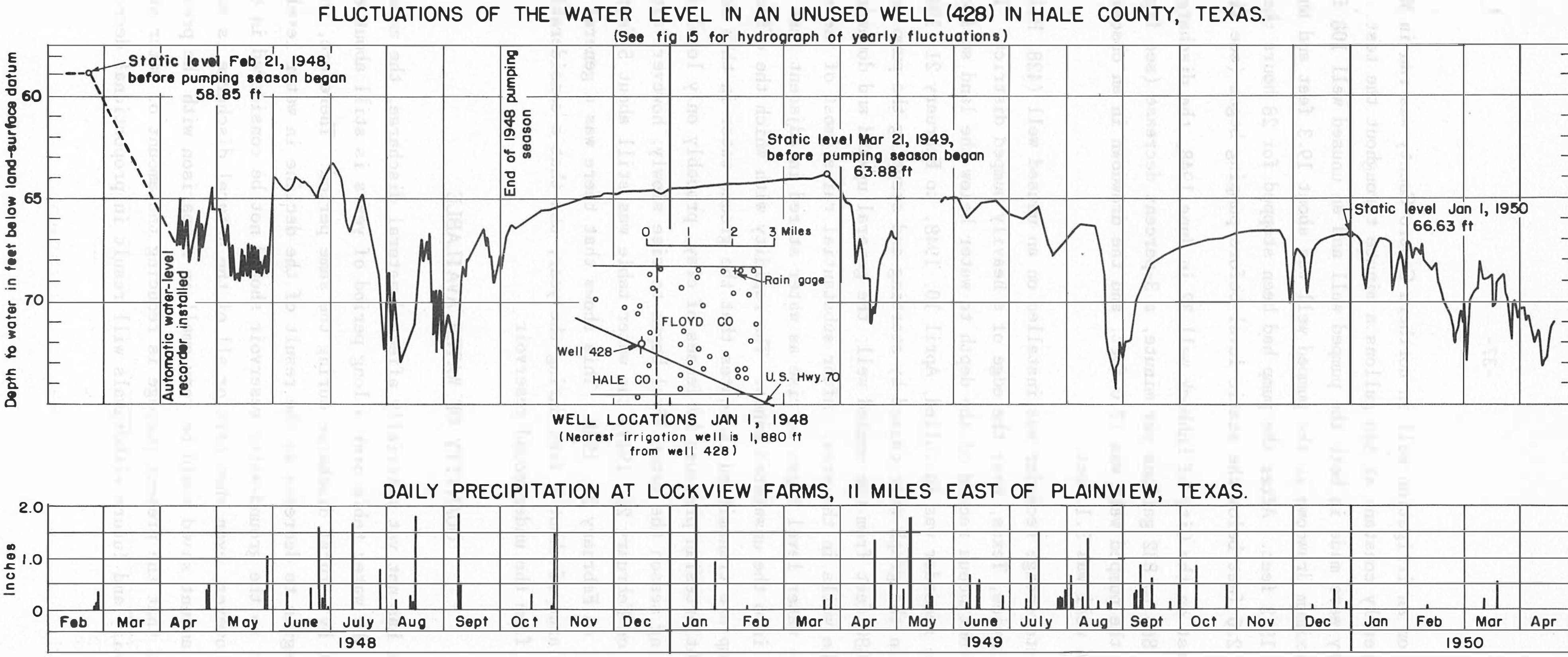

FLUCTUATIONS OF THE WATER LEVEL IN AN UNUSED WELL (428) IN HALE COUNTY, TEXAS.
(See fig 15 for hydrograph of yearly fluctuations)
Depth to water in feet below land-surface datum
60
65
70
Static level Feb 21, 1948, before pumping season began 58.85 ft
Automatic water-level recorder installed
End of 1948 pumping season
Static level Mar 21, 1949, before pumping season began 63.88 ft
Static level Jan 1, 1950 66.63 ft
0 1 2 3 Miles
Rain gage
FLOYD CO
Well 428
HALE CO
U.S. Hwy 70
WELL LOCATIONS JAN 1, 1948
(Nearest irrigation well is 1,880 ft from well 428)
DAILY PRECIPITATION AT LOCKVIEW FARMS, 11 MILES EAST OF PLAINVIEW, TEXAS.
Inches
2.0
1.0
0
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec
Jan
Feb
Mar
Apr
1948
1949
1950

Figure 31

A 28-hour test on an irrigation well in northern Castro County was run in March 1948. The discharge remained nearly constant at 540 gallons a minute throughout the test. Measurements of drawdown and recovery were made in both the pumped well and an unused well 108 feet from the pumped well. The maximum drawdown in the pumped well was about 19.3 feet and the drawdown in the unused well was 15.3 feet. After the pump had been stopped for 28 hours the water level in each well was still 2.0 feet below the static level before pumping began (see fig. 29).

In an 5-hour test on the City of Lubbock well 32 in June 1948, the discharge of the pumped well decreased from 860 to 832 gallons per minute, a 3-percent decrease (see fig. 30). The maximum drawdown in the pumped well was 17.0 feet, and the drawdown in an observation well 178 feet from the pumped well was 3.1 feet.

An automatic water-stage recorder was installed on an unused well (428, Hale County) 10 miles east from Plainview, Texas, near the edge of a heavily pumped district. The graph in the figure 31 is a continuous record of the depth to water below the land surface from the date the water-stage recorder was installed, April 10, 1948, to February 21, 1949. The sharp fluctuations shown in the graph were caused by starting and stopping the pump in the nearest irrigation well, 1,880 feet from the unused well; the general upward and downward trends show the effect of all the wells in the area. After substantial rains, most of the irrigating was discontinued and the water level began to rise as water stored in adjacent less heavily pumped areas flowed into the unwatered sands. The rapidity with which the effects of starting and stopping the pump are transmitted indicates that the ground water in this locality is confined under slight artesian pressure by lenses of clay, probably only local in extent. At the end of the pumping season the water level began to rise slowly; however, after several months of recovery, on February 21, 1949, the water table was still about 5 feet below the level a year before, on February 21, 1948. This shows that there was a general decline of the water level in this area of about 5 feet during the year, and that a considerable quantity of water was withdrawn from the underground reservoir.

QUANTITY OF WATER AVAILABLE

Because pumpage has not yet materially affected natural discharge, the amount of water that infiltrates to the water table over a long period of years is still about equal to the amount of water lost by natural discharge during the same period. Therefore, until the natural discharge begins to decrease as the result of the decline in water levels, the annual replenishment to the ground-water reservoir should not be considered in computing the available supply. However, even when part or all of the natural discharge is salvaged for beneficial use, the amount saved would be very small in comparison with the present withdrawals. It follows that the present pumpage is reducing the amount of water stored in the ground-water reservoir, and future withdrawals will result in proportional decreases in storage.

The specific yield of a saturated formation may be defined as the ratio of the volume of water that the formation will yield by gravity drainage, to the volume of the formation itself. The amount of water that can be withdrawn from the Ogallala formation depends on the specific yield, which is considerably less than the amount of water in storage. Therefore, to evaluate the available supply, it is necessary to know the specific yield and the thickness of the water-bearing deposits. This information is difficult to obtain because the water sands, which were deposited on eroded shales, vary greatly in thickness within short distances, and relatively few wells have penetrated the entire thickness of the Ogallala. Also, lenses of clay that yield little water are interfingered throughout the sands so that the specific yield may vary considerably in different areas and at different depths.

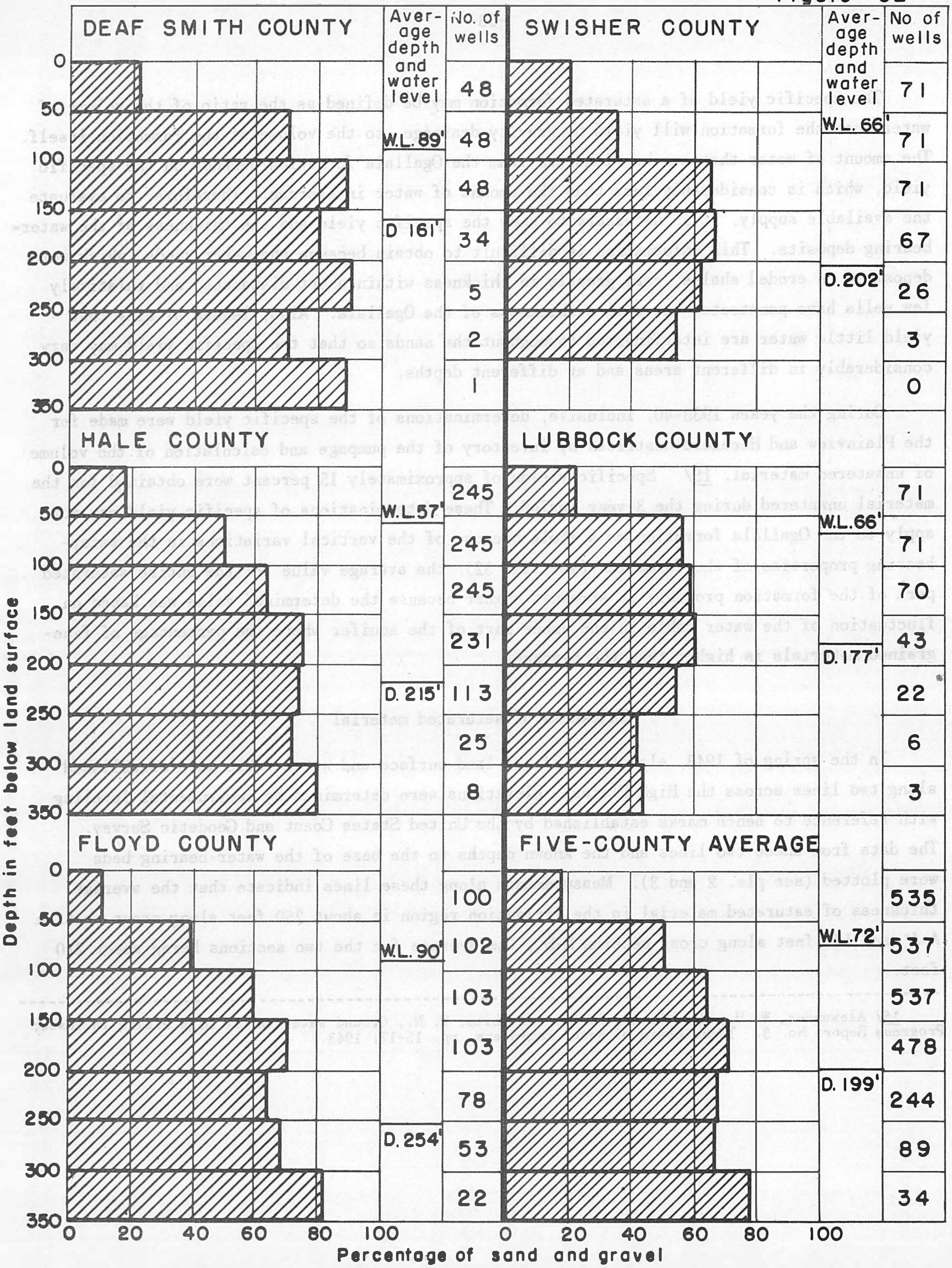
During the years 1938-40, inclusive, determinations of the specific yield were made for the Plainview and Hereford districts by inventory of the pumpage and calculation of the volume of unwatered material. 15/ Specific yields of approximately 15 percent were obtained for the material unwatered during the 3-year period. These determinations of specific yield may not apply to the Ogallala formation as a whole because of the vertical variations in the water-bearing properties of the formation (see fig. 32); the average value for the entire saturated part of the formation probably is somewhat higher because the determined value was based on fluctuation of the water table in the upper part of the aquifer where the percentage of fine-grained materials is higher than the average.

Thickness of saturated material

In the spring of 1948, elevations of the land surface and water table were established along two lines across the High Plains. Elevations were determined by instrumental leveling with reference to bench marks established by the United States Coast and Geodetic Survey. The data from these two lines and the known depths to the base of the water-bearing beds were plotted (see pls. 2 and 3). Measurements along these lines indicate that the average thickness of saturated material in the irrigation region is about 250 feet along cross section A-A' and 170 feet along cross section B-B', the average for the two sections being about 210 feet.

