A Summary of the Occurrence and Development of Ground Water in the Southern High Plains of Texas

By J. G. CRONIN

With a section on ARTIFICIAL RECHARGE STUDIES

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By J. G. Cronin

ABSTRACT

The Southern High Plains of Texas occupies an area of about 22,000 square miles in northwest Texas, extending from the Canadian River southward about 250 miles and from the New Mexico line eastward an average distance of about 120 miles.

The economy of the area is dependent largely upon irrigated agriculture, and in 1958 about 44,000 irrigation wells were in operation. The economy of the area is also dependent upon the oil industry either in the form of oil and gas production or in the form of industries based on the production of petroleum.

The Southern High Plains of Texas is characterized by a nearly flat land surface sloping gently toward the southeast at an average of 8 to 10 feet per mile. Shallow undrained depressions or playas are characteristic of the plains surface, and during periods of heavy rainfall, runoff collects in the depressions to form temporary ponds or lakes. Stream drainage on the plains surface is poorly developed; water discharges over the eastern escarpment off the plains only during periods of excessive rainfall.

The climate of the area is semiarid; the average annual precipitation is about 20 inches. About 70 percent of the precipitation falls during the growing season from April to September.

Rocks of Permian age underlie the entire area and consist chiefly of red sandstone and shale containing numerous beds of gypsum and dolomite. The Permian rocks are not a source of water in the Southern High Plains, and any water in these rocks would probably be saline.

The Triassic rocks underlying the Southern High Plains consist of three formations of the Dockum group: the Tecovas formation, the Santa Rosa sandstone, and the Chinle formation equivalent. The Tecovas and Chinle formation equivalent both consist chiefly of shale and sandy shale; however, the Santa Rosa sandstone consists mainly of medium to coarse conglomeratic sandstone containing some shale. The formations of the Dockum group are capable of yielding small to moderate quantities of water in many parts of the Southern High Plains; however, in practically all places the water is rather saline and probably unsuitable for most uses.

The Cretaceous formations in the Southern High Plains consist of several formations of the Trinity, Fredericksburg, and Washita groups. The rocks underlie a large part of the southern part of the Southern High Plains; they consist of sandstone, shale, and limestone, the sandstone and limestone being the principal water-bearing units. In a few places where the Cretaceous rocks appear to

be in hydraulic connection with the overlying Ogallala formation, moderate quantities of water are obtained, particularly from the limestones. Locally the Cretaceous rocks may be important aquifers where other water is not available, but they generally do not constitute a large source of water for irrigation or municipal use.

The Ogallala formation of Pliocene age is the principal aquifer in the Southern High Plains of Texas; it supplies practically all the water used for all purposes. The formation is continuous throughout most of the Texas part of the Southern High Plains and extends into New Mexico. The formation consists chiefly of sediments deposited by streams that had their headwaters in the mountainous regions to the west and northwest. The Ogallala formation rests unconformably upon an erosional surface of the underlying Triassic and Cretaceous rocks. The Ogallala consists of beds and lenses of clay, silt, sand, and gravel; caliche occurs as a secondary deposit in many places in the formation. In general the Ogallala is thicker in the northern part of the area; the thickness ranges from 400 to 500 feet in central Parmer, west-central Castro, and southwestern Floyd Counties to a knife edge where the formation wedges out against outcrops of the older rocks. The Ogallala formation probably originally formed a continuous blanket of sediments extending from the Rocky Mountains on the west well into Texas. However, erosion has completely isolated the formation, and the segment in the Southern High Plains is cut off in all directions from any underground connection with water-bearing beds outside of the area except through the underlying older rocks which contain highly mineralized water entirely unlike the fresh water in the Ogallala. Consequently, the source of all the water in the Ogallala is precipitation that falls on the surface of the plains in Texas and New Mexico.

Thin deposits of Pleistocene and Recent age overlie the Ogallala formation in many places; they consist of lake or pond, stream, and sand-dune deposits. These rocks are important hydrologically only where they form recharge facilities such as in the sand-dune areas and in the drainageways. The lake or pond deposits consist chiefly of clay and silt and, therefore, generally impede recharge rather than aid it.

Caliche deposits underlie much of the surface of the Southern High Plains of Texas. The caliche consists of beds, lenses, or nodules chiefly of calcareous and siliceous material. The caliche forms the conspicuous caprock of the eastern plains escarpment. In many places the caliche is almost completely indurated and is an impediment to recharge. In other areas the caliche is porous and in places may possibly be of such composition and permeability that it would not hinder the infiltration of recharge from the surface.

Generally the water in the Ogallala occurs under water-table conditions; however, locally it may be under slight artesian pressure. The water in the Ogallala occupies the pore spaces and voids in the rocks and occurs between the water table and the underlying older rocks. The thickness of the zone of saturation in the Ogallala varies throughout the Southern High Plains chiefly because of the uneven nature of the bedrock surface. This thickness ranges from 0 to more than 300 feet.

The coefficient of transmissibility of the Ogallala formation ranges rather widely. Tests at Amarillo indicate a coefficient of 6,000 to 7,000 gpd per ft (gallons per day per foot) and tests in the vicinity of Plainview indicate a transmissibility of about 34,000 gpd per ft. Numerous tests both in the laboratory and in the field indicate a specific yield of about 15 percent.

The movement of water in the Ogallala formation is generally toward the southeast in the general direction of the slope of the water table. The water table slopes roughly parallel to the slope of both the bedrock and land surface, the average slope of the water table being about 10 feet per mile. The rate of movement in the formation in the vicinity of Plainview has been estimated to be about 2 inches per day.

The fluctuations of the water table in the Ogallala formation represent chiefly changes in the amount of water in storage. The trend of the fluctuations throughout the Southern High Plains has generally been a decline that reflects the large quantities of water withdrawn for irrigation. Locally, however, water-level rises have been recorded and indicate recharge at least in some areas.

The depth to water in the Ogallala formation is affected by the topography of the land surface, the proximity to areas of recharge or natural discharge, the proximity to areas of withdrawal of water, and the configuration of the bedrock surface. In 1958, the depth to water in the formation ranged from less than 50 feet to more than 250 feet.

The principal sources of ground-water recharge to the formation in the Southern High Plains of Texas are underflow from New Mexico and precipitation on the land surface in Texas. The amount of underflow is unknown; it is probably small but relatively constant from year to year. The amount of recharge from precipitation depends on many factors including the amount, distribution, and intensity of precipitation and type of soil and vegetative cover. Various estimates of the amount of recharge indicate that it is probably less than one-half an inch annually.

Artificial recharge experiments have been conducted in many parts of the High Plains using the water that collects in the playa lakes during periods of high rainfall. The method of recharge has been by injection through wells drilled near the lakes. A study of the availability of lake water on the High Plains in a sample area consisting of parts of four counties showed that, in an area containing 1,348 lakes, nearly 200,000 acre-feet of water was caught in 1957, a year of above-normal precipitation. In 1958 when the rainfall was below normal, the lakes caught approximately 37,000 acre-feet of water. Experiments have shown that perhaps as much as 80 to 90 percent of the water caught in the lakes can be injected through wells to be stored in the ground-water reservoir for future use.

By far the largest use of water from the Ogallala formation in the Southern High Plains is for irrigation, most of the irrigation development having been started since 1937. In January 1937, about 600 irrigation wells were in use in the entire Southern High Plains; during the succeeding 6 years, new wells were added at rates ranging from 120 to 480 wells per year. From 1943 to 1950 about 11,000 wells were drilled, and in 1951 about 14,000 wells were in use. The development has continued during the 1950's, and in 1958 about 44,000 wells irrigated a total of about 4.3 million acres.

It is estimated that a total of about 36 million acre-feet of water has been pumped from the Ogallala formation in the Southern High Plains during the period 1938 through 1957. The estimated average yearly pumpage since 1954 has been about 5 million acre-feet. Most of the water has been pumped in what could be termed the heavily pumped areas including 11 counties where depletion of the ground-water reservoir amounted to about 26 million acre-feet from the time large-scale development of ground water began in the late 1930's to 1958.

Although these large quantities of water have been removed from the Ogallala formation, it is estimated that about 160 million acre-feet of water remained

in storage in 1958, most of this water being concentrated in the northern part of the area.

The water in the Ogallala formation in the Southern High Plains of Texas can generally be said to be of good chemical quality except that it is hard and has a high silica content. Most of the water is suitable for irrigation and meets the U.S. Public Health Service recommendations for public supplies. The water form some wells has an excessive fluoride content.

The estimated amount of water withdrawn from the ground-water reservoir each year so greatly exceeds even the most optimistic estimates of recharge that it is obvious that ground water is being "mined," that is, it is coming from storage. Without any other foreseeable source of large supplies of water except that which accumulates in the depressions, conservation and the most effective use of the remaining supplies are the only means of combating the depletion and extending the life expectancy of the ground-water supply.

INTRODUCTION

PURPOSE AND SCOPE

The purpose of this report is to evaluate and summarize the ground-water resources of that part of the Southern High Plains of Texas shown on figure 1. Special attention was given to the thickness of the saturated zone of the Ogallala formation, the principal aquifer, and to the quantity of water available to wells from that formation. A report on the ground-water resources of Carson and Gray Counties is in preparation, and for that reason those counties were not included in this report. The investigation on which this report is based was made possible through cooperation between the Texas Board of Water Engineers and the U.S. Geological Survey, and is a part of a statewide program of study of the ground-water resources.

The fieldwork of this investigation, which started in 1958, consisted principally of collecting well logs, measuring depth to water in wells, and determining the altitude of the land surface at wells used as control points for the various maps.

The section on artificial recharge was prepared by B. N. Myers, hydraulic engineer, U.S. Geological Survey, Austin, Tex. The data on which this section of the report is based were obtained during an investigation of the feasibility of using water from depression ponds to recharge the ground-water reservoir in a part of the Southern High Plains; the investigation was carried on by the U.S. Geological Survey in cooperation with the Texas Board of Water Engineers with financial assistance from the Harvest Queen Mills at Plainview, Tex.

Plate 7, which shows the approximate saturated thickness of the Ogallala formation prior to large-scale development of ground water, was prepared in cooperation with the Texas Board of Water Engineers and the High Plains Underground Water Conservation District No. 1.

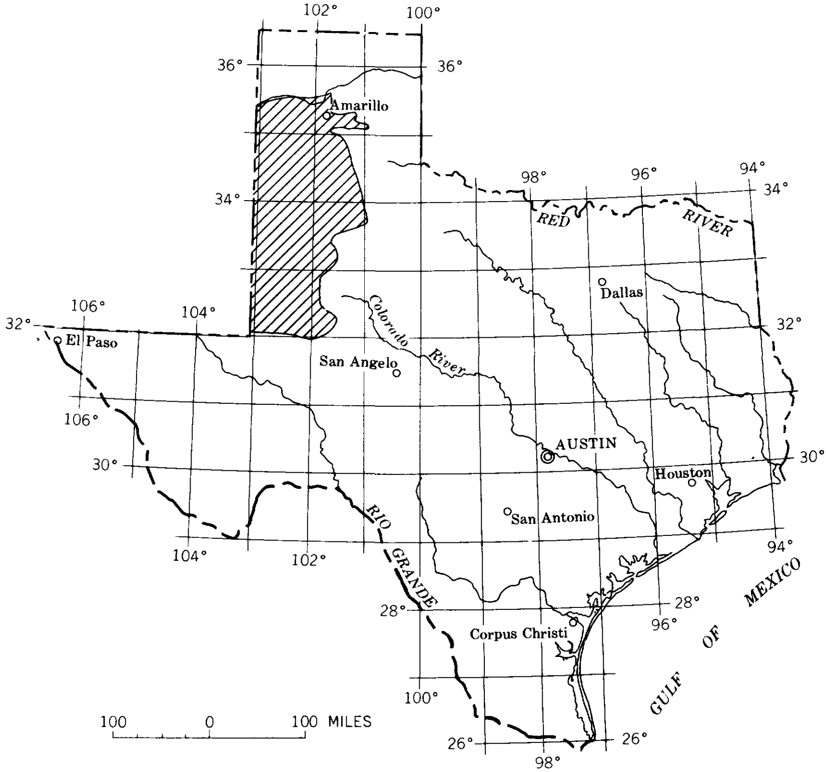

FIGURE 1.—Map of Texas showing area covered by this report.

PREVIOUS INVESTIGATIONS

The geology and, for some areas, the water resources of all or parts of the Southern High Plains of Texas have been discussed in many reports based on investigations made by various Federal and State agencies. Special aspects of the geology of the Southern High Plains also have been discussed in articles published in technical journals. Most of these reports and articles are listed in "References" (p. 83).

Between 1936 and 1946, inventories of water wells in all the counties included in this report except Cochran and Lynn were published in mimeographed form by the Texas Board of Water Engineers. These reports include well records, well logs, chemical analyses of water samples, and maps showing locations of the wells.

The depth-to-water measurements made annually in several hundred observation wells in the Southern High Plains have been reported in various publications of the Texas Board of Water Engineers. Since 1938 the annual reports of the U.S. Geological Survey on water levels and artesian pressures in the United States also have included information on the observation wells in the Southern High Plains.

The public-water supplies of the principal cities and towns in the Southern High Plains were described by Broadhurst, Sundstrom, and Weaver (1951).

Since 1936, seven progress reports on the geology and ground water in the irrigated areas of the Southern High Plains have been published by the Texas Board of Water Engineers in cooperation with the U.S. Geological Survey.

Detailed investigations of the geology and occurrence of ground water have been made in Lamb County by Leggat (1957), in Lynn County by Leggat (1952), and in Hale County by Cronin and Wells (1960).

LOCATION AND GENERAL FEATURES

The part of the High Plains of Texas described in this report occupies an area of about 22,000 square miles extending from the Canadian River southward to Glasscock and Midland Counties and from the New Mexico line eastward to a boundary which, in most places, is sharply defined by a prominent escarpment several hundred feet high. In general, the area is rectangular in shape; it averages about 250 miles from north to south and about 120 miles east to west. The area is known as the Southern High Plains; it also is commonly referred to as the South Plains. The name "Llano Estacado" is also used, this name having been given to the area by the early Spanish explorers.