15/ Alexander, W. H., Broadhurst, W. L., and White, W. N., Ground water in the High Plains in Texas; Progress Report No. 3. Texas Board of Water Engineers, pp. 15-17, 1943.

Figure 32



PERCENTAGE OF SAND AND GRAVEL IN THE OGALLALA FORMATION IN FIVE COUNTIES IN THE SOUTHERN HIGH PLAINS IN TEXAS.

W. L. = Average depth to water   D. = Average depth of wells

Distribution of water-bearing sands

Recently all available logs of wells within the irrigated region were studied for the occurrence of water-bearing material. In 5 counties this study was especially detailed; 537 logs were classified by successive 50-foot intervals into relative percentages of sands and gravels and of non-water-bearing clays. The results of this tabulation are shown graphically in figure 32, including the average depth of water and the average depth of all irrigation wells listed in the latest county reports. The average depth to water in the 5 counties was 72 feet and the average depth of wells 199 feet. For some of the counties very few logs of the lower part of the Ogallala are available; therefore, the number of logs analyzed at each interval of depth is also recorded as a guide to the probable accuracy of the interpretation. The graph of Hale County, which is in the center of the area, is similar to the 5 county average. In Lubbock County, the smaller proportion of sand and gravel at the bottom of the section is probably due to the presence of Cretaceous sediments. An analysis of the 5 county average suggests that more water may be available from storage at lower depths than in the upper sands. A study of all the available logs on the Southern High Plains in Texas, with emphasis on the 5 county area, shows that approximately 65 percent of the saturated material between the water table and the base of the Ogallala will yield water to wells.

Porosity and specific yield of sands

Results of tests on the physical properties of 8 samples of sands from the Ogallala formation in the South Plains are shown in table 20. The porosity in percentage by volume was found by determining first the weight of oven-dry sand required to fill a glass container of known capacity that was filled with water. The sand was added to the water to prevent the formation of air pockets, and a volume of water equivalent to that of the sand particles overflowed to waste. The weight of the remaining water--that retained in the pore spaces--was then determined by subtracting the weight of the dry sand from the weight of the saturated sand. All samples tested were unconsolidated but their natural arrangement had been disturbed so that the determined porosity may have been somewhat different from that of the same material in the ground. The porosities of the 8 samples listed ranged from 30.9 to 37.3 and averaged 33.9.

Table 20.- Physical properties of Tertiary sands from the Southern High Plains in Texas

Sample No.	Size of grain (percent by weight) Larger than 0.84 mm	0.84-0.42 mm	0.42-0.25 mm	0.25-0.177 mm	0.177-0.149 mm	0.149-0.074 mm	Smaller than 0.074 mm	Apparent specific gravity	Porosity (percent)	Moisture equivalent (percent by volume)	Porosity minus moisture equivalent 1/
1	0.2	6.0	55.0	24.9	7.7	5.4	0.8	1.76	37.3	3.3	34.0
2	0.1	11.5	45.7	27.8	9.1	4.9	0.9	1.58	37.0	3.5	33.5
3	1.1	4.7	17.0	44.6	19.3	10.4	2.9	1.62	33.8	2.3	31.5
4	12.7	39.1	23.4	12.3	5.0	5.3	2.2	1.76	30.9	3.7	27.2
5	28.8	54.4	9.3	3.7	1.2	1.4	1.2	1.62	35.4	6.8	28.6
6	27.5	8.0	13.5	23.5	14.0	10.0	3.5	1.70	32.6	7.6	25.0
7	1.9	23.7	34.9	17.8	7.9	9.9	3.9	1.75	31.4	7.5	23.9
8	0.6	9.7	70.1	11.4	5.0	2.7	0.5	1.78	32.5	2.9	29.6
							AVERAGE	1.70	33.9	4.7	29.2

1/ Approximation of specific yield.

Sample No.	Description of location
1	Sand from Tertiary outcrop in White River Canyon, 2 miles east from Crosbyton, Crosby County, Texas.
2	Sand from Tertiary outcrop in White River Canyon, 2 miles east from Crosbyton, Crosby County, Texas. (Slightly lower horizon than sample 1).
3	Sand from well 2½ miles west from Kress, Swisher County, Texas. Sample from 189-208 feet. Rotary rig.
4	Sand from Tertiary outcrop along Wolf Creek, Motley County, Texas. From base of Tertiary deposits.
5	Sand from well in northeast corner of Crosby County, Texas. Sample from 230 feet. Rotary rig.
6	Sand from City of Lubbock Well 28, located 2 miles northeast from Lubbock, Lubbock County, Texas. Sample from 120 feet near base of Tertiary deposits. Cable-tool rig.
7	Sand from well in section 342 blk. M-6, S. K. & K. survey, Castro County, Texas. Sample from 345-355 feet. Rotary rig.
8	Sand pumped from City of Plainview Well 5. In Plainview, Hale County, Texas.

The moisture equivalent is assumed to be an approximation of the specific retention, which is the percentage of moisture remaining in a saturated material after prolonged drainage under the influence of gravity. The moisture equivalent was determined in the manner described by N. D. Stearns in U. S. Geological Survey Water-Supply Paper 596-F, page 136. Five-gram samples were saturated, drained, and then centrifuged for 1 hour at 1,000 times the force of gravity. The moisture equivalent ranged from 2.3 to 7.6 percent by volume and averaged 4.7 percent. The difference between the porosity and the moisture equivalent, where each is expressed as a percentage by volume is believed to be an approximation of the specific yield. 16/ In the 8 samples tested the difference between the porosity and the moisture equivalent ranged from 23.9 to 34.0 and averaged about 30 percent.

The samples tested were selected from several different counties and from various depths in the formation, and the results indicate a fairly narrow range of values in their hydrologic properties. An effort was made to select materials that apparently varied widely in grain size and uniformity, although the samples are far too few to permit reaching a conclusive result.

Total effective storage

An estimate of the total quantity of water underlying the High Plains is of little value in itself, because much of the water will not drain out by gravity and will not be released to wells. If it is assumed that the water-bearing sands will yield water equivalent to 30 percent of their volume and that these sands represent volume and that these sands represent 65 percent of the total volume of the saturated formation, the product of these two factors would be equivalent to a specific yield of about 20 percent for the saturated part of the formation. In addition to the water drained by gravity from the sands and gravels, some water would be squeezed into the sands from the interbedded clays. The ultimate value of the specific yield is believed to be greater than 15 but less than 20 percent, and the total effective storage in the average of 210 feet of saturated material underlying the 4-1/4 million acres within the irrigated region is believed to be near 150 million acre-feet.

If it were established that only the water lying above 200 feet in depth could be utilized economically, the thickness of saturated section would be approximately 130 feet, and the available supply would be approximately 100 million acre-feet. It is to be understood that these computations are based on many assumptions that have not yet been verified and on limited control data that may be adjusted as more information becomes available.

16/ Meinzer, O. E. Ground water, in Physics of the Earth-IX, Hydrology, p. 392, New York McGraw-Hill Book Co., Inc., 1942.

QUALITY OF WATER

Ground water in the High Plains is being developed primarily for irrigation, public supplies, and stock. Standards for measuring water quality depend upon the proposed use. Industrial requirements vary greatly from one industry to another and may be more rigid than municipal or irrigation requirements. However, industrial use of water in the High Plains is largely for purposes for which available public supplies are generally satisfactory.

Water used for municipal supplies, wherever possible, should conform to the limits of the United States Public Health Standards for water used by common carriers in interstate commerce 17/. The average individual can become adjusted to drinking water considerably higher in concentration than set by these standards, but temporary intestinal irritation may result when such water is first used. Public Health Standards place the following limits on the more important minerals commonly found in solution:

Iron (Fe) and manganese (Mn) together should not exceed 0.3 part per million.
Magnesium (Mg) should not exceed 125 parts per million.
Chloride (Cl) should not exceed 250 parts per million.
Sulfate (SO_4) should not exceed 250 parts per million.
Total solids should not exceed 500 parts per million for a water of good chemical quality. However, if such water is not available, a total-solids content of 1,000 parts per million may be permitted.

The effects of high fluoride content in drinking water on the teeth of growing children has become well known 18/. Evidence indicates that water supplies containing more than 1.5 parts per million of fluoride produce significant mottling of teeth, calcification defects, and attrition of enamel. Recently it has been observed that a smaller amount of fluoride is desirable in drinking water to prevent tooth decay. The Texas State Department of Health now recommends a fluoride concentration of 1.0 to 1.5 parts per million as very desirable. Many wells in the High Plains area yield water containing more than this amount of fluoride, and mottled enamel is endemic in the region.

17/ Public Health Service drinking water standards: Public Health Repts., vol. 61, pp. 371-384, 1946.

18/ Van Burkalow, A., Fluorine in United States water supplies: Geog. Rev., vol. 36, no. 2, pp.177-193, 1946.

Sodium percentage is an expression of the quality of an irrigation water used to predict the effects of the use of the water on the physical properties of the soil. It is determined by the formula $\frac{Na \times 100}{Ca + Mg + Na}$ where Ca, Mg, and Na are expressed in equivalents per million. If they are expressed in parts per million the following formula may be used:

$$\text{Sodium percentage} = \frac{\frac{Na}{23} \times 100}{\frac{Ca}{20} + \frac{Mg}{12.2} + \frac{Na}{23}}$$

Boron is one of the elements required in very small amounts for plant growth, but it is injurious when present in irrigation water in large amounts. Boron toxicity may be indicated by yellowing and mottling of leaves and in severe cases by defoliation of plants. Based on a few analyses present information indicates that boron does not constitute a problem in the irrigated region of the High Plains.

The following table has been found useful in evaluating irrigation waters: 19/

Water class	Conductance (micromhos at 25° C.)	Salt content Total (p.p.m.)	Salt content Per acre-foot (tons)	Sodium (percent)	Boron (p.p.m.)
Class 1[1]	1,000	700	1	60	0.5
Class 2[2]	1,000-3,000	700-2,000	1-3	60-75	.5-2.0
Class 3[3]	3,000	2,000	3	75	2.0

1 Excellent to good, suitable for most plants under most conditions.
2 Good to injurious, the higher concentrations probably harmful to the more sensitive crops.
3 Injurious to unsatisfactory, probably harmful to most crops and unsatisfactory for all but the most tolerant. If a water falls in class 3 on any basis, i.e., conductance, salt content, percentage of sodium, or boron content, it should be classed as unsuitable under most conditions. Should the salts present be largely sulfates, the values for salt content in each class can be raised 50 percent.

Most of the water used for irrigation in the High Plains comes either from the Ogallala formation or from Cretaceous rocks beneath the Ogallala. The Ogallala generally yields hard bicarbonate water that is relatively low in dissolved solids, which has been used successfully for irrigation for many years. The ratio of magnesium to calcium is higher in the Ogallala water than is generally found in most calcium bicarbonate waters. The sodium percentage is low, and usually both the chloride and sulfate are low. The Ogallala water ordinarily contains several parts per million of fluoride.

19/ Magistad, O. C., and Christiansen, J. E., Saline soils: U. S. Dept. Agr. Circ. 707, 1944.

Water from the Cretaceous rocks is generally more concentrated than water from the Ogallala. The water ordinarily contains a much higher proportion of sulfate and chloride than the Ogallala. It is hard and may contain magnesium in excess of the calcium. The sodium percentage may be higher than in the Ogallala, but the water is usually entirely satisfactory for irrigation. The Cretaceous water also is generally high in fluoride.