The remarkably flat surface of the Southern High Plains is interrupted by minor features of relief formed by numerous shallow playas, sand dunes, and small stream valleys. The amount and direction of maximum slope of the plains surface varies somewhat in different places, but in general the surface slopes to the southeast at an average 8 to 10 feet per mile. Altitudes range from about 2,600 feet above sea level in Howard County in the southeastern part to about 4,300 feet in northwestern Deaf Smith County in the northwestern part of the area.

Shallow undrained depressions or playas are characteristic of the plains surface throughout much of the Southern High Plains. During periods of heavy rainfall, runoff collects in the depressions to form temporary ponds or lakes. There are also larger and deeper basins, some of which contain "alkali" or "saline" lakes, the high mineral content being the result of concentration by rapid evaporation of the water from the lakes.

Stream drainage of the plains surface is very poorly developed. Long shallow valleys almost devoid of tributaries extend at widely spaced intervals almost across the plains. The valleys form the headward reaches of the Red, Brazos, and Colorado Rivers. The drainage area of the intermittent streams that occupy the valleys is limited to the valley itself and narrow belts of sloping land adjacent to the valleys. Surface water accumulating in the streams ordinarily flows for only a short distance before being lost by seepage and evaporation. It is only during rare periods of excessive rainfall that water flows over the eastern escarpment, off the Southern High Plains. The Canadian River, which forms the northern boundary of the area considered in this report, is entrenched in a deep valley and is the only well-developed drainage system in the High Plains of Texas.

Deep reentrant canyons have been cut into the plains along the eastern escarpment. These canyons provide some of the best exposures of the strata underlying the Southern High Plains and also some of the most striking scenery of the area.

ECONOMIC DEVELOPMENT

The economy of the Southern High Plains of Texas has been based on the presence of fertile soil, ground water, and large quantities of oil and gas. During the early period of development, the raising of beef cattle was the principal occupation; later, dry-land farming became important. In the 1930's and 1940's large-scale irrigation began and large oil and gas pools were discovered.

The principal irrigated district is perhaps the largest intensively cultivated area in Texas, the principal crops being cotton and grain sorghums. Other crops include wheat, barley, oats, corn, sesame, and various vegetables. The raising of beef cattle and some cattle-feeding are still important to the economy of the area.

Lubbock County, having an annual production of more than 200,000 bales of cotton, has been a leading cotton-producing county in Texas for several years. Hale County, which probably has a larger proportion of its cultivated land under irrigation than any other county in Texas, is one of the leading agricultural counties in the State.

Much oil and gas are produced in several of the counties, especially in the southern half of the area. Andrews County had a production of more than 64 million barrels of crude oil and was the leading oil-producing county in Texas in 1956.

The extensive development of irrigation and industries associated with agriculture, coupled with the production of oil and gas, has been the cause of the rapid growth in population and the even greater increase in economic wealth of the Southern High Plains.

CLIMATE

The climate of the Southern High Plains is semiarid. For a long-period comparison, U.S. Weather Bureau records from stations at Lubbock, Plainview, Muleshoe, Dimmitt, and Tulia were supplemented by earlier records from the stations in the same general vicinity (fig. 2). The average annual precipitation for the area represented by these stations is almost 20 inches. The wettest year on record was 1941 when the average precipitation for the five stations was 38.40 inches; the average precipitation in 1917, the driest year, was 10.50 inches, although this was almost equaled in 1954 when the average precipitation was only 10.77 inches. The graph of the monthly distribution of precipitation (fig. 2) shows that about 70 percent of the year's precipitation generally falls during the principal growing season, April to September.

Precipitation records from U.S. Weather Bureau stations at Tahoka, Lamesa, and Seminole indicate that the average annual precipitation in the southern part of the Southern High Plains is slightly below the average indicated for the five stations of figure 2. For ex-

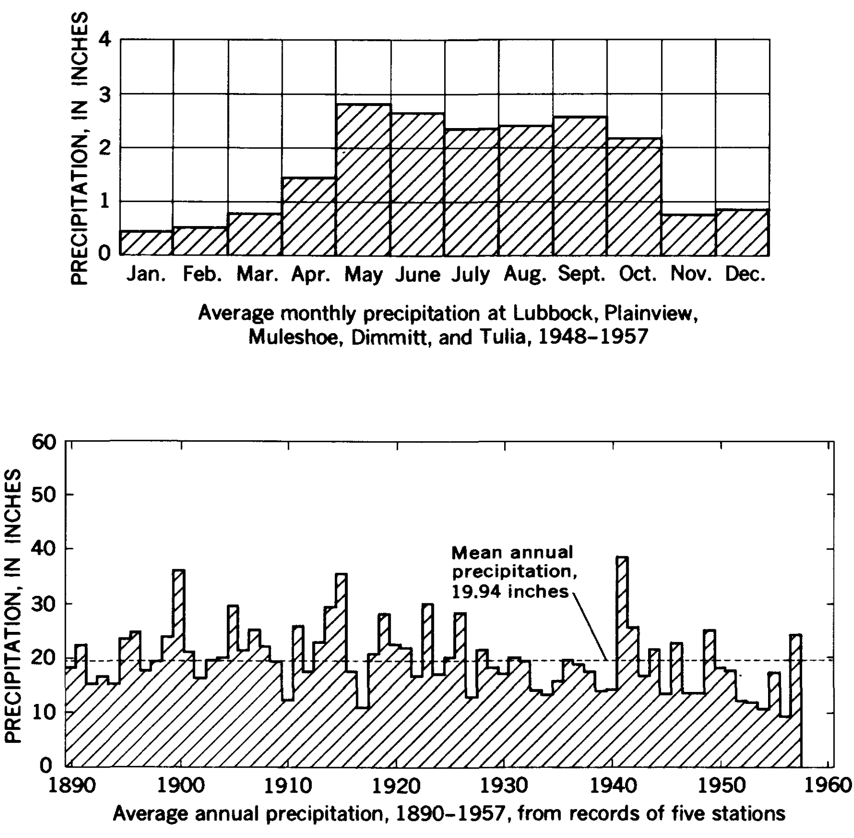

FIGURE 2.—Precipitation in the Southern High Plains of Texas (from records of the U.S. Weather Bureau).

ample, at Lamesa for the period 1911 to 1957, the average annual precipitation was 17.43 inches as compared with the 20-inch average for the five stations to the north.

The mean annual temperature at Plainview during the 57-year period 1899–1955 was 59.8°F. The average monthly temperature ranges from 78.5°F in July to 40.80°F in January. Temperatures in the southern part of the area are slightly higher than that at Plainview.

The high summer temperatures, rather low humidity, and strong breezes cause a high rate of evaporation in the Southern High Plains. Weather records indicate that the average evaporation rate is about 80 inches per year; however, the rate may be considerably higher in years when the temperature is abnormally high and the humidity low.

ACKNOWLEDGMENTS

Appreciation is expressed to the many farmers, well drillers, pump dealers, and oil companies, who generously contributed information used in the preparation of this report. Acknowledgment is also made for the information furnished by several cities and to the Texas Highway Department for information about bench marks along the highways. Special thanks are due the High Plains Underground Water Conservation District No. 1 at Lubbock for giving free access to their files of water-well logs and for other information contributed during the investigation. Recognition is given to the many individuals and business firms who contributed time and material in drilling the recharge well and observation wells and in providing other facilities for the artificial recharge tests. Particular thanks are due Dr. T. C. Longnecker, director, and his staff at the High Plains Research Foundation for their cooperation in the artificial-recharge studies.

GEOLOGY

The rocks that crop out in the Southern High Plains range in age from Paleozoic to Cenozoic, and include rocks belonging to the Permian, Triassic, Cretaceous, Tertiary, and Quaternary systems (pl. 1). Rocks ranging in age from Precambrian to Paleozoic are present in the subsurface. The geologic history of the Southern High Plains that is pertinent to this report begins with the Permian; discussion of the older rocks in the subsurface is therefore omitted. Table 1 briefly summarizes the geologic and water-bearing properties of the formations exposed in the area. Table 2 gives the estimated ages and duration of the geologic time units discussed.

GEOLOGIC HISTORY

At the beginning of Permian time the present area of the Southern High Plains was almost entirely covered by the sea. Pre-Permian rocks already had been folded and subsequently had subsided to form basinlike areas which were at least partly separated by elevated land which had been uplifted along the major structural features of the area (pl. 1). According to Hoots (1925, p. 119), subsidence in the basins probably continued throughout Permian time.

TABLE 1.—*Stratigraphic units and their water-bearing properties, Southern High Plains of Texas*

System	Series	Formation or group	Thickness (feet)	Lithologic description	Water supply
Quaternary	Recent		0- 15	Chiefly windblown sand and silt.	Yields no water to wells. Sandy areas form excellent recharge facilities.
	Pleistocene		0- 144	Sand, clay, diatomaceous earth, volcanic ash, limestone.	Mostly above water table; does not yield large supplies.
Tertiary	Pliocene	Ogallala formation.	0- 500	Fine to coarse sand and gravel; clay, silt, and caliche.	Yields large supplies of water throughout the Southern High Plains.
Cretaceous	Comanche	Washita, Fredericksburg, and Trinity groups.	0- 200+	Fine to coarse sandstone and conglomerate; limestone, blue and yellow shale or clay.	Locally important as source of small supplies of water; should not be considered as a major source of water for the Southern High Plains in general.
Triassic		Dockum group: Tecouas formation. Santa Rosa sandstone. Chinle formation equivalent.	150-1,800+	Varicolored shale and sandy shale; gray or brown cross-bedded sandstone and conglomerate.	Probably capable of yielding small to moderate supplies of water; most of the water is at least slightly saline.
Permian			8,000±	Soft red sandstone, shale, and clay; beds of gypsum and dolomite.	Not known to yield water to wells; water is probably saline.

During Permian time the basins were filled with sediments and the elevated lands also were covered by a thick series of sediments which underlies all of the Southern High Plains. The diversity in lithology of the Permian sediments indicates varying conditions of deposition. Rocks ranging from strictly marine to continental origin and various chemical precipitates, such as salt, anhydrite, and gypsum, were deposited. Marine sediments became less prevalent later in the Permian, and the deposition of evaporites and nonmarine sediments indicates an intermittent but progressive withdrawal of the sea, in

TABLE 2.—*Geologic time scale from the Permian to the Quaternary*

[Age values given are the Holmes "B" time scale points (Holmes, 1947, p. 145). Dates are rounded to the nearest 5 million years. The errors are unknown, but more recent age determinations by various physical methods are in general agreement with these values]

Era	System or Period	Series or Epoch	Estimated duration in millions of years	Estimated ages of time boundaries in millions of years
Cenozoic	Quaternary	Recent	1	
		Pleistocene		1
	Tertiary	Pliocene	9	10
		Miocene	15	25
		Oligocene	15	40
		Eocene	20	60
		Paleocene	65	
Mesozoic	Cretaceous	Upper (Late) Lower (Early)		125
	Jurassic	Upper (Late) Middle (Middle) Lower (Early)	25	150
	Triassic	Upper (Late) Middle (Middle) Lower (Early)	30	180
	Permian		25	205

general to the southwest. Uplift of the land probably accompanied or followed the withdrawal of the sea.

Erosion and deposition of continental sediments characterized the early part of the geologic history of the Mesozoic era in the Southern High Plains. During early and middle Triassic time, the area was subjected to erosion. In Late Triassic time, continental sediments of the Dockum group, were deposited. Hoots (1925, p. 125-126) suggests that subsidence of the basin areas occurred during Triassic time.

The Southern High Plains area was apparently subjected to erosion throughout all or much of the Jurassic period. Nonmarine sediments of this age, which are present in Quay County, N. Mex. (Dobrovolny, Summerson, and Bates, 1946, sheet 2) a few miles west of the Texas-New Mexico State line, have not been found in the Southern High Plains of Texas. Their absence may possibly be due to nondeposition, but they may have been subsequently removed by erosion along with some of the Upper Triassic rocks prior to the deposition of the Lower Cretaceous strata.

In Early Cretaceous time the sea advanced from the southeast across the Southern High Plains and deposited sediments belonging to the Comanche series. Following the deposition of these sediments, the sea withdrew, and thus ended the last marine transgression of this area. Extensive erosion during Late Cretaceous and early Cenozoic time removed a part of the Triassic and Cretaceous rocks, the latter being entirely removed from a part of the area (fig. 3).

During Late Cretaceous time and at intervals throughout much of Cenozoic time, orogenic movement, uplift, and volcanic activity were taking place in the area to the west and northwest of the Southern High Plains in New Mexico and Colorado. These widespread and repeated orogenies resulted in the development of the Southern Rocky Mountains and the mountain ranges to the south of them in New Mexico and Texas. Baker (1915, p. 22) has suggested that the southeast dip of the Mesozoic rocks of the Southern High Plains, which, according to King (1959, p. 128), developed prior to the deposition of the Ogallala formation, was the result of tilting of the area probably during the early stages of these orogenies.

The Cenozoic era was marked in the Southern High Plains by erosion and by the deposition of continental sediments derived largely from the rising mountains to the west and northwest. The building of the Southern High Plains was climaxed and the destruction and physiographic isolation of the plains began during the Cenozoic era.

The Southern High Plains was probably being eroded during most of Tertiary time until the Pliocene epoch, when streams flowing eastward from the recently uplifted mountains to the west and northwest deposited sediments of the Ogallala formation on the eroded surfaces of the older rocks. Stream deposition ceased, probably near the end of middle Pliocene time, when the plains surface had been aggraded to nearly its present level. The surface of this alluvial plain remained in a state of near equilibrium, probably through late Pliocene. The caprock caliche, which is conspicuously exposed along the plains escarpment, probably started to form at or near the surface during this period of equilibrium.

Events in the geologic history of the Southern High Plains during Quaternary time include cycles of erosion and sedimentation of streams and, according to Evans (1956, p. 16), "The formation and retreat of bounding escarpments, with consequent physiographic isolation of the Llano Estacado, took place mainly during the Pleistocene epoch. Deep reentrant canyons also formed during the Pleistocene and there is evidence that canyon-cutting took place mainly during intervals of accelerated erosion interrupted by long intervals of relative stability."

Baker (1915, p. 59) described the events that resulted in the formation of the bounding escarpment and physiographic isolation of the Southern High Plains as follows, "Then the Pecos River cut its valley on the west and south sides of the Plains, the Canadian River cut through the Plains on the north, separating the Llano Estacado from the rest of the High Plains, and the various tributaries of the Red, Brazos and Colorado Rivers cut back on the east. Today the Llano Estacado is a high, eastwardly-sloping plateau or mesa, separated by its bounding escarpment or 'breaks' from the lower, more eroded plains which surround it." Frye and Leonard (1957, p. 37–38) estimated that the eastern plains escarpment had retreated to its approximate present position by Kansan time, near the middle of the Pleistocene epoch.

The plains surface was modified during the Pleistocene and Recent epochs by the widespread deposition of eolian sands, by the accumulation of sediments in basin areas (the origin of which has been discussed by Evans and Meade, 1945, p. 486–490, and by Frye and Leonard, 1957, p. 22, 32), and by alternating erosion and deposition along the stream valleys which were probably shallow in most of the main plains area but became deeper as they approached the deep canyons along the escarpment.

PERMIAN SYSTEM

Rocks of Permian age underlie all the Southern High Plains and are the oldest rocks that crop out in the area (pl. 1). They occur at the surface only at the northern and northeastern edges of the escarpment and in the canyons of the larger streams that have cut through the overlying formations. They may be seen at the edges of the escarpment in Armstrong and Donley Counties, in the Tule Canyon in northern Briscoe County, and at several places in the Canadian River Valley.

The exposed Permian rocks belong to the Whitehorse group and consist mainly of soft red sandstone, shale, and clay, gypsum ledges, and a few beds of dolomite. The exposed thickness of these rocks is at least 300 feet in some places. In the areas where Permian rocks are exposed beneath Triassic rocks, it is difficult to distinguish between the two because of the close resemblance of the upper part of the Permian rocks to the overlying Triassic rocks. Baker (1915, p. 18–19) has suggested several means of distinguishing between the Triassic and Permian rocks, among which are the occurrence of flakes of mica in the Triassic sandstones and the presence of conglomerate beds in the Triassic; neither the mica flakes nor the conglomerate beds occur in the underlying Permian rocks. The color contrast between the light brick-red of the Permian shales and the deep maroon of the Triassic shales is also a distinguishing feature.

Although rocks of the Permian system crop out in only a small part of the Southern High Plains and only a small part of the Permian section is exposed in these outcrops, many facts concerning the geologic history and formations of the Permian system are known from the results of drilling of deep tests for oil. The total thickness of the Permian rocks underlying the Southern High Plains is as much as 8,000 feet in places.

At no place on the Southern High Plains is water known to be pumped from the Permian formation, and any water available from these formations would probably be saline.

TRIASSIC SYSTEM

DOCKUM GROUP

The beds of the Dockum group, considered to be of Late Triassic age, lie unconformably on the eroded surface of the Permian rocks throughout the Southern High Plains, except in the extreme northeastern part (parts of Armstrong and Donley Counties) where the Triassic rocks are absent, probably due to erosion subsequent to deposition rather than to nondeposition. Triassic rocks crop out along the eastern plains escarpment from Armstrong to Howard Counties, in the valley of the Canadian River along the northern and northwestern margins of the Southern High Plains, and as scattered outcrops in the interior of the plains mainly in the southern part (pl. 1). Most of these scattered outcrops are small and, therefore, are not shown on the geologic map.

The beds of the Dockum group are of continental origin and were probably laid down as river-channel and flood-plain deposits. Adams, as quoted by Adkins (*in* Sellards, Adkins, and Plummer, 1932, p. 241) suggests that the Dockum beds were deposited in a basin which underwent folding both before and after the Triassic deposition. The general dip of the Triassic rocks in the Southern High Plains is reported by Adkins (*in* Sellards, Adkins, and Plummer, 1932, p. 247) to be to the southeast and to average 8 feet per mile.

The thickness of the Triassic rocks ranges from about 150 feet as measured in an outcrop in the Canadian Rivery valley (Gould, 1907, p. 22) to more than 1,800 feet in western Terry County as reported by Jones (1953, p. 42). Depth to the Triassic beds ranges from a featheredge adjacent to the outcrops to 500 feet or more in parts of Parmer, Castro, and Floyd Counties.

Several investigators have subdivided the "Dockum beds" since they were first described and named by Cummins (1890, p. 189) from the type locality at Dockum, Dickens County, Tex. Drake (1892, p. 225–235) studied the Triassic rocks along a section extending northward from Big Spring to the vicinity of Amarillo and thence westward to near Tucumcari, N. Mex., and subdivided them into three units. Gould (1907, p. 21–29), working in the Texas Panhandle, subdivided the Dockum group into two formations—a lower, consisting largely of shale, the Tecovas; and an upper, composed mainly of sandstone and conglomerate and interbedded shale, the Trujillo. Hoots (1925, p. 89) subdivided the Dockum group in the southern part of the Southern High Plains into two more or less distinct formations, as follows: "* * * a lower one with a maximum thickness of 275 feet, characterized by red clay and numerous beds of massive gray cross-bedded sandstone * * * and an upper one with a maximum thickness of 175 feet or more, consisting almost entirely of red clay." Concerning the Dockum group in the southern part of the area, Adams (1929, p. 1045) stated, "In the area south of the 33d parallel the Dockum consists of red and non-red conglomerate, sandstone, and shale beds of terrestial origin. An examination of the series in well samples shows that it is composed of two formations. The names Santa Rosa and Chinle, as used for the Triassic of central New Mexico, are extended to include the equivalent formations in the Texas section." Regarding the nomenclature used in describing the subdivisions of the Dockum group, Reeside and others (1957, p. 1477–1478) said, "The currently used threefold division of the Dockum into Tecovas Formation, Santa Rosa Sandstone, and 'Chinle' Formation was introduced by Adams (1929), who correlated the Santa Rosa Sandstone of eastern New Mexico with the Trujillo Sandstone of Gould (1907, p. 26–29), in the Canadian River valley and Palo Duro Canyon, Texas. Current opinion holds the Trujillo, Santa Rosa, and the 'Middle sandstones' of Drake (1892) to be correlative." In this report the Dockum group will be considered to be composed of three formations, given here in ascending order as, Tecovas formation, Santa Rosa sandstone, and Chinle formation equivalent.

TECOVAS FORMATION

The Tecovas formation was described by Gould (1907, p. 23–26) from exposures in the vicinity of the Canadian River valley and Palo Duro Canyon, Tex. The Tecovas is the basal formation of the Dockum group lying uncomformably on the underlying Permian rocks.

Gould (1907, p. 23) described the Tecovas formation as follows: "It is divided lithologically into two parts, distinguished by the texture and color of the rocks. Of these, the lower is composed of more or less sandy shale of various colors, with maroon, lavender, yellow, and white predominating, and the upper of dark-red or magenta shale." F. E. Green (written communication, 1954) has suggested that Dockum sedimentation could have been initiated by slight subsidence in the areas where Tecovas sediments are found, and he suspected that these areas were limited or controlled by older tectonic frameworks, because the Tecovas formation is absent in the Tucumcari region, N. Mex., where the Santa Rosa sandstone is the basal unit and very thin in the Canadian River valley. Furthermore, the Tecovas formation appears to attain its maximum thickness in an area roughly similar to the Plainview (Palo Duro) basin (pl. 1); it thins rapidly to the south in the neighborhood of the Matador arch, where it is absent locally, and becomes thicker southward in Crosby and Garza Counties. According to Reeside and others (1957, p. 1478), shales below the Santa Rosa sandstone in the Midland basin (fig. 3) were indentified as Tecovas, but more recent petrographic studies by D. N. Miller, Jr. (written communication, 1955), strongly suggest that these beds should be assigned to the underlying Late Permian. The exposed thickness of the Tecovas formation in the Southern High Plains ranges from 90 feet along the Canadian River to 220 feet in Palo Duro Canyon (Gould, 1907, p. 23).

SANTA ROSA SANDSTONE

In this report the Trujillo formation named by Gould for exposures on Trujillo Creek, Oldham County, Tex., is included as a part of the Santa Rosa sandstone. F. E. Green (written communication, 1954) indicates that the contact between the Tecovas and the Santa Rosa sandstone (Trujillo) is conformable in many places, but in some places such as the Lingos Falls vicinity where the Santa Rosa rests on Permian rocks, there is evidence of an erosional unconformity.

The Santa Rosa sandstone (Trujillo) consists of massive gray or brown crossbedded sandstone and conglomerate that contains interbedded red and gray shales, according to Gould (1907, p. 26–27). The exposed thickness indicated in measured sections by Gould (1907, p. 22–29) ranges from less than 50 feet at places in the Canadian River valley to more than 200 feet in the vicinity of Palo Duro Canyon in eastern Randall County.

In the southern part of the Southern High Plains where the Santa Rosa sandstone overlies the Tecovas(?) formation and underlies the Chinle formation equivalent, Jones (1953, p. 42) has reported the formation to consist of medium to coarse subangular arkosic gray calcareous conglomeratic sandstone interbedded with soft red and green shale. The average thickness of the formation is about 350 feet, but it may have a maximum thickness of 600 feet or more (Adams, 1929, p. 1052).

CHINLE FORMATION EQUIVALENT

The beds of the Chinle formation equivalent are considered to be absent from the the northern part of the Southern High Plains (Sellards, Adkins, and Plummer, 1932, p. 251). In the southern part, they overlie the Santa Rosa sandstone and are overlain by Cretaceous or Cenozoic rocks.

The Chinle formation equivalent in the Southern High Plains has been described by Jones (1953, p. 42) as follows: "The Chinle consists mainly of brick red to maroon and purple shale. Green and gray mottlings and yellow streaks are common * * * Thin beds of red or gray sandstone, commonly micaceous, and of finer texture than those of the Santa Rosa are common. Cream or red limestone occurs as nodules in the shale, or locally in beds several feet thick * * * The thickest section of Triassic is in western Terry County, where the beds above the Santa Rosa are about 1,800 feet thick."

WATER SUPPLY IN THE TRIASSIC ROCKS

The water supply in the Triassic rocks in the Southern High Plains has been discussed by Sellards and Baker (1934, p. 396), who said, "The quality of the Triassic waters is likewise uncertain. At least in some places the lower Triassic waters contain deleterious mineral constituents derived from the underlying Permian. For instance, the deep wells in Hale County, Texas, report salty water from the Triassic sands."

According to Broadhurst, Sundstrom, and Weaver (1951, p. 136–138), four wells owned by the city of Canyon in Randall County pumped water for municipal use in 1947 from an aquifer in the Dockum group. The depth of each well was approximately 500 feet, and the static water level given for one well was 250 feet below land surface. The yields of the wells ranged from 150 to 450 gpm (gallons per minute). The chemical analysis of a composite water sample from the four wells showed the dissolved-solids content to be 390 ppm (parts per million), somewhat less than reported in analyses of water from the Dockum group in most places. The wells are in the vicinity of Palo Duro Canyon where rocks of the Dockum group crop out along the canyon walls.

Leggat (1957, p. 13) in discussing the possibility of developing a water supply from the Dockum group in Lamb County also described several tests of the Dockum in adjoining and nearby counties as follows:

> Although the sandstones of the Dockum group have not been completely penetrated by water wells in Lamb County, electric logs of tests for oil and gas indicate the presence of water too highly mineralized for irrigation or public use. Similar information regarding the quality of water in the Dockum was obtained from several exploratory wells drilled in Floyd, Lubbock, Bailey, and Cochran Counties. The chemical analysis of a sample of water from a well drilled into the Dockum group by the city of Lubbock in 1949 showed 35,000 ppm of dissolved solids and 12,000 parts of chloride. The water was obtained from

the Santa Rosa sandstone of the Dockum group at a depth of 900-940 feet. A well testing the sandstone in southwestern Floyd County yielded water that contained 13,700 ppm of dissolved solids and 7,320 parts of chloride. The yield of this well decreased from 250 to 150 gpm after 72 hours of pumping. An exploratory well testing the Dockum group 1 mile west of the Lamb-Bailey county line was reported to have yielded an insufficient supply of water for irrigation after a 10-minute period of pumping. The chemical analysis of a drill-stem sample of water from the Dockum group in Cochran County showed 2,070 ppm of dissolved solids and 590 parts of chloride. However, in a preliminary pumping test the well yielded only 15 gpm and had a specific capacity of 0.3 gpm per foot of drawdown.

Available data suggest that the water in the Dockum group in Lamb County is too highly mineralized for most purposes, but that the mineralization decreases toward the area of outcrop in New Mexico. The yield of the Triassic sandstones in general, is insufficient for irrigation, municipal, or industrial supplies.

The water-yielding properties of the Dockum group were tested in southwestern Floyd County in a well drilled to a depth of 800 feet. This was a carefully controlled test in which the water in the overlying Ogallala formation was sealed off by cementing the casing at the Ogallala-Triassic contact. A 6-inch-diameter deep-well turbine-type pump set at 480 feet was used during the test, and after it was pumped for a total of about 14 hours, a sample of water was collected for chemical analysis. The results of the analysis showed 6,020 ppm dissolved solids, 3,020 ppm chloride, and 2,170 ppm sodium. Broadhurst (1957c, p. 4) in summarizing the results of the test has said, "(1) the static water level stood 290 feet below the land surface; (2) with a pumping level of 480 feet, the well produced only 75 gallons of water a minute; and (3) the water was too salty for irrigation."

An irrigation well drilled to a depth of 767 feet about 6 miles northeast of Hereford in Deaf Smith County is believed to be pumping water from an aquifer in the Dockum group. The driller's log of this well shows the Ogallala-Triassic contact to be at 215 feet below land surface. Red and blue shale and "rock" mainly are indicated between 215 and 680 feet; from 680 to 755 feet the log indicates 34 feet of gravel, 7 feet of rock or large gravel, and 34 feet of gravel, all colors. "Red bed," which is a term used especially by drillers to describe the Triassic or Permian shale, is logged between 755 and 767 feet. The Triassic rocks are probably about 1,000 feet thick in this vicinity; it is assumed, therefore, that the well was bottomed in rocks of the Dockum group.

Casing was cemented at 680 feet to seal off the water from the overlying formations. The static water level was reported to be 378 feet below land surface, and the yield of the well, after being pumped for an unknown period of time, was reported to be about 700 gpm.