The following table gives analyses of water from representative wells in the High Plains area:

Analyses by Geological Survey, United States Department of the Interior
(Parts per million)

	1	2	3	4
Date of collection	6/23/48	11/14/44	4/23/48	8/30/48
Silica (SiO_2)	80	36	46	62
Iron (Fe)	0.00	0.02	0.35	0.15
Calcium (Ca)	32	49	73	88
Magnesium (Mg)	43	33	62	128
Sodium (Na)	25	20	154	275
Potassium (K)	8.0	10	7.2	25
Bicarbonate (HCO_3)	328	297	232	404
Sulfate (SO_4)	34	20	395	700
Chloride (Cl)	7.0	28	118	215
Fluoride (F)	3.2	2.0	4.0	5.2
Nitrate (NO_3)	2.8	5.0	3.2	0.0
Total dissolved solids	372	325	977	1,700
Total hardness as $CaCO_3$	257	258	437	746
Boron (B)	0.28		0.50	0.93
Sodium percentage	20	18	43	43
Conductance (microhms)	584	-	1,470	2,470

1. City of Amarillo, Greeley No. 1, Randall County; Ogallala formation.
2. City of Abernathy, Public Supply, Hale County; Ogallala formation.
3. Irrigation well, Cochran County; Ogallala formation and Cretaceous sediments.
4. Test well, City of Lubbock, Lubbock County; Ogallala formation and Cretaceous sediments.

Analyses of water samples from numerous wells and springs in the High Plains region are tabulated in the county reports listed on page 4.

UTILIZATION OF GROUND WATER

As the thickness of water-bearing material beneath the High Plains is reduced by water-level declines, the reduction in yields of wells takes place in greater proportions. For example, assume that a well yields a maximum of 1,000 gallons a minute from 100 feet of homogeneous sand. If the regional water level is lowered 50 feet, reducing the contributing section by half, the yield of the well will be reduced to substantially less than 500 gallons a minute. Moreover, the water must be lifted a greater distance to the surface.

Mutual interference between wells during the pumping season also contributes to the progressive decrease in yields and increase in pumping lifts. As a result of the combined effects of decreased yields and increased lifts an economic limit will be reached beyond which the returns from the use of the water will not justify continued withdrawals. Under present physical, mechanical. and economic conditions, there is little danger of completely exhausting the ground-water supplies; however, present trends of the water-level decline indicate a limited life of large-scale pumping in some districts. Improvements in well and pump design and prevention of waste may add considerably to the life expectancy. It is definite, however, that eventually there must be a reduction in the annual rates of withdrawals.

Some suggestions to be considered by which maximum beneficial use of water may be obtained are outlined below:

(1) Conserve rainfall by proper methods of cultivation.

(2) Select crops that produce the greatest returns from a minimum of irrigation water.

(3) Locate new wells as far as possible from existing wells to lessen mutual interference.

(4) Drill wells through the entire thickness of water-bearing sediments so that all sand strata will contribute to the well.

(5) Case the wells with pipe of sufficiently large diameter to permit the pumps to be lowered as the water table declines.

(6) Screen wells adequately so that screen loss will not be excessive. Slots should be of a size that will permit proper well development without allowing great quantities of sand to be pumped continually. In some areas gravel-walled wells might be advisable.

(7) Keep the well open to the bottom by periodic cleaning or by installing "tail pipe" below the pump bowls to keep the sand removed.

(8) Pump the wells at rates adapted to the transmission capacity of the aquifer.

(9) Use a power unit adapted for the load to obtain maximum efficiency.

(10) Reduce ditch losses by using pipe or an impermeable liner.

(11) Apply water at proper times and in proper amounts.

(12) Maintain supervision while applying water to prevent waste.

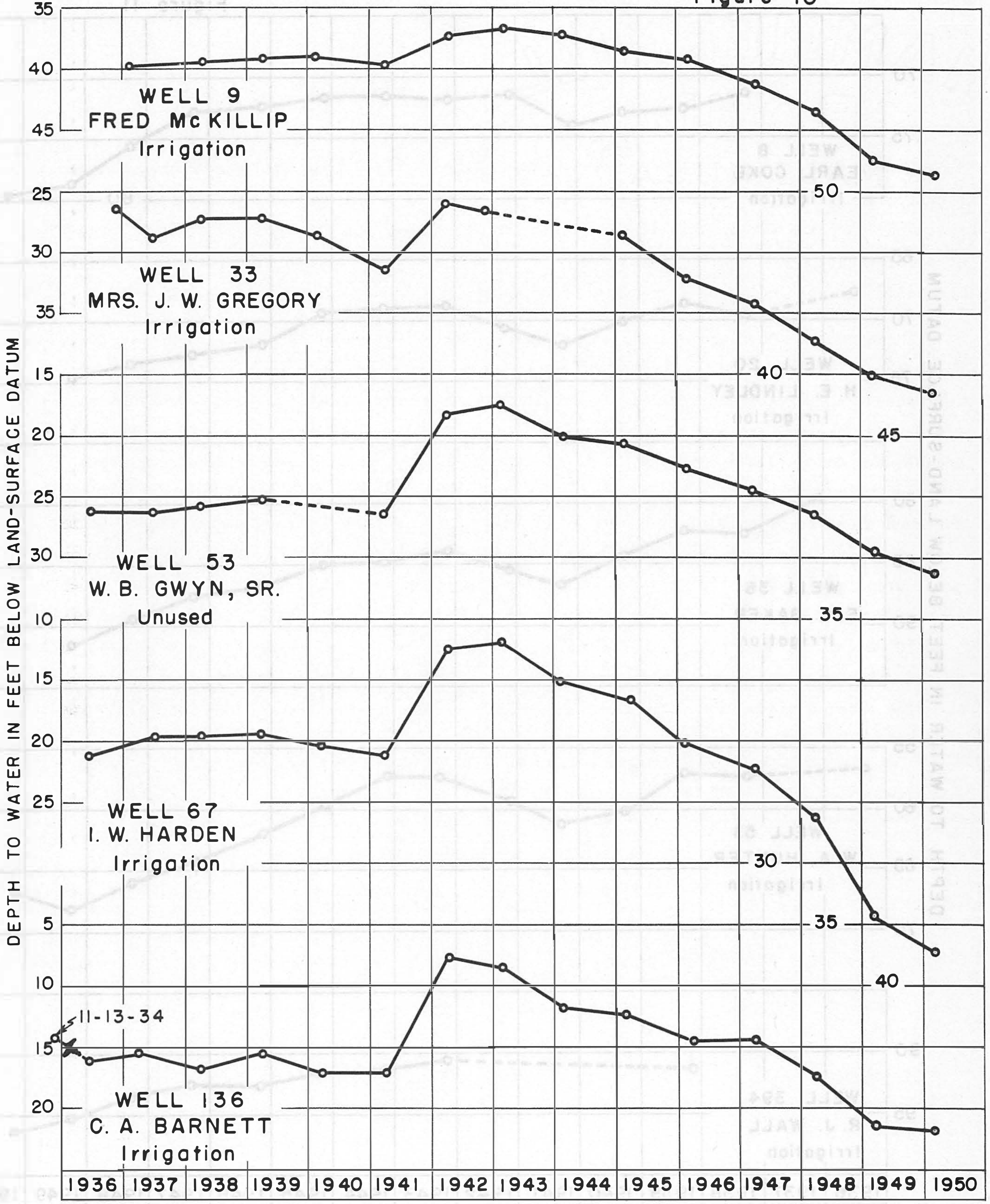
(13) Keep accurate records of pumpage, and acreage irrigated.

CONCLUSIONS

Ground water is considered to be a replenishable resource, but the rate of ground-water recharge in the Southern High Plains in Texas is so small compared to present pumpage that for practical purposes withdrawals may be considered as coming from storage. In several large areas, irrigation and municipal wells are so closely spaced that mass interference is reducing the yields of most wells during the pumping seasons and is increasing the pumping costs.

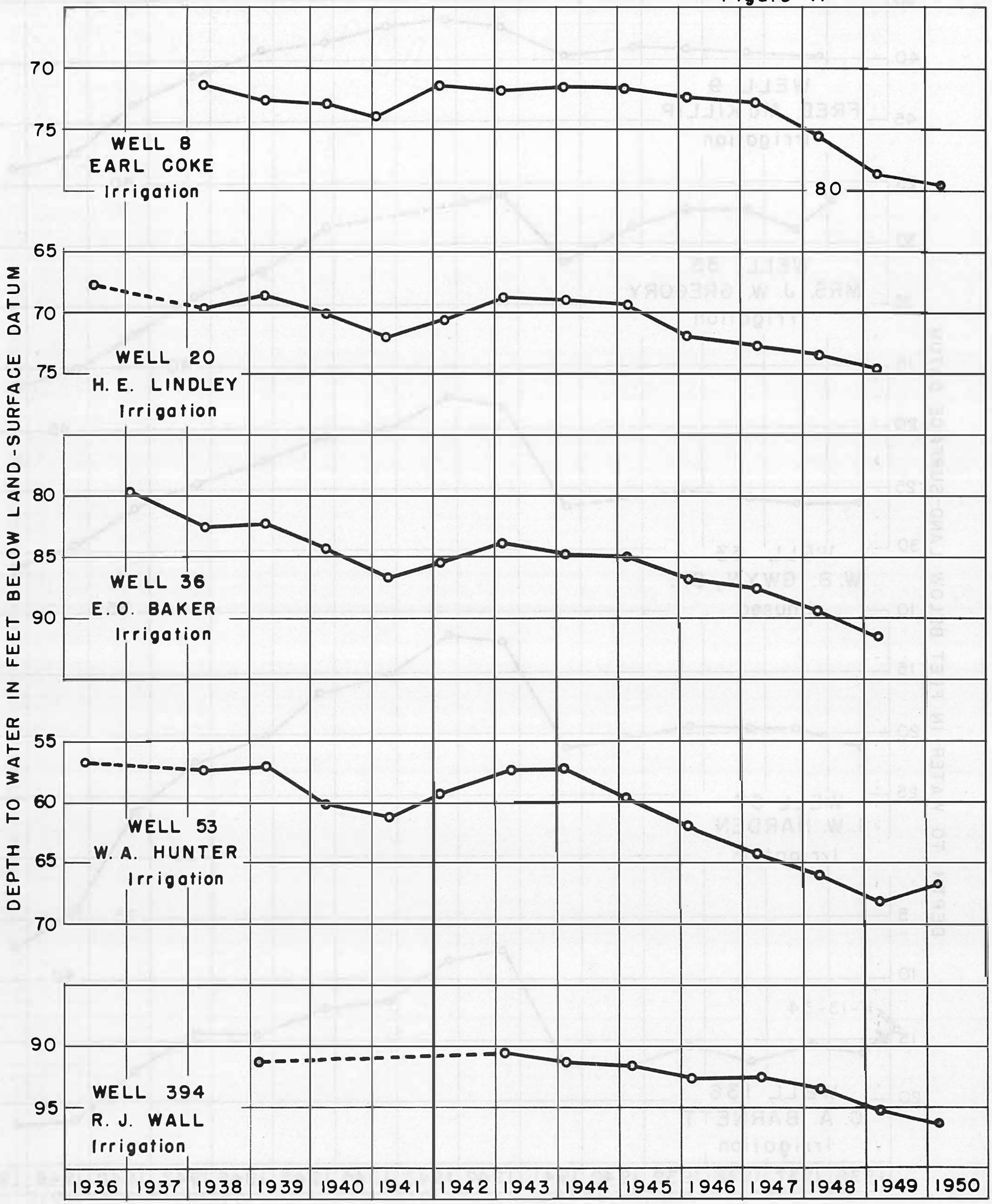
The available supply of water is estimated to be of the order of 150 million acre-feet, which means that the present annual withdrawal of approximately 1-1/4 million acre-feet will not exhaust the entire underground reservoir within the near future. However, declines in yields and pumping levels will effectively limit the life of large-scale pumping where withdrawals are concentrated in small areas. Furthermore the saturated sections in some areas are much thinner than the average, perhaps only 50 to 100 feet in thickness. It is possible for such areas to be completely unwatered by heavy pumping from adjacent deeper sands; however, the lateral movement would be slow and might require many years. During 1948, some small areas were materially affected and, if present trends of pumping and water-level decline continue, those areas and other parts of the irrigated region will be seriously affected within 5 to 10 years. In some other large areas within the irrigated region where the wells are widely spaced, the water-level declines have been small, mutual interference has been negligible, and if the wide spacing and present rate of withdrawals per well are maintained, the life of large-scale pumping may be extended for a much longer period of time.