A sample of water was obtained from the well during bailing operations and a second sample was collected after the well had been pumped for 5 hours. Both samples of water were analyzed in the laboratory of the Geological Survey in Austin; the results of the analysis show that the water contained 775 ppm of dissolved solids, 37 ppm of chloride, and 275 parts of sodium. The sodium content was computed to be 96 percent of the equivalents per million of the positive ions, which on most soils would be considered objectionable in water used for irrigation.

The quantity and quality of water available from aquifers in the Dockum group in Andrews County has been discussed by Long (1957, p. 8) who said:

> The yield of the Triassic sands is low to moderate. Sand lenses in the Chinle yield only meager supplies from depths ranging between 700 and 1,100 feet below land surface. Sands in the Santa Rosa sandstone yield moderate amounts of water from depths ranging between 1,100 and 1,800 feet below land surface * * *
>
> Because of relatively high mineralization, water from the Dockum group is suitable mainly for stock use and certain industrial uses. It is undesirable for culinary and general household uses, but because it is the only supply available in some local areas, it is so used. Industrial uses of Santa Rosa water include oil field drilling and reservoir flooding.
>
> Laboratory analyses of samples from five wells that tap the Santa Rosa sandstone were made by the U.S. Geological Survey. The results of these five analyses, together with three supplied by oil companies, are given * * *. The total dissolved-solids content ranges from 1,554 to 2,720 parts per million, and the chloride content from 286 to 948 ppm.

Although it is realized that the Dockum group has been tested in only a few places, the information currently available indicates that the yield of wells pumping from aquifers in this group would range from low to moderate and that the water would be rather saline, probably unsuitable in most instances for irrigation or public supply and perhaps limited to certain industrial uses.

CRETACEOUS SYSTEM

The Cretaceous rocks are represented in the Southern High Plains by sediments belonging to the Trinity, Fredericksburg, and Washita groups. These sediments were laid down on the eroded surface of the Triassic rocks and, according to Brand (1953, p. 5), they dip to the southeast at the rate of 7 to 8 feet per mile.

Rocks of Cretaceous age crop out in places along the eastern escarpment of the Southern High Plains from Lubbock County to Glasscock County, along the margins of some of the deeper playa basins, and at scattered outcrops mainly in the southern part of the area.

The sea that invaded the area of the Southern High Plains during Early Cretaceous time, although probably shallow, was widespread and probably extended well beyond the limits of the present Southern High Plains. Brand (1956, p. 13) has suggested that the original Cretaceous units of this area were eroded and completely removed from parts of the area preceding the deposition of the Ogallala formation and that the remaining Cretaceous rocks consist of remnants of units which probably covered the entire High Plains and adjacent areas.

The approximate extent of the Cretaceous rocks in the subsurface in the Southern High Plains is shown on figure 3. Cretaceous rocks form buried escarpments 100 feet or more in height in places in the subsurface. Buried escarpments near Littlefield in Lamb County, in south-central Hale and north-central Lubbock County, and in southeastern Gaines County, are rather conspicuous features of the pre-Ogallala surface. Rocks of Cretaceous age crop out south of the area outlined on figure 3, and they are undoubtedly present in the subsurface in other places. However, because of the lithologic similarities of the Ogallala and Cretaceous rocks in this part of the Southern High Plains, it was impossible to separate the formations in some places.

In other parts of the Southern High Plains more or less isolated remnants of Cretaceous rocks have been found in the subsurface. The outlier of Cretaceous rocks in southeastern Hale County is composed of rocks of the Fredericksburg and Washita groups which has a maximum thickness in places of 110 feet (Cronin and Wells, 1960, p. 22, 23). Cretaceous rocks of undetermined age were identified in one well log in Floyd County. This well was drilled over a high point in the pre-Ogallala surface (pl. 2) about 6 miles north of Floydada and about 2 miles west of the Floydada-Silverton highway. It is possible that these Cretaceous rocks may correlate with the Edwards limestone of the Fredericksburg group identified by Brand (1953, p. 54) in a caliche pit about 4 miles north of Floydada on the Floydada-Silverton highway.

The thickness of the Cretaceous rocks in the Southern High Plains ranges from 0 to more than 200 feet. Leggat (1957, p. 13–14) has indicated that the Comanche series in Lamb County has an aggregate thickness of about 115 feet. Information given by Lang (1945, p. 12a–18a) shows that the thickness of undifferentiated Lower Cretaceous rocks in 4 test holes drilled by the city of Lubbock at locations 3½ and 8¾ miles northeast, 7½ miles west, and 7½ miles northwest of the post office at Lubbock, were 84, 35, 68, and 73 feet, respectively. The aggregate thickness of the Cretaceous rocks in Lynn County is reported by

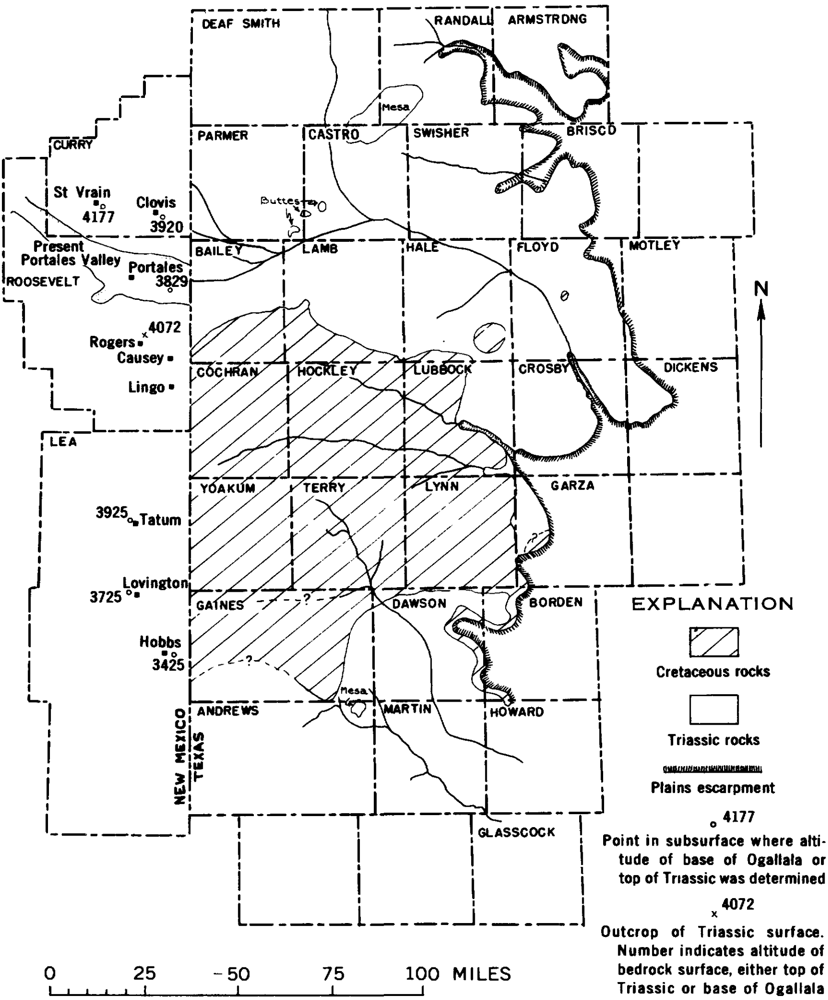

FIGURE 3.—Sketch map showing drainage and other features of the pre-Ogallala surface and subsurface extent of Cretaceous rocks.

Leggat (1952, p. 9) to be more than 200 feet. Scott and others (1941, p. 69) reported 55 feet of Cretaceous rocks in a well near Midland.

The following discussion of the Cretaceous formations was taken from reports by Brand (1953; 1956), except where other authors are cited.

TRINITY GROUP

Hill (1901, p. 132–140) considered the basal Cretaceous sands of the Southern High Plains area to be the equivalent of the Paluxy sand which is the top formation of the Trinity group near Waco and Fort

Worth, Tex. Hoots (1925, p. 98) in discussing the southern part of the Southern High Plains said " * * * In the region herein described the Trinity is composed entirely of sand, commonly conglomeratic, and the Trinity group, as the deposits to the east are called, here becomes the Trinity sand." This usage is followed in this report although other investigators have used the term Paluxy in describing the basal sand of the Cretaceous in the southeastern and southern parts of the area (Brand, 1953, p. 8; Jones, 1953, p. 42).

TRINITY SAND

The Trinity sand disconformably overlies the beds of the Dockum group. Brand (1953, p. 8) described the Trinity sand as consisting of white to purple, loosely consolidated fine- to coarse-grained well-sorted unfossiliferous quartz sandstone containing scattered lenses of quartz gravel. Livingston and Bennett (1944, p. 14) in a report on the Big Spring area reported that in some parts of the area the sandstone is cemented by silica at the outcrop, probably due to weathering, and that the cemented beds probably grade into friable sandstone beneath the land surface. They also reported lenses of red clay at scattered places in the Trinity sand and a coarse conglomerate about 5 to 10 feet thick, consisting of red and black pebbles of chert and other varieties of quartz, generally occuring at the base of the sandstone. The thickness of the Trinity sand in the Big Spring area is reported by them to range from about 60 to 100 feet. Jones (1953, p. 43) described the Trinity sand in the vicinity of Midland as consisting of as much as 80 feet of medium to coarse rounded white sand, locally very ferruginous, weathering to a rust color and containing white, black, and red pebbles scattered throughout but particularly abundant at the base.

Brand (1953, p. 27–55) measured the Trinity sand in several outcrops north of Midland, and reported 10 feet of Trinity in central Andrews County and 22 feet along the plains escarpment in southeastern Lynn County. Trinity sand is also indicated to be present in a section in the valley of the Double Mountain Fork of the Brazos River southeast of Lubbock.

FREDERICKSBURG GROUP

The Fredericksburg group in Texas is divided into four formations which are, in ascending order, the Walnut clay, the Comanche Peak limestone, the Edwards limestone, and the Kiamichi formation, all of which are present in the Southern High Plains.

WALNUT CLAY

The Walnut clay in the Southern High Plains consists of from 4 to 40 feet of light-gray to brown argillaceous sandstone, calcareous shale, and argillaceous limestone. The Walnut crops out along the southeastern and southern parts of the plains escarpment and along the northwest margin of Cedar Lake in the northeastern part of Gaines County. Traced northward from exposures in southeastern Garza County, the Walnut becomes less calcareous and argillaceous and in the northernmost exposures in southeastern Lubbock County, it consists entirely of sandstone and argillaceous sandstone. Except in southeastern Lubbock County and eastern Lynn County, where the contact is distinct between the sandstone at the top of the Walnut and the limestone of the overlying Comanche Peak limestone, the upper contact of the Walnut is gradational and must be selected on the basis of slight lithologic and faunal differences.

COMANCHE PEAK LIMESTONE

In the Southern High Plains the Comanche Peak limestone consists of yellowish-gray, thinly bedded to massive argillaceous limestone containing thin light-gray shaly interbeds. Where the formation is exposed along the plains escarpment in Lubbock, Lynn, Garza, Borden, and Dawson Counties, the thickness ranges from about 30 feet to as much as 70 feet. Isolated exposures occur in Ector County and along the margin of Cedar Lake in Gaines County where the thickness is about 38 feet. The contact between the Comanche Peak and the overlying Edwards limestone is gradational in most places and can be identified only on the basis of slight lithologic and paleontologic differences.

EDWARDS LIMESTONE

The Edwards limestone in the Southern High Plains ranges from 0 to 35 feet of hard light-gray to grayish-yellow, thickly bedded to massive, fine- to coarse-grained limestone. The Edwards crops out along the plains escarpment in southern Garza, northern Borden, and northeastern Dawson Counties. It also occurs in isolated exposures near Tahoka in Lynn County and in the wall of a caliche pit north of Floydada in Floyd County. The contact between the Edwards and Kiamichi, exposed only in the Lynn County locality, apparently is conformable.

KIAMICHI FORMATION

In the Southern High Plains the Kiamichi formation consists of dark-gray to yellowish-brown shale, light-colored clay, thin light-gray limestone, yellowish-brown sandstone, coarse gravel, and sand. The basal contact is exposed only near Tahoka in Lynn County, but upper Kiamichi beds are exposed in Lynn, Terry, Hockley, Lamb, and Bailey Counties. In discussing the Kiamichi formation in Lynn County, Leggat (1952, p. 14) has said, "Underlying most of the county * * * the Kiamichi formation ranges in thickness from a feather edge to about 100 feet and the top is encountered at depths ranging from 19 feet in southern Lynn County to about 200 feet in the northern part."

Leggat (1957, p. 13) measured 99 feet of the Kiamichi formation in an outcrop in southwestern Lamb County; reporting on the Kiamichi formation in Lamb County where the formation rests on the eroded Triassic rocks, he stated, "The basal beds of the Kiamichi formation consist of coarse gravel that grades upward through a mixture of sand and gravel into a light-gray to brown, coarse- to fine-grained sand and light-colored clay. The basal coarse-grained unit apparently thins in a northwest direction * * *"

The contact between the Kiamichi formation and the overlying Duck Creek formation is difficult to identify in most localities in the Southern High Plains. Typically, both units consist of shale and thin-bedded limestone, and although the basal Duck Creek at most places contains more limestone than the upper Kiamichi, the exact line of contact cannot be determined.

WASHITA GROUP

DUCK CREEK FORMATION

Beds of the Duck Creek formation, exposed in Lynn, Terry, Hockley, Lamb, and Bailey Counties, consist of yellow shale and thin yellowish-brown limestone, ranging in thickness from 0 to 36 feet. In Lynn County the basal bed is composed of light gray argillaceous limestone, whereas in Hockley, Lamb, and Bailey Counties, this limestone is absent or poorly developed. Leggat (1957, p. 14) measured 16 feet of the Duck Creek in an outcrop in southwestern Lamb County.

WATER SUPPLY IN THE CRETACEOUS ROCKS

The Cretaceous rocks yield water to wells in a few areas in the southern part of the Southern High Plains. The production of water from Cretaceous rocks in southeastern Hale County is discussed by Cronin and Wells (1960, p. 23) as follows, "Cretaceous rocks yield water in amounts as much as 900 gpm * * * to wells from cracks or caverns in the limestone * * *. Aquifiers in the Cretaceous limestones presumably are recharged through the overlying Ogallala formation * * *." Water is being produced under similar conditions in north-central Lubbock County. Leggat (1957, p. 12) reported that small quantities of moderately mineralized water are obtained from sands and gravels in the Kiamichi formation in the southern part of Lamb County.