Figure 10



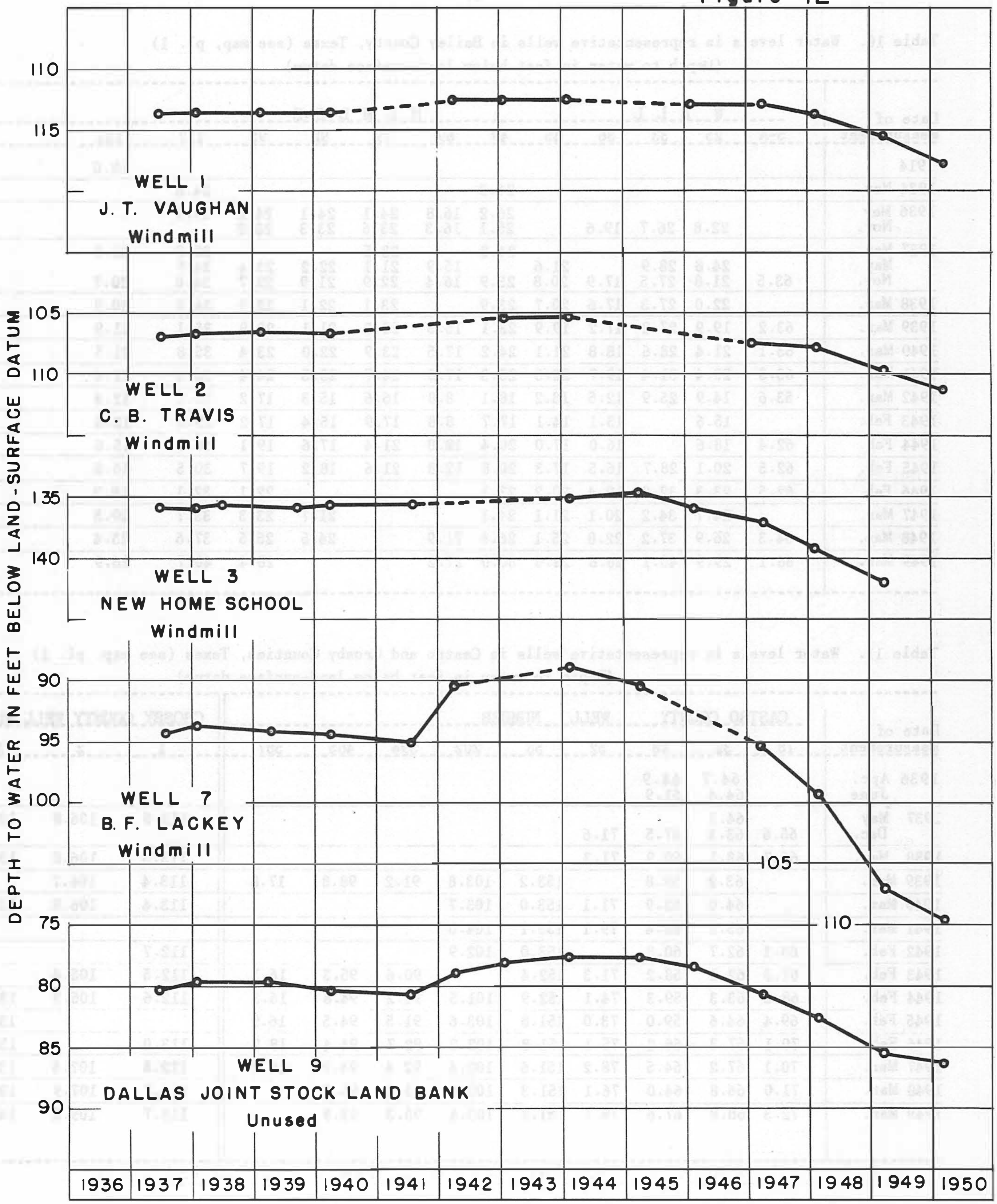
DEPTH TO WATER IN WELLS IN BAILEY COUNTY, TEXAS.

Figure 11



DEPTH TO WATER IN WELLS IN CASTRO COUNTY, TEXAS.

Figure 12



DEPTH TO WATER IN WELLS IN CROSBY COUNTY, TEXAS.

Table 10. Water levels in representative wells in Bailey County, Texas (see map, pl. 1)
(Depth to water in feet below land-surface datum)

Date of measurement	WELL NUMBER 5-A	25	33	36	45	49	69	79	92	95	117	131
1914												18.0
1934 Nov.						24.3					34.6	
1936 May						26.2	16.8	24.1	24.1	24.2	34.9	
Nov.		22.8	26.7	19.6		25.1	16.3	23.6	23.3	23.2		
1937 Mar.						24.8		23.5			35.0	21.0
May		24.8	28.9		21.6		15.9	21.1	22.2	23.4	34.9	
Nov.	63.5	21.8	27.5	17.9	20.8	23.9	16.4	22.9	21.9	22.7	34.8	20.7
1938 Mar.		22.0	27.3	17.6	20.7	23.9		23.1	22.1	22.9	34.9	20.9
1939 Mar.	63.2	19.9	27.2	17.2	19.9	23.1	15.5	22.3	21.1	22.9	35.1	21.9
1940 Mar.	63.1	21.4	28.6	18.8	21.1	24.2	17.5	23.9	22.0	23.4	35.8	21.5
1941 Mar.	63.3	23.4	31.4	19.7	22.3	25.3	17.8	24.7	23.5	24.4	36.4	22.4
1942 Mar.	53.6	14.9	25.9	12.5	13.2	18.1	8.8	16.6	15.3	17.2	30.5	12.3
1943 Feb.		15.6		13.1	14.1	17.7	8.8	17.9	15.4	17.2	29.0	12.6
1944 Feb.	62.4	18.6		16.0	17.0	20.4	12.0	21.4	17.6	19.1	30.1	15.6
1945 Feb.	62.5	20.1	28.7	16.5	17.3	20.8	12.8	21.6	18.2	19.7	30.5	16.8
1946 Feb.	62.5	23.3	32.2	19.4	20.2	23.1				22.1	32.1	19.3
1947 Mar.		24.7	34.2	20.1	21.1	24.1			21.7	23.3	33.7	20.3
1948 Mar.	64.3	26.9	37.2	22.8	25.1	26.8	21.9		24.5	25.5	37.6	23.4
1949 Mar.	66.1	29.9	40.1	26.8	28.6	30.0	27.2			28.4	40.7	26.9

Table 11. Water levels in representative wells in Castro and Crosby Counties, Texas (see map, pl. 1)
(Depth to water in feet below land-surface datum)

Date of measurement	CASTRO COUNTY WELL NUMBER 18	32	48	52	58	202	394	465	587	CROSBY COUNTY WELL NUMBER 1	2	3
1936 Apr.		64.7	64.9									
June		64.4	61.9									
1937 May		64.3								113.5	106.8	135.9
Dec.	65.6	63.3	67.5	71.6								
1938 Mar.	66.7	63.1	60.9	71.3						113.5	106.8	135.9
1939 Mar.		63.2	59.8		153.2	103.8	91.2	98.8	17.8	113.4	106.7	
1940 Mar.		64.0	62.9	71.1	153.0	103.7				113.4	106.8	135.6
1941 Mar.		65.5	64.4	79.1	153.1	104.0						
1942 Feb.	68.1	62.7	60.8		153.0	102.9				112.7		
1943 Feb.	67.3	62.1	58.2	71.3	152.4		90.6	95.3	16.1	112.5	105.4	
1944 Feb.	68.5	63.3	59.3	74.1	152.9	101.5	91.2	94.8	16.3	112.6	105.3	135.1
1945 Feb.	69.4	64.6	59.0	73.0	151.8	103.6	91.5	94.5	16.9			134.8
1946 Feb.	70.1	67.3	66.2	75.1	151.8	102.2	92.7	94.4	18.2	113.0		136.1
1947 Mar.	70.1	67.2	64.5	78.2	151.6	102.4	92.4	94.9	18.3	112.8	107.6	137.2
1948 Mar.	71.0	66.8	64.0	76.1	151.3	102.8	93.4	95.5		114.7	107.9	139.2
1949 Mar.	72.3	68.8	67.6	79.7	151.2	103.6	95.3	95.9		115.7	109.8	142.0

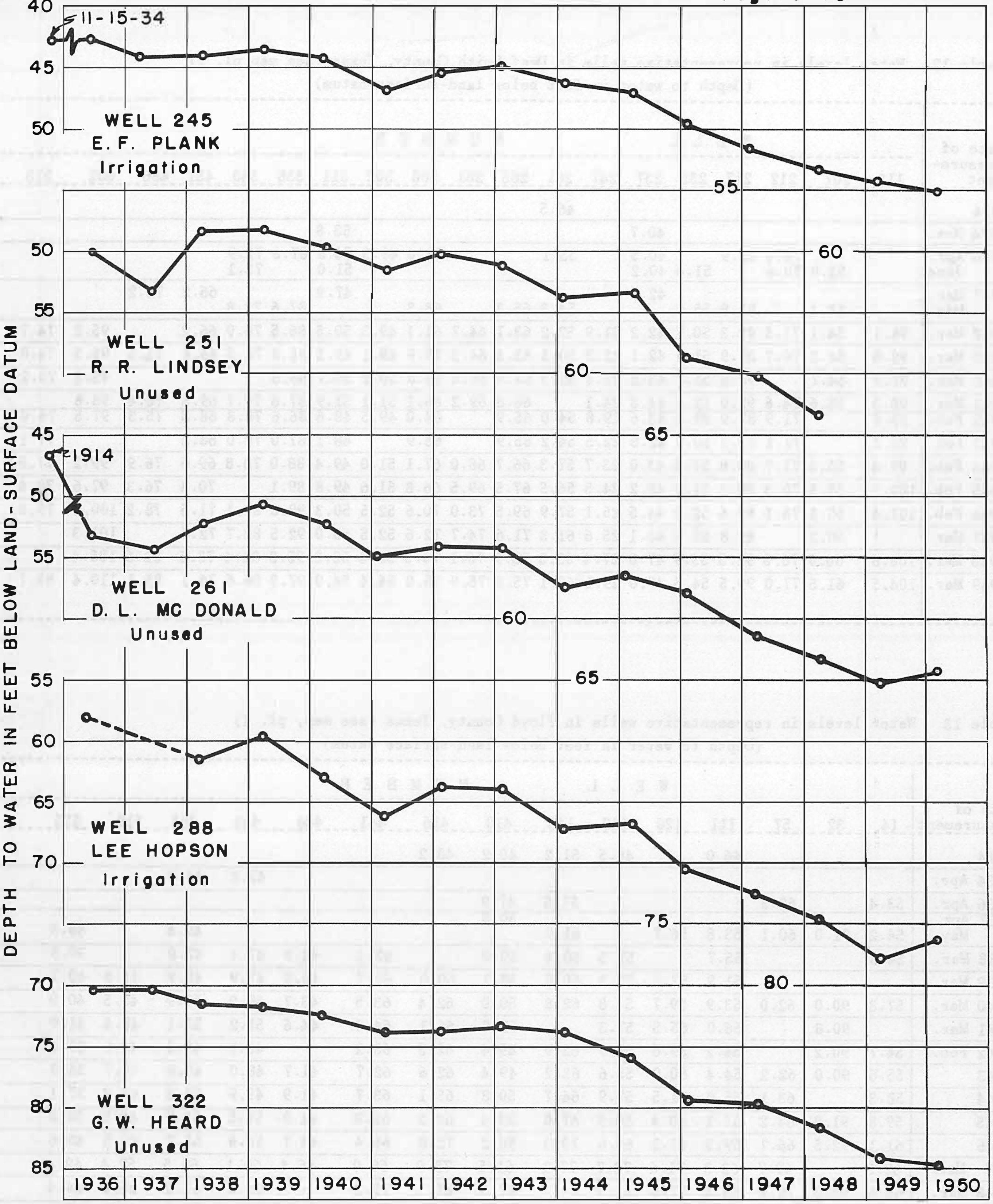
Table 12. Water levels in representative wells in Deaf Smith County, Texas (see map pl. 1)
(Depth to water in feet below land-surface datum)