Rocks of Cretaceous age in Lynn County are not considered to contain an important supply of water; however, Leggat (1952, p. 21) reported that a public-supply well immediately south of the Lynn-Dawson county line is believed to be producing water from a localized porous zone in the Edwards limestone. The total depth of the well is reported to be 27 feet. Because the quality of water is unlike that of water normally obtained from limestone, it is believed that the water may have moved along crevices in the limestone from the Ogallala formation, other Cretaceous rocks, or local accumulations of evaporites. The well was pumped at the rate of 810 gpm on July 13, 1950; it had a drawdown of 0.69 foot and a computed specific capacity of 1,175 gallons per minute per foot. The results obtained from this test are indicative of a cavernous condition in the aquifer.

Some of the irrigation wells in the western, southwestern, and southern parts of Lubbock County draw water from the Ogallala formation and from the underlying Cretaceous rocks. However, in referring to these wells, Lang (1945, p. 27a) stated, "Although the water in the Ogallala is rather hard in some localities it is suitable for irrigation and municipal use, whereas the water in the underlying rocks is, in general, meager and quite highly mineralized."

The Causey-Lingo area in Roosevelt County, N. Mex., adjoins Bailey and Cochran Counties, Tex., on the west. Cooper (1959, p. 32–33) in discussing the ground-water resources of the area has said, "Only a few wells obtain appreciable amounts of water from formations thought to be a part of the consolidated Cretaceous rocks * * *. The principal water-bearing formation in the area is the unconsolidated sand and gravel aquifer of Cretaceous age in the erosion channels in the underlying Triassic red beds in the southern part of the Causey-Lingo area." These channels cut in the Triassic rocks may extend into the adjoining counties in Texas where ground water may occur under similar conditions.

Undoubtedly some water is pumped from Cretaceous rocks in the southern counties of the Southern High Plains where it was impossible to separate the Ogallala formation from the Cretaceous rocks because of lithologic similarity; however, the amount of water pumped from Cretaceous rocks in that area is probably not large.

The lithologic characteristics of some of the Cretaceous rocks indicate that they would not yield water in large quantities, and the sand and gravel seem to be somewhat erratic in occurrence. Furthermore, much of the water obtained from Cretaceous rocks is slightly saline. Locally, where sufficient water is not available from other sources, water from aquifers in the Cretaceous rocks may be important even though the quality of the water may be inferior and the quantity available may be small. However, for the Southern High Plains as a whole, the aquifers in the Cretaceous rocks probably do not constitute an important source of water for large-scale use for irrigation, municipal, or other purposes.

TERTIARY SYSTEM

CONFIGURATION OF THE PRE-OGALLALA SURFACE

The Cenozoic rocks of the Southern High Plains overlie an erosional surface cut in Cretaceous, Triassic, and Permian rocks. The configuration of this buried surface is shown by means of contours on the base of the Ogallala formation (pl. 2). A knowledge of the configuration of this bedrock floor is useful in determining the thickness of the overlying formation and in studying the ancestral drainage pattern which had an important bearing on the mode of deposition of the Ogallala formation. A sketch map which shows in simple form the principal drainageways and prominent features of the pre-Ogallala surface in the Southern High Plains (fig. 3) was prepared from detailed information shown on plate 2.

Delineation of the base of the Ogallala formation is based on drillers' logs of water wells, logs of test holes drilled by various interests to explore the Ogallala formation for special purposes, logs of shot holes, and, in a few places, the exposure of the contact between the Ogallala and underlying rocks.

Because of the time and expense involved in properly collecting and examining samples, drillers' logs do not ordinarily show in detail the lithologic changes in the Ogallala formation. Nevertheless, because of the contrast between the Ogallala and underlying rocks, the contact is in most places readily recognized. Where the Ogallala overlies Cretaceous rocks, the drillers' term "yellow and blue clay" is usually indicative of the Cretaceous rocks, and where the Ogallala is underlain by Permian or Triassic rocks, the term "red beds" usually indicates the red shale or clay of the underlying formation. The use of the term "redbeds," however, must be examined carefully in some places where red clay is present in the Ogallala, otherwise a false bedrock contact (red bed) may be identified.

More than 3,000 logs were collected and examined in selecting control points for the delineation of the bedrock floor. In general, the quantity and quality of the logs available were adequate except in some places in the southern counties where it was necessary to interpret the position of the contours from relatively few points.

The altitude of land surface was supplied with the shot holes and with a few of the other logs. For the remainder of the logs used as control points, the surface altitudes were determined by spirit leveling or by altimeter or were interpolated or taken directly from topographic maps; all surface altitudes were referred to mean sea level.

The altitude of the point on the bedrock floor was determined by subtracting the depth to the base of the Ogallala from the land-surface altitude at that point.

Geologic sections showing the thickness of the geologic formations and the relations of some of the prominent features of the bedrock floor are shown on plate 3. The north-south section (*B–B′*) shows that the altitude of the Triassic rocks ranges from about 3, 660 feet above sea level in southern Randall County on the north to about 2, 800 feet at the Andrews-Midland county line on the south, the distance between these points being about 180 miles. The noteworthy features along this line are the buried Triassic high which centers approximately at the junction of the Randall-Castro county line, and the broad buried valley extending from about 12 miles south of the Randall-Castro county line to a point about 10 moles north of the Lamb-Hockley county line where the bedrock floor rises abruptly and the Triassic rocks are overlain by Cretaceous rocks. North of this point the Ogallala formation overlies Triassic rocks, whereas in general to the south to about the Gaines-Andrews county line, the Ogallala overlies Cretaceous rocks. The greatest thickness of the Ogallala formation (about 400 feet) along the line of the section is in the low point of the buried valley immediately north of the Lamb-Castro county line.

The altitude of the Triassic rocks along the east-west section (*A–A′*, pl. 3) ranges from about 3,810 feet at the west end of the section to about 2, 660 feet at the east end, the distance between these points being about 115 miles. The line of the section passes through a part of the "sandhill" area that extends eastward from Bailey County to Hale County, and the surficial mound shown in eastern Bailey County is due to the presence of the sandhills.

Several irregularities are shown in the bedrock floor along the east-west section, the most conspicuous being the Triassic high capped by Cretaceous rocks in southeastern Hale County immediately west of the Hale-Floyd county line. The thickest section of the Ogallala formation along the line of the section is a few miles east of the Hale-Floyd county line where the formation reaches a thickness of about 400 feet.

The lateral extent of the features of the bedrock surface shown along the sections may be seen on plate 3. The contour lines show that the main channel of the buried valley shown on section *B–B′* (pl. 3) extends in a general easterly direction from northern Bailey County across the southern part of Castro County to about the junction of the Castro-Swisher county line with the north line of Hale County. The channel then continues southeastward across Hale

County to about the Hale-Floyd county line cast of Plainview. From this point the channel continues in a more southerly direction between the high points in the bedrock surface southeast of Hale Center in Hale County and north of Floydada in Floyd County. The lower reach of this buried channel in Floyd and Crosby Counties occupied somewhat the same area as the present day White River.

The Portales Valley in Roosevelt County, N. Mex., adjoins Bailey County, Tex. (fig. 3). Theis (1932, p. 114) has suggested that the Portales Valley coincides, in part at least, with a valley in the underlying red beds. In discussing the history of the Pecos River, Fiedler and Nye (1933, p. 99) have said, "It is probable that the part of the present Pecos River above Fort Sumner (New Mexico) once continued southeastward across the Llano Estacado through the Portales Valley and that it was established before the beginning of the Pleistocene and was instrumental in the construction of the northern part of the Llano Estacado." In view of these statements it was decided to make some attempt, with such information as was available, to investigate the relation of the bedrock surface in the vicinity of the Portales Valley in Roosevelt County, N. Mex. to the bedrock surface in the adjoining area of the Southern High Plains in Texas.

Data from Theis (1932, p. 157) Erickson (1954, p. 11–35), and from topographic maps permitted computation of the altitude of the base of the Ogallala at several points in Curry and Roosevelt Counties, N. Mex., which adjoin Parmer, Bailey, and Cochran Counties in Texas. The contours on the base of the Ogallala, as shown on plate 2, were extended from these control points into parts of the above-named counties in New Mexico. A report by Cooper (1959, pl. 1) on the Causey-Lingo area south of the Portales Valley in Roosevelt County, N. Mex., was also studied and the map showing the contours on the top of the Triassic was compared with plate 2 of this report.

This cursory investigation of the bedrock surface in parts of Roosevelt and Curry Counties, N. Mex., indicates that the conspicuous buried ridge in western Deaf Smith County has receded to the west in the vicinty of the Portales Valley. The extent of this retreat may be roughly estimated from the altitude of the top of the Triassic at the town of St. Vrain, 25 miles west of the Texas-New Mexico state line, which is 4,177 feet (fig. 3). Thus, the 4,100-foot contour shown in the southwest corner of Deaf Smith County on plate 2 would be extended in a southwesterly direction beyond St. Vrain to about the center of the Portales Valley. The altitude of the Triassic rocks that crop out near the town of Rogers, south of the Portales Valley and about 10 miles west of the Texas-New Mexico state line, is 4,072 feet (fig. 3), and indicates that the 4,100-foot contour would be drawn close to this point.

The fact that the buried Triassic ridge, as outlined above, has retreated to the west in the vicinity of the Portales Valley is an indication that the buried valley shown on section *B–B′* of plate 3 and described on page 27 extended westward into New Mexico from the Southern High Plains of Texas. Because of insufficient data, it was not possible to determine definitely if the gradient of the bedrock surface had increased to the west in New Mexico or to delineate a definite channel in the buried valley in New Mexico.

If Fiedler and Nye (1933, p. 99) are correct that prior to the Pleistocene epoch the part of the present Pecos River above Fort Sumner, N. Mex., continued southeastward across the Llano Estacado through the Portales Valley, then the main channel of that stream across the Southern High Plains of Texas probably coincided with the main channel of the buried valley as described on page 27. The main channel of the buried valley is shown on figure 3.

The contours on the bedrock surface (pl. 2) show that bluffs which are composed of Triassic rocks capped by Cretaceous rocks are present in several places along the buried Triassic-Cretaceous contact (fig. 3), for example, in the vicinity of the midpoint of the Hale-Lubbock county line. In other places along the line, the transition from a bedrock surface of Cretaceous rocks to a Triassic bedrock surface occurs without any sharp topographic break in the bedrock surface.

The drainage pattern on the bedrock surface underlain by Cretaceous rocks is different from that underlain by Triassic rocks. In the area underlain by Triassic rocks, drainage is centered chiefly around a main channel which, as described above, extends in a general east-southeasterly direction across the Southern High Plains. In the area underlain by Cretaceous rocks, the contours show a moderately rolling surface characterized by shallow troughs which served as drainageways.

The Cretaceous rocks have been removed from all of Dawson County except for narrow strips along the northern edge of the county and along the plains escarpment in the eastern part (fig. 3). The rocks were probably removed by erosion along a broad shallow drainageway which extended in a southeasterly direction from Terry County through Lamesa in Dawson County and northeastern Martin County to the vicinity of the city of Big Spring in Howard County. In Martin County, a channel, having a depth of at least 100 feet in places, was cut in the bedrock surface in approximately the same area occupied by the present-day Mustang Draw (pl. 2).

It was not within the scope of this investigation to study the structural geology of the Southern High Plains and the extent to which the older tectonic frameworks and crustal deformation influenced the development of the bedrock surface. Nevertheless, it is pertinent to point out that the abrupt rise in the bedrock floor in southern Lamb County and the bluff about midpoint on the Hale-Lubbock county line (pl. 2) approximately overlie the Matador Arch (pl. 1), a structural feature formed prior to Permian time. The main drainage channel cut in the Triassic bedrock surface parallels, at least in part, but does not directly overlie what has been assumed to be the axis of the Palo Duro (Plainview) basin, also a structural feature developed prior to Permian time. Baker (*in* Reed and Longnecker, 1932, p. 6), in a foreword to a report on the geology of Hemphill County, Tex., said, "* * * it is reasonable to infer from effect to cause that the Amarillo uplift [pl. 1] was upfolded and the Anadarko Basin [pl. 1] downfolded contemporaneously with the last Cordilleran orogeny, which was just previous to, or in part contemporaneous with, the Lower Pliocene sedimentation." It seems reasonable to assume that if downfolding occurred in the Anadarko Basin on the north side of the uplift, the same thing may have occurred in the Palo Duro (Plainview) basin (pl. 1) on the south side of the uplift. If this assumption is true, then it might be speculated that events that affected the development of the pre-Ogallala bedrock surface of this area occurred as follows: Following the deposition of the Cretaceous rocks and the retreat of the sea, orogenic movements occurred in the area to the west and north of the Southern High Plains, and as a result the area of the Southern High Plains was tilted to the southeast. The area was then eroded and some of the Cretaceous rocks were removed until, as inferred by Baker, the Amarillo uplift was raised and, as assumed by the present author, the Palo Duro (Plainview) basin was downwarped. The Palo Duro (Plainview) basin area then became a focal point of drainage in the Southern High Plains area and the remaining Cretaceous rocks and perhaps some of the Triassic rocks were removed by erosion. The southern part of the Southern High Plains was left as a generally southeast-sloping surface underlain by Cretaceous rocks.

OGALLALA FORMATION

The Ogallala formation, named by Darton (1898, p. 732–742) from a type locality in western Nebraska, is considered to be of Pliocene age and underlies almost all the Southern High Plains of Texas. It rests unconformably on the eroded surfaces of Permian, Triassic, and Cretaceous rocks. The formation consists chiefly of sediments deposited by streams that had their headwaters in the mountainous regions to the west and northwest, although, as discussed below, perhaps a small part of the sediments were from a local source.

Previous investigators of the Cenozoic deposits in this and adjoining areas in Texas have described and given local names to these deposits. In some reports both Tertiary and Quaternary sediments were included under one name, and locally the deposits were subdivided into units which were probably identifiable only in one particular locality and which were not applicable to the deposits of the entire area. For further information concerning the history of these investigations and terminology used prior to 1932, the reader is referred to the work of Plummer (*in* Sellards, Adkins, and Plummer, 1932, p. 763–776).