Date of measurement	WELL							NUMBER											
	113	207	212	217	235	237	247	261	265	281	288	302	311	336	340	431	486	502	513
1914								46.5											
1934 Nov.						40.7							53.8						
1936 Apr.			70.4	83.9		40.5		53.1			58.0	49.3	54.8	87.3	72.9				
June		53.8	70.6		51.4	40.2							51.0		73.1				
1937 Mar.						42.0							47.9			66.2	71.2		
May		58.4		91.8	55.3			54.3	65.3		68.3			87.6	73.8				
1938 Mar.	98.1	54.1	71.5	92.3	50.7	42.2	21.9	52.2	63.1	64.7	61.1	49.3	50.5	86.5	76.9	66.2		95.2	74.7
1939 Mar.	98.0	54.2	70.7	87.9	51.1	42.1	22.2	50.5	63.3	64.5	59.9	49.1	49.5	85.8	76.5	66.6	71.5	95.3	74.8
1940 Mar.	97.9	54.7		90.6	51.7	43.2	23.4	52.3	64.4	66.4	63.0	50.2	50.7	86.5				95.2	75.2
1941 Mar.	98.3	55.6	74.6	92.0	52.6	44.8	24.1		66.6	69.2	66.1	51.1	51.9	87.6	79.7	69.5	76.4	98.8	
1942 Feb.	98.4		71.9	87.9	49.3	43.6	19.8	54.0	65.9		64.0	49.5	48.6	86.6	78.8	68.3	75.3	97.5	76.0
1943 Feb.	98.2		71.1	87.3	50.0	42.8	22.5	54.2	65.9		63.9		48.1	87.0	78.0	68.2			77.1
1944 Feb.	99.4	55.5	71.7	88.8	51.6	43.0	23.7	57.3	66.7	68.0	67.1	51.0	49.4	88.0	78.8	69.6	76.9	99.2	77.9
1945 Feb.	100.3	55.5	70.3	88.2	51.9	43.2	24.5	56.5	67.5	69.5	66.8	51.6	49.8	89.1		70.4	76.3	97.6	78.4
1946 Feb.	101.4	55.8	73.5	89.6	52.2	44.5	25.1	57.9	69.5	73.0	70.6	52.5	50.3	90.8	81.1	71.5	78.2	100.8	79.0
1947 Mar		58.2		89.8	52.6	46.1	25.6	61.3	71.6	74.7	72.6	52.5	50.0	92.5	82.7	72.6		101.3	
1948 Mar.	103.6	60.0	76.5	91.5	53.9	47.8	27.4	63.3	73.9	76.1	74.5	53.4	52.2	95.3	84.4	73.6	81.6	105.4	
1949 Mar.	104.5	61.5	77.0	99.5	54.5	49.0	29.1	65.1	75.0	75.9	78.0	54.4	54.0	97.3	86.6	76.1	85.1	110.4	82.7

Table 13. Water levels in representative wells in Floyd County, Texas (see map, pl. 1)
(Depth to water in feet below land-surface datum)

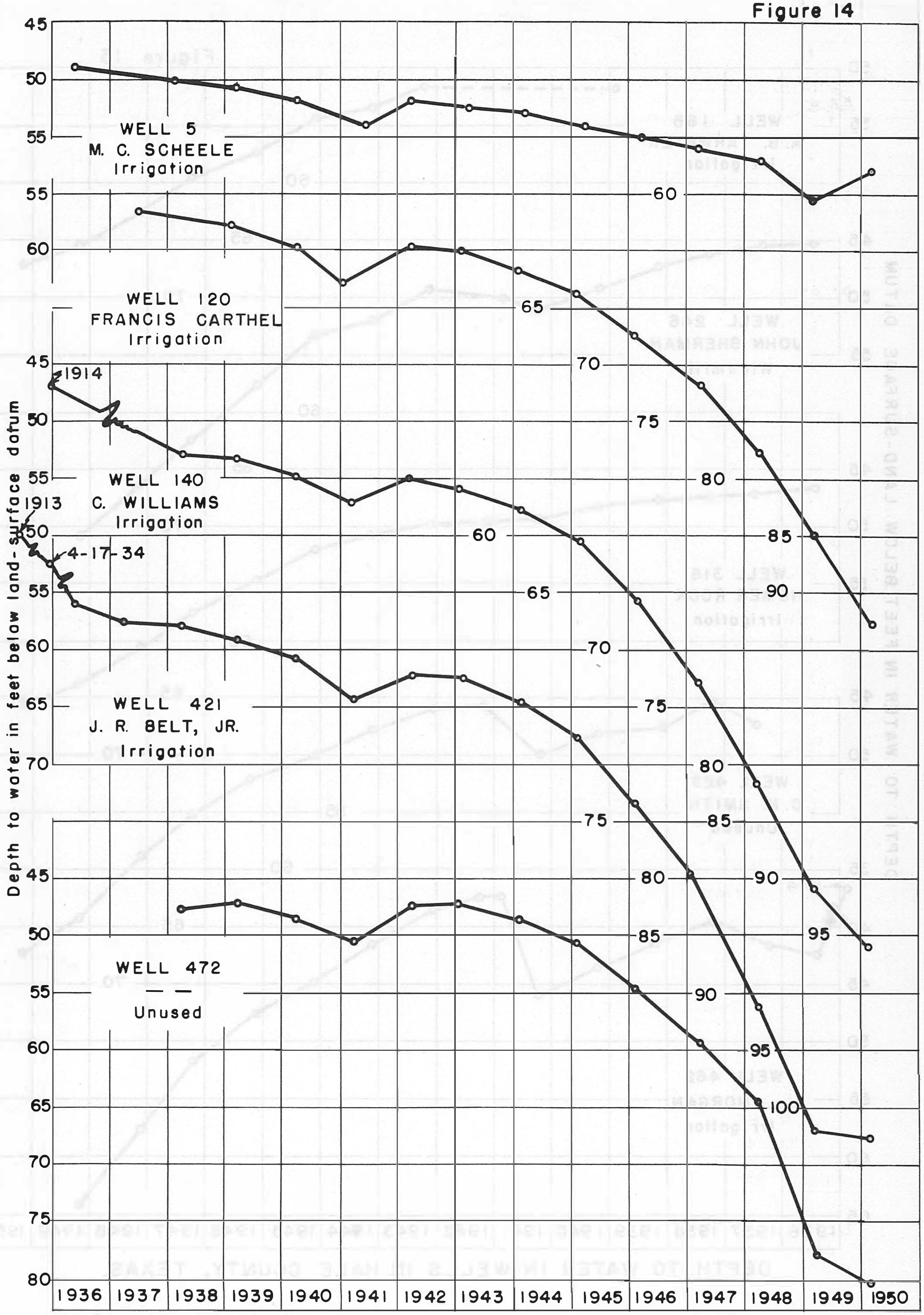
Date of measurement	WELL							NUMBER						
	14	32	57	111	120	140	143	410	416	441	446	459	463	510	525
1914				46.0		46.5	51.2	40.2	48.2						
1934 Apr.												43.9	44.9		
1936 Apr.	53.4		60.3				57.5	47.9							
1937 Apr.								50.3							
May	54.2	91.0	60.1	53.8	56.7		61.0						49.6		40.3
1938 Mar.	54.8			55.7		52.5	60.4	50.9		62.1	42.9	47.4	47.9		39.9
1939 Mar.				51.9	57.8	53.3	60.8	48.1	60.0	62.7	43.2	47.9	48.9	41.8	40.1
1940 Mar.	57.3	90.0	62.0	53.9	59.7	54.8	62.8	50.0	62.4	63.5	43.7	49.2	50.9	45.5	40.9
1941 Mar.		90.8		56.0	65.5	57.3		52.5	66.1	64.6	44.6	51.2	53.1	49.4	41.9
1942 Feb.	54.7	90.2		54.2	59.6	54.9	62.9	49.4	62.5	63.2		48.1	49.2	40.6	37.8
1943	55.6	90.0	62.2	54.4	60.0	55.6	63.2	49.4	62.6	62.7	41.7	48.0	48.9	40.7	36.8
1944	58.3		63.1	55.6	61.5	57.9	64.7	50.8	65.1	63.7	41.9	49.9	50.3	43.3	37.1
1945	59.8	91.8	64.2	57.1	63.4	60.5	67.0	53.4	68.2	65.0	42.9	51.5	53.0	46.5	38.8
1946	61.1	92.5	66.7	59.3	67.2	65.6	70.3	56.2	72.8	66.4	44.7	55.3	55.7	49.5	40.6
1947 Mar.	62.3		69.7	63.3	71.6	72.7	77.1	61.5	78.9	68.0	46.4	60.1	60.5	52.4	42.6
1948 Mar.	63.6	96.0	72.7	65.4	77.8	81.9	-	67.3	87.3	72.3	-	66.6	67.2	56.0	44.4
1949 Mar.	65.9	98.2	-	69.9	84.3	88.7	88.6	74.5	97.4	79.0	-	-	72.8	59.3	46.2

Figure 13



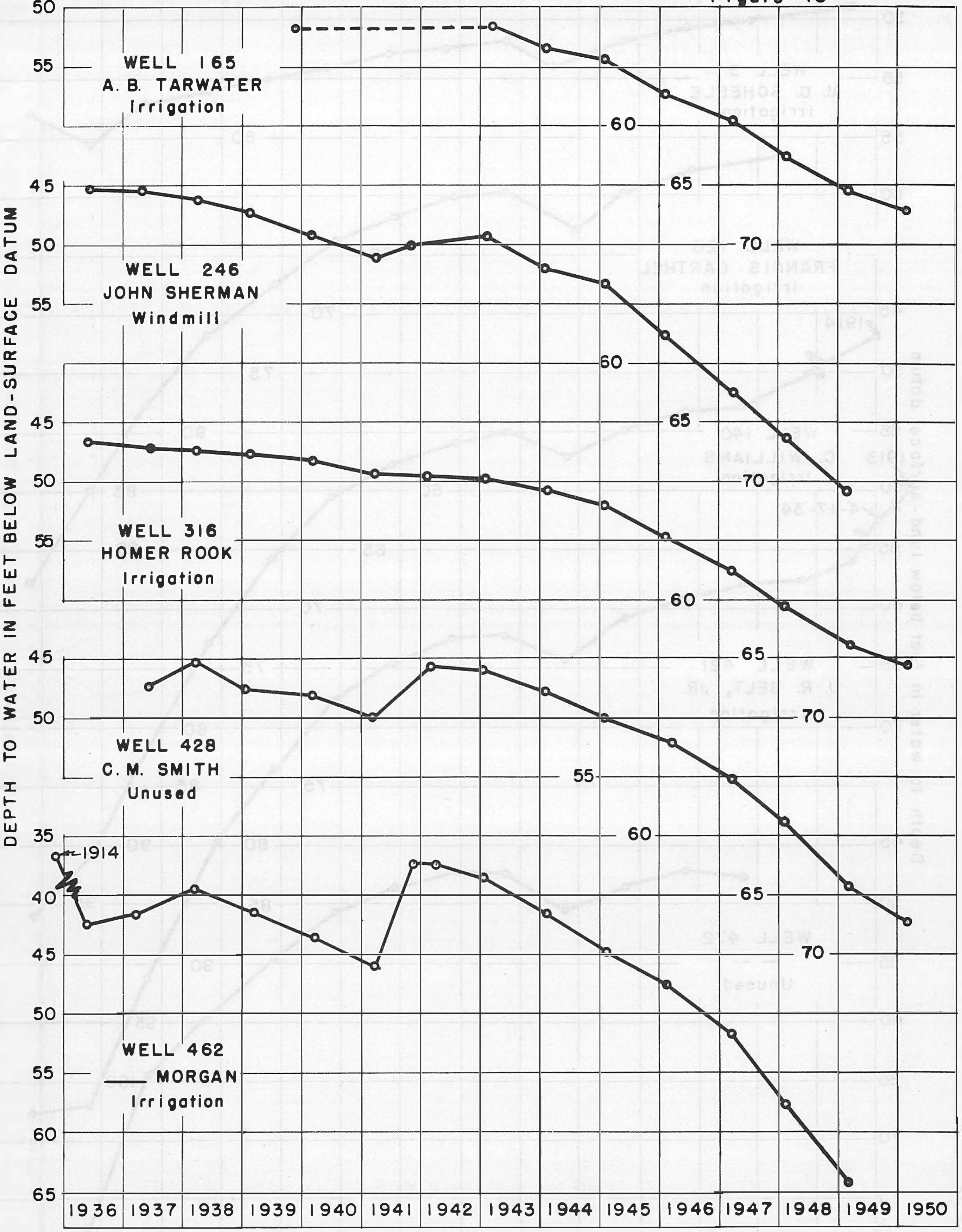
DEPTH TO WATER IN WELLS IN DEAF SMITH COUNTY, TEXAS.