Evans (1956, p. 17–22) has proposed that the Ogallala formation be considered a group and that it include the Couch and Bridwell formations which he has described from localities in Crosby and adjoining counties. Frye and Leonard (1957, p. 14–18; 1959, p. 21–26) have subdivided the Ogallala formation in the Southern High Plains into biostratigraphic units on the basis of fossilized remains of plants represented for the most part by preserved fruits or hulls of seeds found in the formation.

As used in this report, the Ogallala formation includes the Tertiary sediments considered to be of Pliocene age overlying the Permian, Triassic, and Cretaceous rocks and underlying the Pleistocene and Recent deposits.

In general the Ogallala formation is thicker in the northern part of the area than in the southern part. The thickness ranges from 400 to 500 feet in the thickest sections in east-central Parmer, west-central Castro, and southwestern Floyd Counties to 0 where the formation wedges out against older rocks.

The Ogallala formation consists of red and yellow clay, silt, fine to coarse gray and buff sand, gravel, and caliche. From a study of 537 drillers' logs of wells in Deaf Smith, Hale, Floyd, Swisher, and Lubbock Counties, Barnes and others (1949, p. 12) concluded that 68 percent of the saturated material in the Ogallala formation between 72 and 350 feet below the surface is sand.

Drillers' logs of wells serve many purposes and have been very helpful in this investigation. Nevertheless, it must be recognized that some of these logs are based on the "feel" of the drill, on the rate of penetration, and on somewhat cursory inspection of cuttings. Most of the wells in the Southern High Plains are drilled with rotary drills, and the time and expense involved in collecting representative samples would be prohibitive and, for most purposes, unnecessary. Such logs as are available may not give in sufficient detail the association of the various lithologic elements; for example, many logs indicate that some gravel is present in the basal part of the formation. Drillers' logs do not usually indicate whether the gravel is clean and well sorted or whether sand and silt are associated with it. Such information is important in a study of ground-water conditions because the finer sediments, if present, would fill the interstices between the gravel so that the hydrologic properties of the gravel might be less favorable than the same properties of a well-sorted, though finer, sand.

Frye and Leonard (1957, p. 40–51) have published measurements of several geologic sections along the eastern plains escarpment. Some general conclusions concerning the lithology of the Ogallala formation in the Southern High Plains may be drawn from a study of these sections: The formation is composed principally of fine to coarse sand, the fine to medium grades predominating. Silt is commonly associated with the fine- or medium-grained sand in the upper part of the section, but the same type of material may be present in the basal part of the same or other sections. Coarse-grained well-sorted sand generally occurs in the lower part of the formation. Gravel is present at the base of the formation in many places where it is commonly associated with sand and silt, and may be cemented; gravel is also present as lenses or interbedded with sand at other horizons. The sand, gravel, and silt are, in part, unconsolidated and, in part, cemented, in most places irregularly and in varying degrees. Caliche occurs throughout the formation as stringers, as disseminated nodules, as a concentration of nodular material as much as 3 to 5 feet thick, and in single or multiple layers in the uppermost part of the formation at many places.

Barnes and others (1949, p. 12) indicated that because the Ogallala formation becomes increasingly sandy towards the base, the lower beds may have greater permeability and storage capacity. Because of the heterogeneous character of the sediments, the present author believes that, if the above-cited geologic sections measured by Frye and Leonard can be assumed to be typical of the Ogallala formation throughout the Southern High Plains, then it is unwarranted to assume that the permeability and storage capacity would be greater in the lower beds.

As noted above, the sand, gravel, and silt in the Ogallala formation are in part unconsolidated and in part are cemented, chiefly by calcium carbonate. The cementation occurs irregularly throughout the formation and the degree of cementation ranges from well cemented to loosely cemented. Leggat (1957, p. 15) has noted that reported information indicates that in the vicinity of Littlefield (Lamb County) the sands are cemented and of relatively low permeability and yield insufficient water for public-supply wells, but in other areas the finer sands are loose and subject to caving.

Observations of the formation made at many places by the author and the examination of several hundred drillers' logs of wells throughout the Southern High Plains and the above cited geologic sections measured along the eastern plains escarpment by Frye and Leonard indicate that the individual beds or lenses of silt, sand, gravel, and clay are not continuous over wide areas. Instead, as illustrated by Leggat (1957, pl. 2), the individual beds or lenses generally pinch out or grade, perhaps imperceptibly, both laterally and vertically into the finer or coarser material of another bed or lense. A possible exception to the above might be the caprock caliche which occurs at or near the surface throughout much of the Southern High Plains.

Most authors of reports describing the Ogallala formation of the Southern High Plains of Texas agree that the larger part of the sediments of this formation were derived from rocks in the mountains to the west and north and that these sediments were transported by streams having their headwaters in the same vicinity as the source terrain.

However, there have been some differences of opinion concerning the method of deposition of the Ogallala. Plummer (*in* Sellards, Adkins, and Plummer, 1932, p. 769) indicated that these sediments, beginning as alluvial fans at the mouths of the mountain streams, spread outward until they eventually coalesced to produce a broad alluvial apron. Baker (1915, p. 26-28) in discussing the deposition of the later Cenozoic (Ogallala) said, "They were deposited as alluvial materials brought down by rivers having their sources in the Rocky Mountain regions * * *. As the mountains were worn lower by erosion and less debris, as a consequence, could be gathered by streams in their headwaters regions, the alluvial slopes formerly piled up at the sites of emergence upon the plains of streams from the mountains, would be dissected and their materials shifted farther and farther out on the plains." On the basis of studies made in Kansas (Frye, Leonard, and Swineford, 1956) and the High Plains of Texas, Frye and Leonard (1959, p. 7) stated, "These data lead clearly to the conclusion that the mechanism of Ogallala deposition was not that of alluvial fan building but rather was one of valley alluviation * * *. In any case it seems certain that earliest deposition occurred along significant segments of the major valleys but did not reach into the mountains, and if it reached a point of contact with marine sediments in the Gulf, it did so at few places." Some investigators such as Baker (1915, p. 29) have suggested that during dry periods the winds may have aided the deposition by shifting the finer materials from one place to another.

The deposition of the Ogallala formation has been variously interpreted as being due to reduced gradient of streams, climatic conditions such as an arid climate in the plains area, tectonic movements, or a combination of any of these. Even to attempt to determine the merits of any of these depositional theories or causes of deposition would exceed the scope of this report.

However, the methods suggested above by Baker and by Frye and Leonard are somewhat similar, and if it is assumed that the sediments were deposited in accordance with either one of these methods, the likely place to expect a stream to enter this area from headwaters in the mountainous area to the west and north would be in the vicinity of the Portales Valley in Roosevelt County, N. Mex. (p. 29). If this is true, then alluviation possibly started along the channel that was cut through the northern part of this area from Bailey County to Floyd County and beyond, as described on page 27.

A small part of the sediments of the Ogallala formation probably was derived from local sources. Frye and Leonard (1957, p. 40-51) have reported in sections measured along the eastern plains escarpment the presence of fragments of Triassic and Cretaceous rocks in the lower part of the Ogallala formation, generally near the basal contact.

Lang (1945, p. 8a), discussing the results of test drilling in Lubbock County, said, "* * * In the test holes west of Lubbock the Ogallala sands consist of poorly sorted grains of limestone and quartz, apparently derived mostly from reworked Cretaceous rocks." Leggat (1952, p. 14) indicated that the basal part of the Ogallala formation in Lynn County consists of coarse gravel and sand intermixed with water-worn Cretaceous fossils. The presence of these fossils may indicate a nearby source, otherwise, owing to their friable nature, they probably would have been destroyed if transported a long distance by streams. In discussing the presence of Cretaceous fossils in the gravels of the Southern High Plains, Baker (1915, p. 24) said, "Their presence also shows either that previous to the deposition of the later Cenozoic, high-level gravels covered the surface of mid-Cenozoic time, or else that an uplift or warping in the region of the Llano renewed processes of erosion at the same time that streams were bringing deposits derived from the newly uplifted Rocky Mountain region * * *."

An inspection of the bedrock topography shown on plate 2 shows that within the area now underlain by Cretaceous rocks (fig. 3) the slope of the bedrock surface is in general to the east and southeast. If erosion of the Cretaceous rocks occurred, the sediments would be transported in the direction of the slope of the bedrock surface, that is, to the east and southeast. Erosion of the Cretaceous rocks and redeposition could, therefore, have been taking place at the same time that sediments from the mountainous region to the west and north were being deposited, as assumed above, along the west-east channel in the northern part of the area. Furthermore, if the Palo Duro

(Plainview) Basin was downwarped after the Cretaceous rocks had been removed, then any gravel left on the mid-Cenozoic surface, as suggested by Baker, would have been removed with the Cretaceous rocks. However, within the area of the remaining Cretaceous rocks, some gravel could have remained on the surface; thus, in the vicinity of the west-east channel, extending from Bailey County to Floyd County in the northern part of the area, the basal part of the Ogallala formation may have been deposited in a different manner than in at least part of the area where the Cretaceous rocks were present.

WATER SUPPLY IN THE OGALLALA FORMATION

The Ogallala formation is the principal water-bearing formation in the Southern High Plains of Texas. It is the major source of water for irrigation, public supply, industry, rural domestic use, and stock-watering purposes.

White, Broadhurst, and Lang (1946, p. 385–386) indicated that the Ogallala formation in this area is hydrologically isolated when they wrote, "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 both of these segments, 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." This fact has been illustrated by Barnes and others (1949, pls. 2, 3).

Additional information concerning the occurrence of ground water in the Ogallala formation, configuration of the water table and movement of water, hydrologic properties of the Ogallala formation, quantity of water in storage in the Ogallala formation that is available to wells, the development of ground water, and quality of the ground water are given on pages 39–81.

QUATERNARY SYSTEM

PLEISTOCENE SERIES

In general, the Pleistocene deposits in the Southern High Plains overlie the Ogallala formation; however, in places along the eastern plains escarpment, the Pleistocene deposits are reported by Frye and Leonard (1957, p. 30–51) to rest unconformably on Triassic and Permian rocks. The fact that Evans and Meade (1945, p. 503–506) have listed 28 localities in the Southern High Plains where vertebrate fossils of Pleistocene age have been found indicates that Pleistocene deposits are much more widespread in the area than has been generally recognized. Frye and Leonard (1957, p. 20–36) have reported on the presence of molluscan faunas (fossil snails) of Pleistocene age at several localities in the Southern High Plains.

The main types of Pleistocene deposits as indicated by Evans and Meade (1945, p. 486) are lake or pond, stream-valley and wind deposits. The deposists consist mainly of sand, clay, diatomaceous earth, bentonitic clay, volcanic ash, and fresh-water limestone. The maximum thickness of Pleistocene deposits in measured sections along the eastern plains escarpment is 144 feet (Frye and Leonard, 1957, p. 40–51); the average thickness is considerably less, perhaps one-half or less of the maximum.

The Pleistocene deposits in most places are above the water table, and are not known to yield large quantities of water to wells. However, because of the porous character of the sands, which are hydrologically continuous with the deposits of the underlying Ogallala formation, they may, where present in advantageous places such as stream channels, act as recharge areas.

RECENT SERIES

Deposits of Recent age occur in the Southern High Plains of Texas as sheets of windblown material, sand dunes, and valley fill. The sheets of windblown material consist principally of sand and silt covering wide areas and ranging in thickness from 0 to 15 feet or more.

One of the largest sand-dune areas in the Southern High Plains extends eastward from the New Mexico state line across central Bailey and Lamb Counties into west-central Hale County where it terminates a few miles east of the Lamb-Hale county line. The dune area is about 9 miles wide in Bailey and much of Lamb County and becomes narrower to the east; it is only about 4 miles wide in Hale County. Leggat (1957, p. 16) has described the sand dunes in Lamb County as follows: "They generally form a superficial covering and are made up of actively migrating dunes and older, stabilized modified dunes. The active dunes are characterized by the typical dune topography, absence of vegetation, and a light-gray color, whereas the older dunes are characterized by a lower and rolling surface and a characteristic reddish-orange color, and they are anchored by vegetation. The dunes are not of great height; few are more than 40 feet high." Other sandhill areas occur in the Southern High Plains, generally in the southern and western parts.

Around the eastern and southeastern margins of some of the larger playa lakes, dune ridges have formed from material blown out of the lakes during prolonged dry periods. They commonly consist of sand, silt, and in places, crystals of selenite (gypsum).

The valley-fill deposits of Recent age are found in the channels of streams that have been cut in the plains surface. Evans and Meade (1945, p. 500) indicate that the deposits consist mainly of humic-stained sand and clay and have a thickness of perhaps 5 feet. Leggat (1957, p. 16) has reported that at one place in Lamb County deposits of Recent age have filled the stream channel of the Double Mountain Fork of the Brazos River and cover seeps that formerly issued at the surface.

The sediments of Recent age generally are above the water table, and, therefore, do not yield water to wells. However, the deposits serve as catchment areas for precipitation and thus aid in the recharge of the Ogallala formation. This fact is especially true of the sand-hill areas because the sand absorbs precipitation rapidly and allows little or no runoff; the areas are thus exceptionally favorable for intake or recharge to the ground-water reservoir.

CALICHE

The term "caliche" has widely divergent meanings in different parts of the world. According to Howell (1957, p. 42), the definition of caliche as used in the southwestern United States, is, "gravel, sand or desert debris cemented by porous calcium carbonate; also the calcium carbonate itself."

The caliche underlying much of the surface of the Southern High Plains of Texas is more resistant to erosion than the underlying beds, and it forms the caprock along the plains escarpment. It also crops out around the margins of some of the larger lakes and along some of the stream valleys.

Leggat (1957, p. 16) indicated that the caliche in Lamb County ranges in thickness from 0 to about 30 feet and consists principally of calcium carbonate, bands of secondary silica, and variable amounts of sand and clay. The caliche varies from a soft white chalky or powdery material to a hard mass. In places the caliche contains channels formed by the solvent action of percolating water and, in places, the caliche has a coarse platy texture and is strongly fractured and distorted.