Figure 14



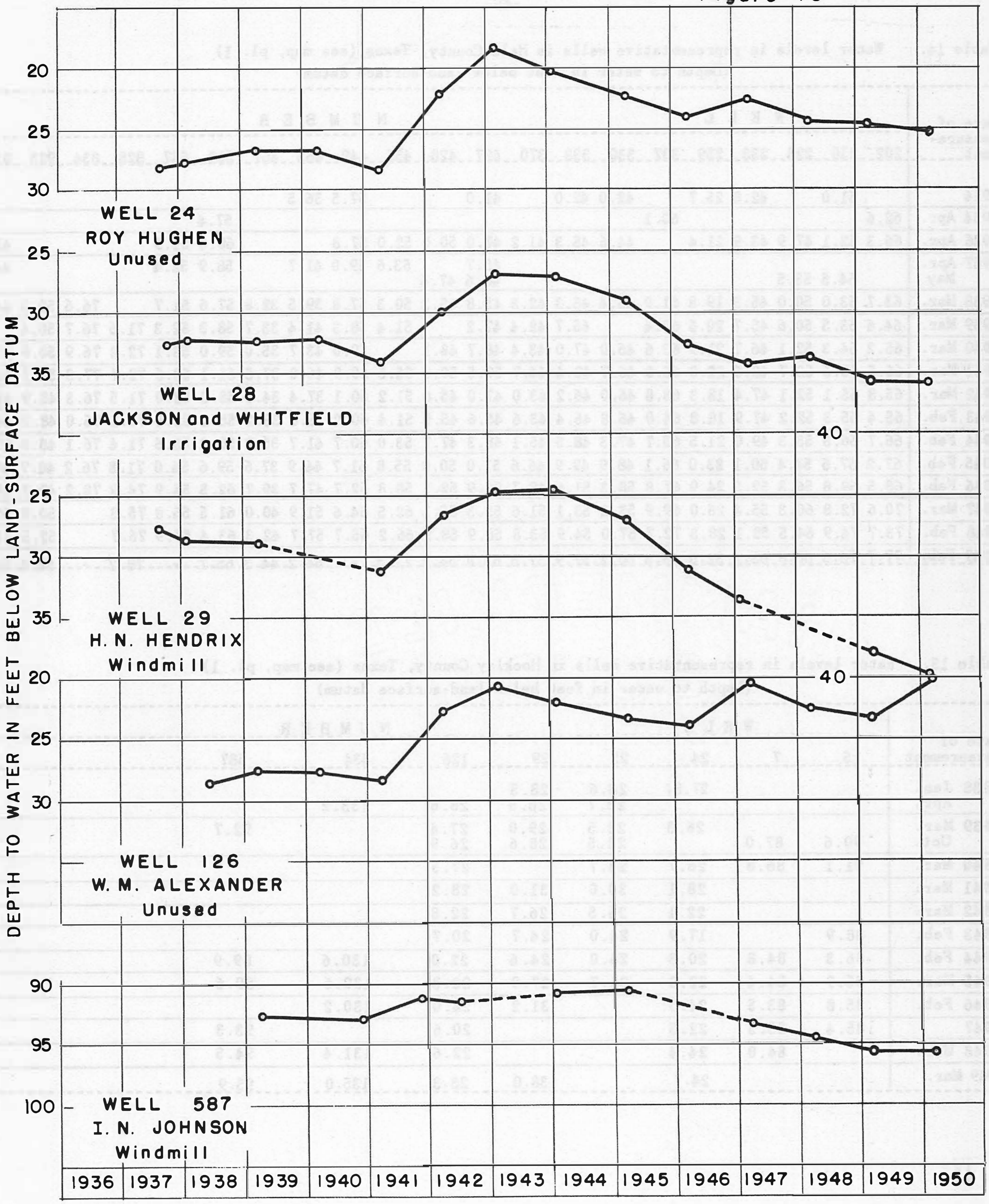
DEPTH TO WATER IN WELLS IN FLOYD COUNTY, TEXAS.

Figure 15



DEPTH TO WATER IN WELLS IN HALE COUNTY, TEXAS.

Figure 16



DEPTH TO WATER IN WELLS IN HOCKLEY COUNTY, TEXAS.

Table 14. Water levels in representative wells in Hale County, Texas (see map, pl. 1)
(Depth to water in feet below land-surface datum)

Date of measurement	WELL NUMBER 202	210	223	238	259	307	330	338	370	427	428	436	449	462	467	552	567	828	834	923	936
1914		61.0		42.0	25.7		42.0	42.0		41.0			57.5	36.5							
1934 Apr.	62.6					60.1										57.4					
1936 Apr.	66.3	62.1	47.9	43.9	21.4		44.6	45.3	41.2	47.0	50.0	52.0	57.8			60.3	51.9				43.2
1937 Apr.										45.7		53.6	59.0	41.7		58.9	52.4				44.5
May		64.5	53.5							48.6	47.4										
1938 Mar.	63.7	63.0	50.0	45.3	19.8	61.9	45.4	45.3	42.3	45.8	45.3	50.3	57.8	39.5	32.8	57.6	51.7		76.6	50.0	44.4
1939 Mar.	64.6	63.5	50.6	45.7	20.6	62.4		45.7	42.4	47.2		51.4	58.3	41.4	33.7	58.3	52.3	71.6	76.7	50.4	
1940 Mar.	65.2	64.3	52.1	46.7	21.9	63.6	46.0	47.0	43.4	48.7	48.1		59.0	43.7	35.0	59.0	53.1	72.2	76.9	50.9	47.3
1941 Mar.	66.5	65.5	53.7	48.6	22.8	65.0	46.7	48.4	44.7	50.5	50.0	55.5	60.9	46.0	37.5	61.1	53.6	72.7	77.3	51.7	49.0
1942 Mar.	65.8	65.1	52.1	47.4	18.3	63.8	46.0	46.2	43.0	47.0	45.6	51.2	60.1	37.4	34.0	58.3	52.0	71.5	76.3	48.9	45.5
1943 Feb.	65.4	65.3	52.2	47.9	18.8	64.0	46.8	46.4	43.6	46.6	45.9	51.4	60.0	38.6	33.2	58.2	52.6	71.1	76.0	48.2	44.1
1944 Feb.	66.7	66.8	53.3	49.0	21.5	65.7	47.3	48.5	45.1	48.3	47.7	53.0	60.7	41.7	35.2	58.8	53.5	71.4	76.1	48.0	45.4
1945 Feb.	67.2	67.6	54.4	50.1	23.0	66.1	48.9	49.9	46.6	51.0	50.0	55.8	61.7	44.9	37.6	59.6	54.0	71.8	76.2	48.7	46.2
1946 Feb.	68.5	69.8	56.3	52.5	24.9	67.8	50.3	51.6	48.7	52.9	52.1	58.8	62.7	47.7	39.7	62.3	54.9	74.9	78.2	49.7	48.8
1947 Mar.	70.6	72.8	60.3	55.4	26.0	69.9	53.3	53.1	51.6	55.3	55.1	62.5	64.6	51.9	40.0	61.5	55.8	75.3		50.8	50.4
1948 Feb.	73.7	74.9	64.5	58.1	28.3	72.7	57.0	54.9	53.8	58.9	58.9	66.2	65.7	57.7	42.3	63.4	57.9	76.7		52.5	51.2
1949 Feb.	77.7	76.6	68.8	63.2	32.0	76.4	60.2	57.9	57.6	63.8	64.2	71.3	-	64.2	44.3	65.7	-	78.2	-	54.4	52.1

Table 15. Water levels in representative wells in Hockley County, Texas (see map, pl. 1)
(Depth to water in feet below land-surface datum)

Date of measurement	WELL NUMBER 5	7	24	25	29	126	434	587
1938 Jan.			27.8	28.6	28.5			
Apr.				28.7	28.8	28.6	133.2	
1939 Mar.			26.8	28.5	29.0	27.4		92.7
Oct.	90.6	87.0		28.5	28.6	26.9		
1940 Mar.	91.1	86.8	26.7	28.7		27.5		
1941 Mar.			28.1	30.0	31.0	28.2		
1942 Mar.			22.1	26.5	26.7	22.8		
1943 Feb.	88.9		17.9	24.0	24.7	20.7		
1944 Feb.	86.3	84.8	20.3	24.0	24.6	22.0	130.6	89.9
1945 Mar.	85.9	84.4	22.3	25.7	27.0	23.3	130.6	89.6
1946 Feb.	85.8	83.5	24.0		31.2	24.0	130.2	
1947	85.4	83.3	22.5			20.6		93.3
1948 Mar.		84.0	24.4			22.6	131.4	94.5
1949 Mar.			24.7		38.0	23.3	135.0	95.9

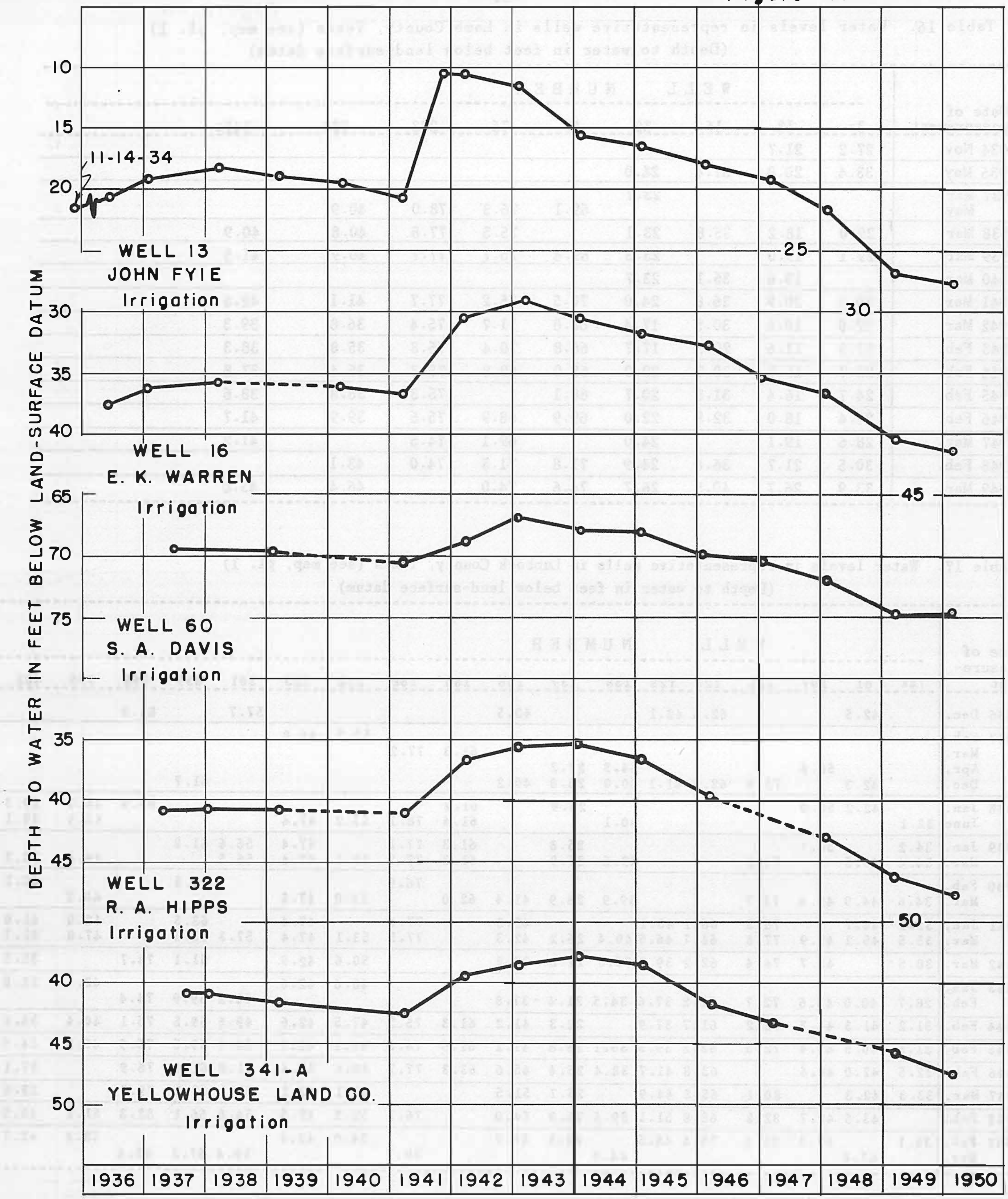
Table 16. Water levels in representative wells in Lamb County, Texas (see map, pl. 1)
(Depth to water in feet below land-surface datum)