The following discussion of caliche has been taken from a report by Brown (1956, p. 1–15), who studied the caliche deposits in the northern part of the area considered in this report. The majority of his observations were made at or close to the eastern plains escarpment where the caliche profile is deepest and least disturbed.

Caliche occurs as single, double, or, in a few places, multiple layers, each consisting of relatively unindurated caliche grading upward into indurated caliche. The caliche commonly rests upon uncemented gravel, sand, and silt of the Ogallala formation, but where the Ogallala is missing, the caliche rests directly upon the older rocks.

The caliche in the Southern High Plains of Texas can be divided into two main types: indurated and friable. However, in undisturbed sections this arbitrary division is not valid because the caliche grades from a soft calcareous earthy zone at the base of the soil through a semiconsolidated friable form into the indurated caliche forming the caprock.

The friable form is principally a structureless porous semiconsolidated rock, normally containing water. In the field, filled animal burrows cause some variation in the appearance. The friable caliche varies in color from dull white to salmon, but upon exposure it becomes somewhat case-hardened and darker in color.

The completely indurated caliche, the caprock, is principally a massive, very durable rock in undisturbed sections. It occurs in structureless or banded forms, has no bedding, and weathers into fragments of irregular size and shape. It varies in color from grayish white to light brownish red. The porosity of the indurated caliche varies from 25 to 40 percent and is the result of microscopic and submicroscopic openings. The permeability of the indurated caliche is very low.

Quartz is by far the predominant clastic mineral in the caliche. The binding material of the caliche is a mixture of calcium carbonate and silica in the form of opal. The opal predominates by a ratio of 3 to 1, but examples exist where either is present alone.

Brown presented arguments to prove that the caliche could not have been deposited by surface waters (lakes and streams) or evaporation of ground water, and concluded that the caliche of the northeastern part of the Southern High Plains is a result of long-continued soil processes operating in an eolian aggrading profile. The mechanics of formation appear to be as follows: The wind and rain bring in all the materials that ultimately form the soil and its associated caliche, and deposit these materials on the soil surface. The calcium carbonate and silica gel are leached downward by percolating rainwater and deposited as a subsurface evaporite, largely as molds around roots and organisms that separated the clastic particles. This inception of lithification may be interrupted and the deposits destroyed by descending water following heavy rains, but eventually they will become permanent.

The caliche underlies most of the surface of the Southern High Plains and, therefore, is an important factor to consider in appraising the recharge to the ground water reservoir. The foregoing discussion of the caliche taken from a report by Brown (1956, p. 1–15) indicates that the indurated caliche in the area covered by his study has a very low permeability. If it can be assumed that the permeability of the indurated caliche throughout the Southern High Plains is of the same order of magnitude as in the area investigated by Brown, then it can be concluded that, because of the low permeability, the indurated caliche, where present, would probably impede the infiltration of water from the surface.

The friable caliche is porous and, although definite proof is not available, it is possible that in some places the caliche may be of such composition and permeability that it would not hinder the infiltration of recharge from the surface.

The permeability of the indurated caliche was determined by laboratory methods. Such factors as fractures in the rock, boreholes by rodents, and solution channels would not be considered in laboratory determinations of permeability, but they might be of some importance in a study of recharge by infiltration from the surface.

The caliche generally is not considered a source of water in the Southern High Plains. Nevertheless, Lang (1945, p. 11a–20a) reported the presence of porous caliche in the saturated section of several test holes in the vicinity of the city of Lubbock. He also reported the presence of some hard, relatively impermeable caliche layers in the saturated section of some of the test holes. Leggat (1952, p. 15–17) has indicated that in a small area in northern Lynn County, a group of shallow wells 60 to 90 feet deep draw water from honeycombed silicified caliche. The thickness of the caliche ranges from 23 to 71 feet.

The caliche in the Southern High Plains ranges in thickness from 0 to 150 feet or more; however, the average thickness throughout the plains area probably is much less than the maximum. The caliche apparently has been forming intermittently since Pliocene time.

GROUND WATER IN THE OGALLALA FORMATION

SOURCE AND OCCURRENCE

The Ogallala formation is the principal water-bearing formation in the Southern High Plains, and it supplies almost all the water used for irrigation, public-supply, industrial, rural-domestic, and stock-watering purposes.

The Ogallala formation in the Southern High Plains of Texas and the adjoining part of New Mexico has been hydrologically isolated from the surrounding areas by erosion. The source of the ground water in that part of the formation in Texas is the precipitation that falls on the land surface in Texas and the water that moves into the area through the Ogallala formation from the adjoining part of New Mexico.

The aquifer or ground-water reservoir is continuous throughout much of the Southern High Plains. It is absent in such places as in the vicinity of some of the larger playa lakes where the formation has been removed by wind action and in places where the underlying consolidated rocks are above the water table.

Ground water occurs in the Ogallala formation generally under water-table conditions—that is, the upper surface of the saturated material, or water table, is unconfined and the water will not rise in wells above the level at which it is found in the formation. Locally, however, a slight artesian pressure may exist where the water is confined beneath lenticular bodies of clay of limited areal extent. Relatively impermeable clay and shale strata of Permian, Triassic, or Cretaceous age generally form the lower boundary of the aquifer. In some areas, however, for example in southeastern Hale County, the water in the Cretaceous rocks is hydrologically connected with the water in the Ogallala formation, and the Cretaceous rocks may be considered as part of the aquifer. This condition probably exists also in the extreme southern part of the Southern High Plains where the lithology of the Ogallala and Cretaceous formations are similar.

The zone of saturation occupies the space between the lower boundary of the aquifer and the water table. In this zone the pore spaces and voids in the rocks are filled with water. The pore spaces in clay and silt are generally very small, and although these rocks may store large quantities of water, they do not readily yield the water; therefore, most of the water that is available to wells from the Ogallala formation occurs in the voids of sand and gravel.

The thickness of the zone of saturation of the Ogallala formation varies throughout the Southern High Plains chiefly because of the unevenness of the bedrock surface. Plate 4 shows that the thickness of the saturated zone of the Ogallala formation in the Southern High Plains as of 1958 ranged from 0 to more than 300 feet.

HYDRAULIC PROPERTIES OF THE AQUIFER

The potential development of an aquifer is largely dependent upon its hydraulic properties, principally the ability to transmit water and the capacity to store water which is available to wells. The terms "coefficient of transmissibility" and "specific yield" are used to describe these properties. The term "coefficient of storage" is sometimes used instead of "specific yield" and where the ground water occurs under water-table conditions as it does in the Southern High Plains, the difference between the coefficient of storage and specific yield is negligible. In this report the term "specific yield" is used exclusively.

The coefficient of transmissibility is the number of gallons of water which will move in 1 day through a vertical strip of the aquifer 1 foot wide and having the height of the aquifer when the hydraulic gradient is unity (Theis, 1938, p. 894).

The specific yield of water-bearing material is the ratio of the volume of water it will yield by gravity to the bulk volume of the material drained, the ratio being expressed as a percentage or a decimal fraction.

The hydraulic properties of water-bearing material may be determined in the laboratory by testing samples collected in the field, or they may be determined in the field by analyzing data obtained during long-term pumping tests on wells. The pumping-test method under favorable conditions has advantages because, among other reasons, of the difficulty of obtaining a sample that is representative of the undisturbed water-bearing material. Previous ground-water investigations in the Southern High Plains have employed both methods; however, the pumping tests conducted prior to 1954 were generally too short in duration for an accurate determination of the coefficient of transmissibility or specific yield.

The specific yield of the Ogallala formation has been estimated by comparing the volume of water pumped with the volume of Ogallala deposits dewatered during the 3-year period 1938–41 (Alexander, Broadhurst, and White, 1943, p. 15–16). Estimates based on the assumption that there was no recharge during the period indicated the specific yield to be 14.5 percent for the "Plainview district" and 14.1 percent for the "Hereford district." By laboratory methods Barnes and others (1949, p. 41) concluded that the average specific yield of the Ogallala formation probably is greater than 15 but less than 20 percent. In 1954 and 1955, long-duration recharge tests of wells near Amarillo, Tex. (Moulder and Frazor, 1957, p. 15), showed that the coefficient of transmissibility of the aquifer ranged from 6,000 to 7,000 gpd per ft (gallons per day per foot) and the specific yield from 9 to 16 percent. A 120-day pumping test of the Ogallala formation at Plainview in Hale County indicated that the coefficient of transmissibility at the test site was between 24,000 and 38,000 gpd per ft, and was probably somewhat less than 38,000, but probably not less than 34,000 gallons per day per foot. The specific yield was determined to be between 11 and 14 percent, but probably nearer 14 (Cronin and Wells, 1960, p. 35).

In 1957 a long-duration aquifer test of about 5 months, was made at the city of Lubbock well field in Lamb and Bailey Counties. Results obtained from this test showed the specific yield of the Ogallala to be 12 percent (E. A. Moulder, written communication, 1958).

Analysis of the values obtained from the various tests, both in the laboratory and in the field, indicate that the specific yield of the Ogallala formation in the Southern High Plains is about 15 percent.

MOVEMENT OF GROUND WATER

The configuration (shape and slope) of the water table in most of the Southern High Plains of Texas is shown on plate 5 by contour lines. The altitude of the water table is the same for each point along a given contour line and the direction of maximum slope of the water table is at right angles to the line. Ground water moves in the direction of the slope of the water table. The steepness of the slope is indicated by the spacing of the contour lines: the slope is relatively gentle if the lines are far apart, and relatively steep if they are closely spaced.

The map (pl. 5) shows that in the Southern High Plains the water table slopes generally east-southeast towards the eastern plains escarpment. The slope of the water table is roughly parallel to the slope of both the bedrock surface (pl. 2) and the land surface. The average slope of the water table measured along a line extending from the New Mexico State line through the towns of Friona, Plainview, and Floydada to the eastern plains escarpment is about 10 feet per mile. The slope of the water table is almost 11 feet per mile along a line extending from the northwest corner of Gaines County to the southeast corner of Dawson County.

Uniform hydrologic conditions are generally reflected by a smoothly sloping water table, whereas differences in the recharge-discharge relation, in the permeability (capacity for transmitting water under hydraulic head) or thickness of the water-bearing material, or in the configuration of slope of the bedrock surface underlying the aquifer are reflected generally by irregularities in the slope of the water table.

The down-gradient flexure of the contours about 8 miles south of Muleshoe, Bailey County, indicate a low ridge on the water table. The ridge underlies a part of the sandhills area and probably indicates an area of recharge to the ground-water reservoir. Depressions in the water table are indicated by the up-gradient flexure of the contours in places along the eastern plains escarpment where the reentrant canyons, such as the Double Mountain Fork of the Brazos River, have cut their channels below the water table.

About 8 miles north of Floydada, Floyd County, the closed contours indicate a mound on the water table, the mound overlying a high point on the bedrock surface (pl. 2). Very little water is pumped in the vicinity of the closed contours, but a few miles to the west large quantities of water are pumped for irrigation. Since 1938, when a network of observation wells was established in the area, the decline of the water level in the two wells used as control points for the closed contours has been 2 feet and 6 feet. But in a well 3 miles west of the closed contours, the water level has declined about 89 feet since 1938. The impervious bedrock "high" has apparently acted as a dam and prevented the normal movement of the ground water in response to the pumping. Prior to the development of irrigation and large-scale pumping of water, ground water was impounded behind the bedrock high until the water table was at or above the top of the high point of the bedrock surface. As the water was pumped from the area to the west of the closed contours, the water table declined. Normally the decline of the water table in the heavily pumped area to the west of the closed contours would have spread in all directions and probably would have caused some decline of the water table in the vicinity of the closed contours even though very little water is pumped in that area. But in this instance, the cone of depression could not spread to the east because of the impervious character of the high point in the bedrock surface. Therefore, the thin section of saturated material was left on top of the high point in the bedrock surface and the water table sloped away in all directions.

The Ogallala formation is absent in some places, such as in the vicinity of some of the larger playa lakes, and some of these lakes are probably fed by ground-water discharge (Leggat, 1957, p. 22). Because of the scale of the map, it was not possible to show these and other small details in the configuration of the water-table surface. Because of insufficient data, the contours on the water table are not shown in Armstrong and Donley Counties and in places in the extreme southern part of the Southern High Plains.

The depths to water on which the altitude of the water table is based were measured, in general, at times when the wells had been idle for an extended period of time—as much as 2 to 3 months or more in many instances. For this reason the contours probably do not reflect local depressions in the water table caused by the pumping of individual wells.

Ground water moves into Texas in the Ogallala formation by underflow from New Mexico. Within the Southern High Plains in Texas, the ground water moves principally east-southeast towards the eastern plains escarpment. Locally, however, the water table may intersect the land surface in the vicinity of some of the larger playa lakes and in these areas the direction of movement is deflected toward these nearer points of discharge. Other local conditions may have an influence on the direction of movement of the ground water.

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For example, ground water moves northeastward off the low ground-water ridge south of Muleshoe in Bailey County.

Ground water moves at a rate of about 2 inches per day in the vicinity of Plainview in Hale County, according to Cronin and Wells (1960, p. 36). It is recognized that this estimate is valid only under the geologic and hydrologic conditions assumed; however, it is believed that the estimate is of the proper order of magnitude for the Ogallala formation throughout the Southern High Plains.

FLUCTUATIONS OF THE WATER TABLE

The water table rises or declines depending on various factors. Changes in altitude of the water table represent changes in the amount of water in storage. If recharge to the ground-water reservoir exceeds discharge, the water table will rise; if discharge exceeds recharge, the water table will decline. The discharge from wells is, of course, the most important among the factors controlling the decline of the water table in the Southern High Plains.

The U.S. Geological Survey in cooperation with the Texas Board of Water Engineers has measured water levels annually in several hundred wells in the Southern High Plains since 1936. Fluctuations of the water table in 39 of the wells are illustrated by hydrographs shown in figures 4–10; the locations of these well are shown in figure 11.

The wells, except for well P-1 in the sandhills of west-central Bailey County and well 6a in Gaines County, are in what could be termed "heavily pumped areas." Well B–166 in Lamb County and well B–3 in Gaines County are in well field operated by the Southwestern Public Service Co.; the former is in a well field in the sandhills area 2 miles from irrigation wells to the north and 4 miles from irrigation wells to the south; the latter is in a well field adjacent to irrigated land. Well A–2a, Randall County, is in the city of Amarillo West-Tex well field; well H–5, Martin County, is in the Colorado River Water District well field. Well 201, Castro County, and well 326, Floyd County, are in areas which have been extensively developed for irrigation only in recent years.