Date of measurement	WELL NUMBER 3a	13	16	30	60	76	243	322	341a
1934 Nov.	27.2	21.7							
1936 May	33.4	20.8	37.4	24.0					
1937 Mar.				23.7					
May					69.1	76.3	78.0	40.9	
1938 Mar.	29.0	18.2	35.8	23.1		75.5	77.8	40.8	40.9
1939 Mar.	29.1	19.0		23.3	69.4	75.7	77.7	40.9	41.5
1940 Mar.		19.6	36.1	23.7					
1941 Mar.	30.5	20.9	36.8	24.0	70.5	75.2	77.7	41.1	42.5
1942 Mar.	22.9	10.6	30.5	17.4	68.8	71.7	75.4	36.8	39.3
1943 Feb.	21.9	11.6	29.3	17.7	66.8	70.4	75.3	35.8	38.3
1944 Feb.	23.7	15.7	30.7	20.0	68.0	69.8	75.3	35.4	37.8
1945 Feb.	24.7	16.4	31.8	20.7	68.1		75.3	36.8	38.6
1946 Feb.	26.4	18.0	32.8	22.0	69.9	68.9	75.6	39.9	41.7
1947 Mar.	28.6	19.1		24.0		69.1	74.5		41.2
1948 Feb.	30.5	21.7	36.6	24.9	71.8	71.3	74.0	43.1	
1949 Mar.	33.9	26.7	40.5	26.7	74.6	74.0		46.4	45.8

Table 17. Water levels in representative wells in Lubbock County, Texas (see map, pl. 1)
(Depth to water in feet below land-surface datum)

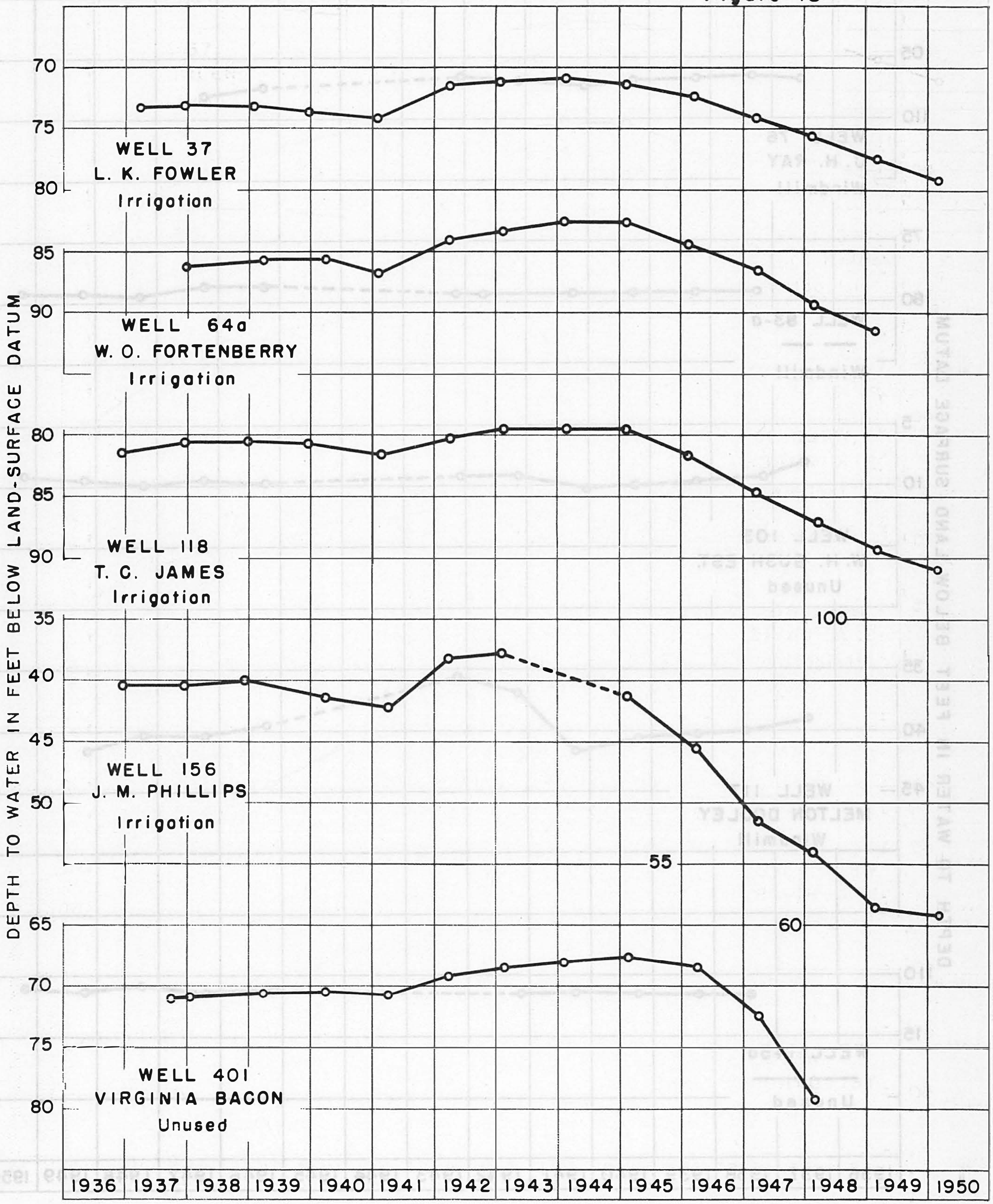
Date of measurement	WELL NUMBER 74a	81	107	121	123	128	138	139	156	185	188	222	223	301	339	369	395	403
1936 Dec.		42.5			62.4	42.1			40.5					57.7		81.0		
1937 Feb.												53.7	46.8					
Mar.										61.3	77.2							
Apr.			50.6				44.3	27.2										
Dec.		42.3		73.8	62.0	41.1	40.0	25.8	40.2						61.7			
1938 Jan.		42.2	50.0					25.9		61.2						80.9	44.0	39.3
June	32.1						40.1			61.4	78.1	53.2	47.4				43.9	39.1
1939 Jan.	34.2		50.1					25.8		61.3	77.1		47.4	56.6	61.8			
Mar.	34.4	43.5		74.2			39.6	25.9		61.3	77.5	53.1	47.4	56.5			44.0	38.7
1940 Feb.											76.9				62.5			40.1
Mar.	34.6	44.9	49.4	75.7			39.9	24.9	41.4	62.0		53.0	47.5				46.2	
1941 Jan.	35.1	44.7		76.3	66.1	43.1			42.3		77.6		47.4		63.5		48.0	41.8
Mar.	35.5	45.2	49.9	77.8	64.7	46.5	40.4	26.2	42.3		77.5	53.1	47.4	57.3	63.5		47.8	41.7
1942 Mar.	30.5		45.7	74.4	62.2	39.3	36.3	22.8	38.2			50.6	42.9		61.1	74.7		35.5
1943 Jan.												48.6	42.6				42.1	32.8
Feb.	28.7	40.0	43.6	72.7	61.2	37.6	34.5	21.4	37.8					50.2	59.9	74.4		
1944 Feb.	31.2	41.3	44.3	72.2	61.7	37.9		22.3	41.2	61.3	75.2	47.5	42.6	49.6	59.5	76.1	40.4	34.6
1945 Feb.	31.6	40.5	45.4	72.5	62.2	39.3	36.1	23.8	41.2	61.9	74.3	48.1	42.7	50.1	59.5	75.9	45.2	34.5
1946 Feb.	32.5	42.0	46.4		63.8	41.7	38.4	25.4	45.6	63.3	77.7	48.6	42.4	51.8	61.5	76.9		37.1
1947 Mar.	33.3	42.3		80.1	65.8	44.9		25.7	51.5			51.1	42.2	53.1	63.1	79.7		39.6
1948 Feb.		43.5	48.7	82.2	68.8	51.1	39.6	26.9	54.0		76.1	52.2	42.5	54.0	66.1	82.3	51.8	40.5
1949 Feb.	36.1		49.3	82.0	76.0	48.5		29.3	58.7			54.0	42.6				53.8	43.7
Mar.		45.4					44.9				80.1			59.4	67.2	86.4		

Figure 17



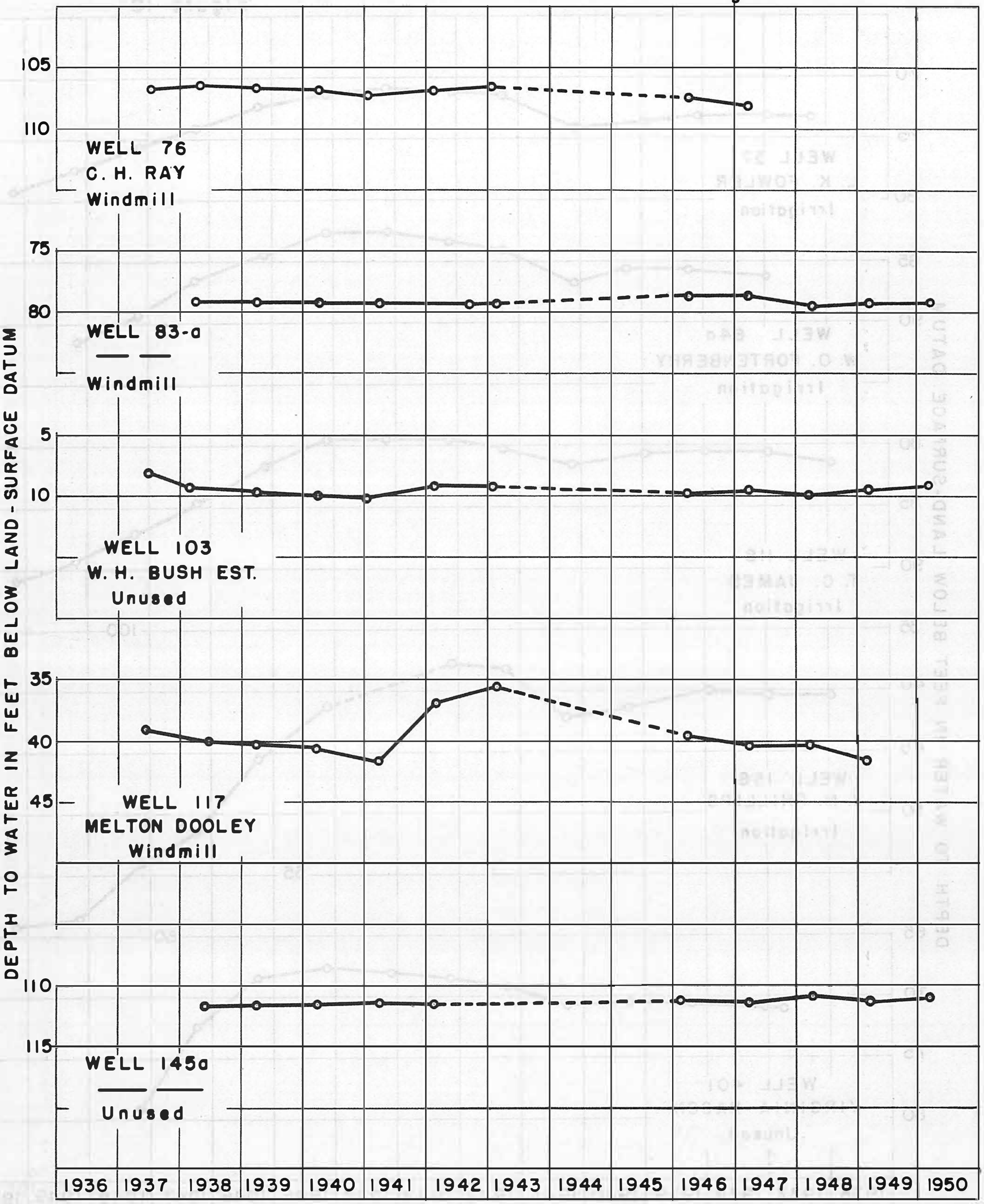
DEPTH TO WATER IN WELLS IN LAMB COUNTY, TEXAS.

Figure 18



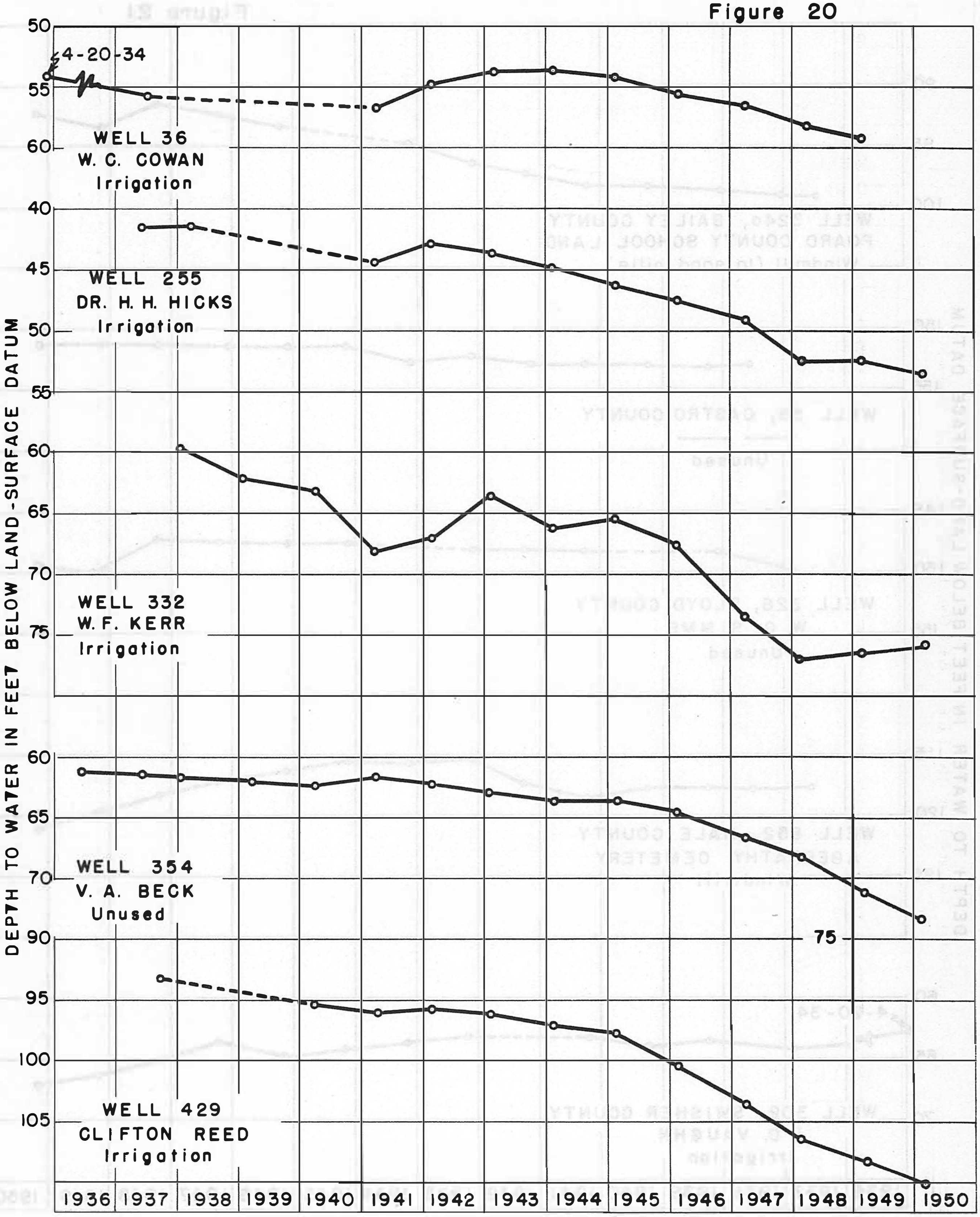
DEPTH TO WATER IN WELLS IN LUBBOCK COUNTY, TEXAS.

Figure 19



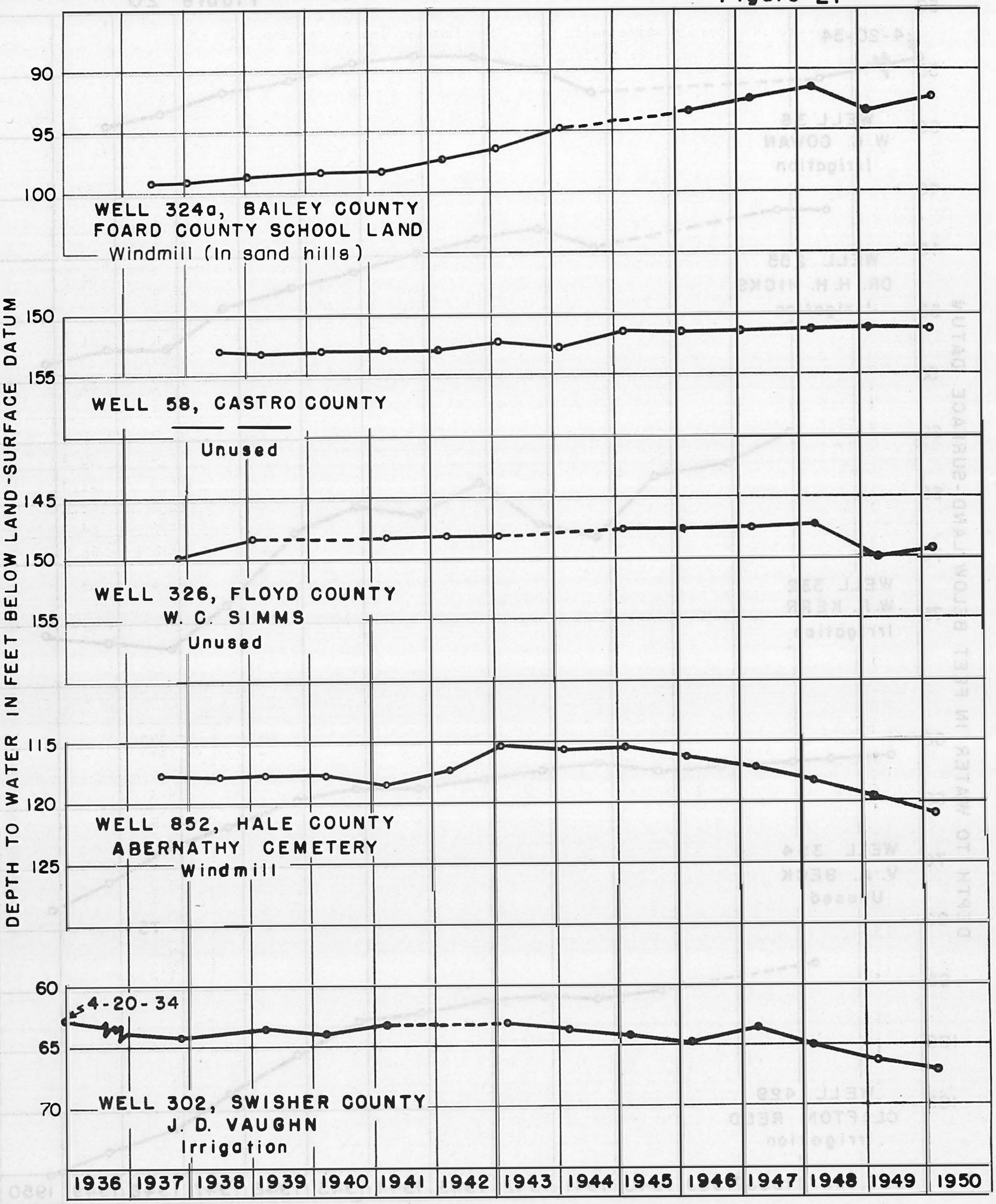
DEPTH TO WATER IN WELLS IN RANDALL COUNTY, TEXAS.

Figure 20



DEPTH TO WATER IN WELLS IN SWISHER COUNTY, TEXAS.

Figure 21



DEPTH TO WATER IN WELLS REMOTE FROM AREAS OF HEAVY PUMPING.

Table 18. Water levels in representative wells in Swisher County, Texas (see map, pl. 1)
(Depth to water in feet below land-surface datum)

Date of measurement	WELL NUMBER 2	16	38	108	258	302	354	359	370	383	421
1934 Apr.				70.7		62.7				70.7	
1936 Apr.					50.6					73.1	
June							61.2		71.7		
1937 Apr.											59.2
May		61.4	55.0		51.2		61.5			76.2	
1938 Mar.	77.9	61.8	55.1		51.6		61.8	74.7	72.5	72.7	
1939 Mar.	77.7	61.6	55.7		52.0	63.7	62.0	75.1	72.4	71.8	61.1
1940 Mar.	77.8	62.0	56.0		53.3	64.1	62.3	75.3	72.1	72.7	
1941 Mar.	78.0	62.3				64.7	62.8	76.2	73.3	73.7	62.1
1942 Mar.	77.9	61.2			54.1		62.2	75.7	73.8	73.5	
1943 Feb.	77.7	60.9	55.0	71.5	54.2	63.2	62.9	76.0	74.5	73.2	59.4
1944 Feb.	77.7	61.0	54.0		55.1	63.8	63.7	76.7	76.6	74.9	60.9
1945 Feb.	77.7	61.2	54.7	72.2	56.5	64.2	63.8	77.5	79.0	76.3	61.3
1946 Feb.	77.6	62.4	56.4	73.5	58.4	65.0	64.7	79.5	80.5	78.9	63.9
1947 Mar.	77.9	63.4	57.0	74.9	-	63.6	66.7	81.8	83.3	81.5	64.4
1948 Mar.	77.7			75.9	-	65.2	68.4	84.3	85.5	84.8	66.3
1949 Mar.	77.8		63.9	76.3		66.2	71.1	87.7	88.5	87.4	68.6

Table 19.- Average fluctuations of water levels, in feet

County	1914-38 Number of wells	Decline (-) or rise (+)	1938-49 Number of wells	Decline (-) or rise (+)	1943-49 Number of wells	Decline (-) or rise (+)	1948-49 Number of wells	Decline (-) or rise (+)
Bailey	4	-1.7	30	-5.9	28	-11.9	27	-4.1
Briscoe							12	-1.4
Castro			13	-4.9	18	- 5.1	21	-1.5
Cochran			3	+1.5	2	+ 0.2	6	-0.7
Crosby			7	-7.6	6	- 9.8	13	-2.9
Deaf Smith			39	-9.3	35	- 7.4	47	-1.7
Floyd	15	-7.9	44	-20.7	36	-20.4	68	-5.0
Hale	19	-1.4	69	-11.5	66	-11.6	105	-3.1
Hockley			5	+ 0.8	5	- 7.8	27	-2.1
Lamb	2	-4.9	20	- 3.7	25	- 8.1	27	-2.7
Lubbock			38	-4.8	37	- 9.0	96	-2.4
Parmer			5	+ 1.4	2	- 0.1	9	-0.3
Randall			4	+1.0	4	- 4.2	5	+1.7
Swisher	1	-5.5	12	-9.2	34	-5.7	67	-1.7