The pattern of the fluctuations of the water table in the Southern High Plains may be generally described as follows: Prior to 1941 the water table was lowered in what were then the heavily pumped areas at the average yearly rate of about 1 foot or less. The water-level decline was interrupted by the above-normal precipitation of 1941 which reduced the need for pumping, and in some places contributed a substantial amount of recharge to the ground-water reservoir. The downward trend of the water table started again about 1943 or 1944 and has continued in most areas at varying rates to January 1958.

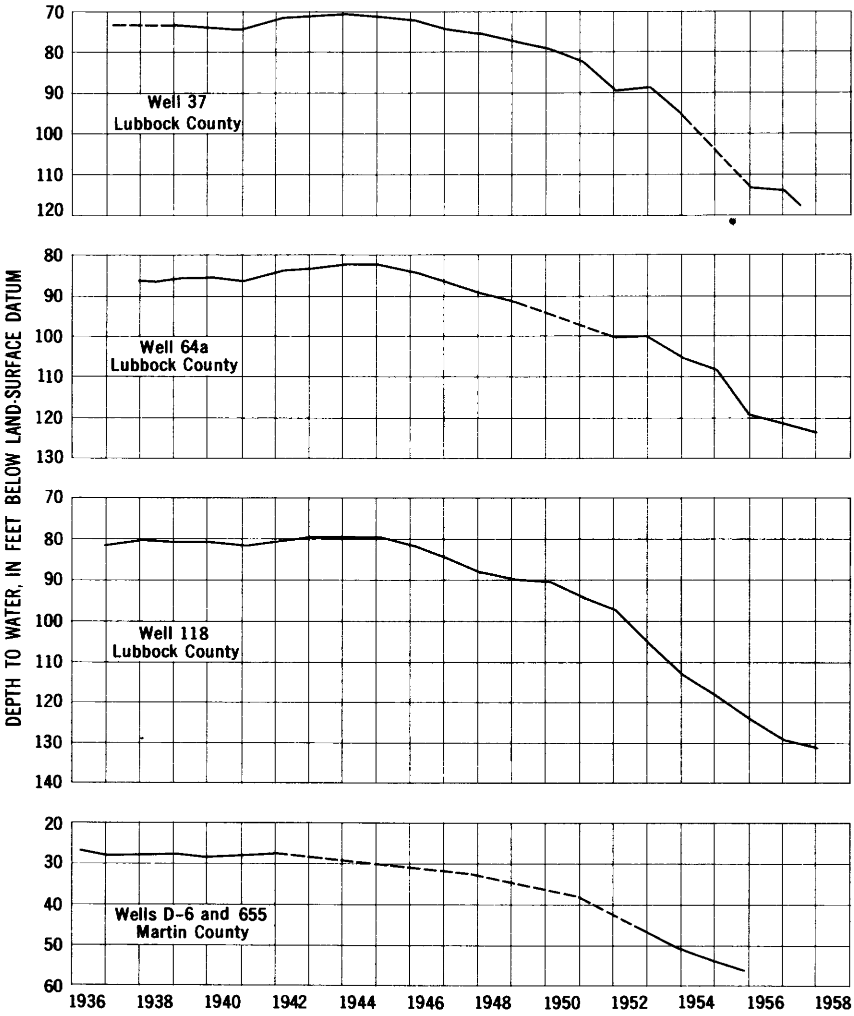

FIGURE 4.—Hydrographs of wells in Lubbock and Martin Counties, Tex.

The decline of the water table in the Southern High Plains is primarily due to withdrawal of water from the ground-water reservoir. The hydrographs show that the decline has varied in individual wells and from one area to another, at least some of the variations in decline being related to variations in the amount of water pumped.

The hydrographs of Hale County wells 407a and 164a shown in figure 9 illustrate the variation in decline within a short distance due to variation in pumpage. Each of the wells is equipped with an automatic recording water-level gage. Well 407a is near Running Water Draw inside the city limits of Plainview where geologic conditions are favor-

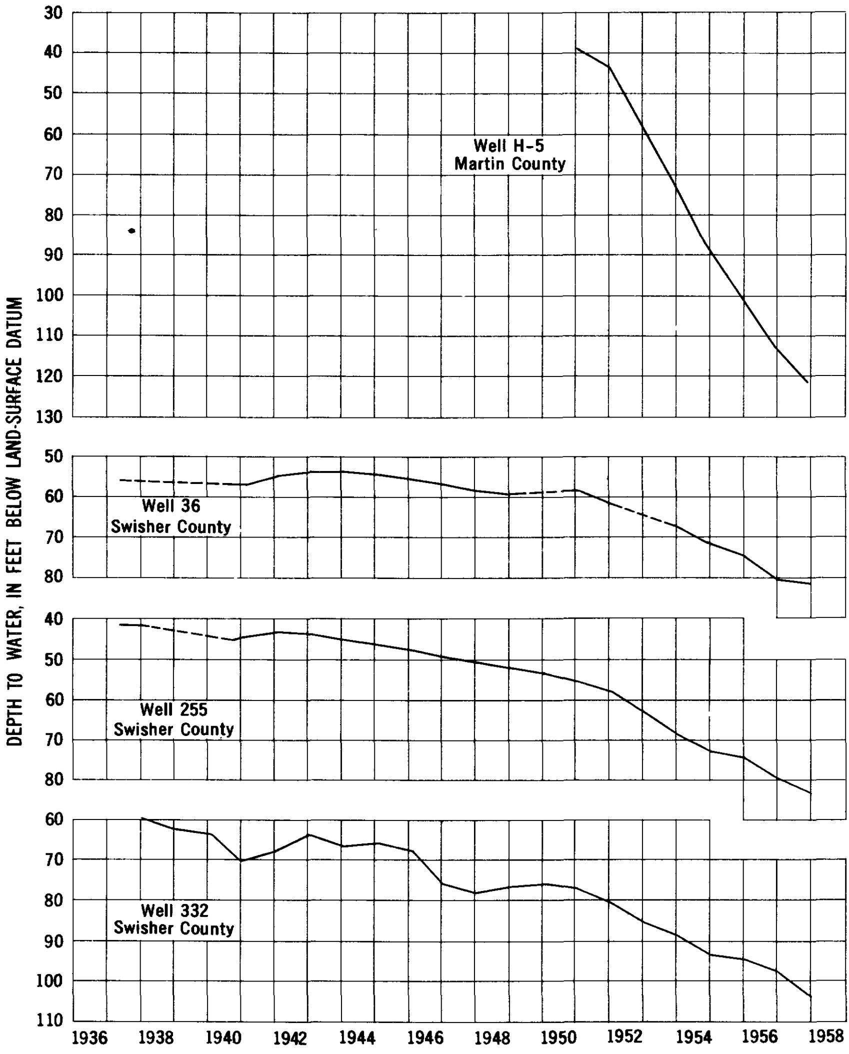

FIGURE 5.—Hydrographs of wells in Martin and Swisher Counties, Tex.

able for recharge. Well 164a is about 6 miles west of Plainview. From January 1950 to March 1955 the water table in well 407a declined at an average yearly rate of 5.01 feet. The record of well 164a, started Feb. 13, 1952, shows the average yearly rate of decline of 4.97 feet to February 1955. During the period from March 1955 to January 1958 the water table in well 407a declined at an average yearly rate of 2.80 feet, whereas the decline in well 164a averaged 5.50 feet yearly. During 1957 the water table declined 5.04 feet in well 164a compared with

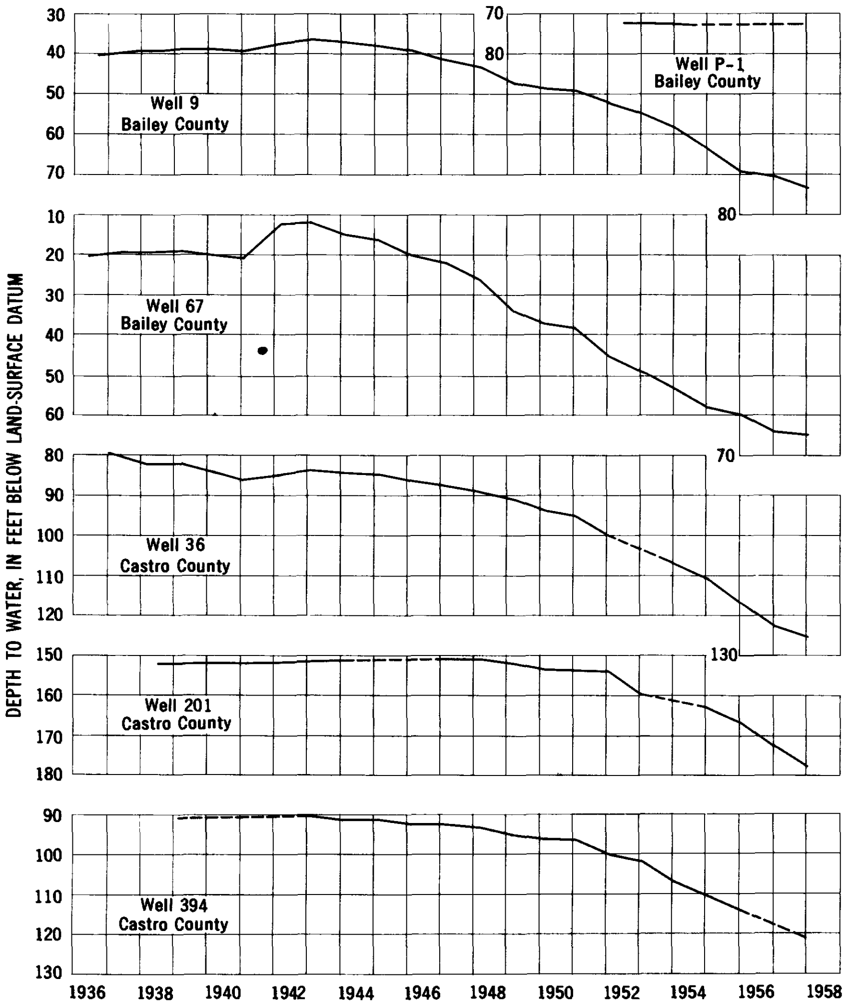

FIGURE 6.—Hydrographs of wells in Bailey and Castro Counties, Tex.

0.60 foot in well 407a. The difference in the decline of the water table in the two wells during the period from 1955 to 1958 and during the year 1957 is due primarily to a difference in rates of pumpage in the vicinity of the wells. The amount and distribution of the precipitation was such that less water was pumped in the vicinty of well 407a during 1957 and consequently the rate of decline was less than in well 164a. Because of the favorable conditions for recharge in the vicinity of well 407a, it is possible that the ground-water reservoir may also have re-

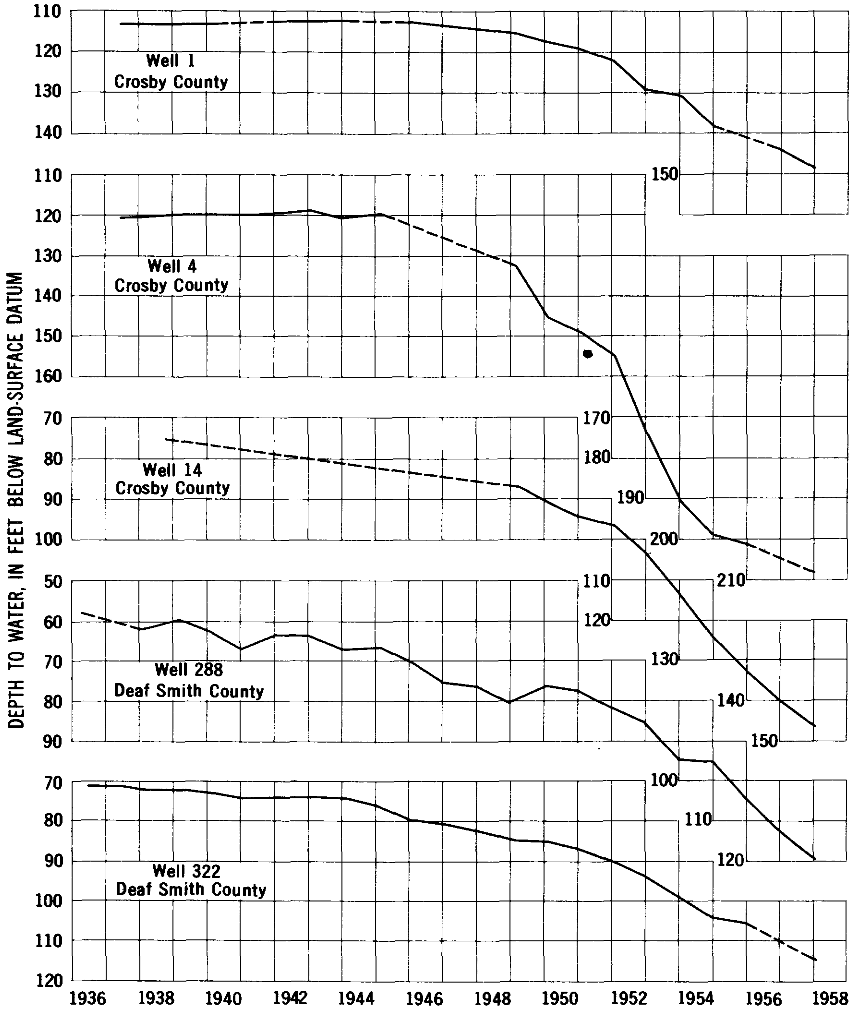

FIGURE 7.—Hydrographs of wells in Crosby and Deaf Smith Counties, Tex.

ceived some recharge from water ponded in the nearby draw after the heavy rains of 1957.

On the basis of data from the annual depth to water measurements, the average yearly rate of decline of the water table in nine counties in the Southern High Plains was computed for two 3-year and two 5-year intervals of the period of record. The number of wells used in computing the average yearly decline and the results of the computations are shown in the following table:

County	1938–41		1945–50		1950–55		1955–58	
	Wells	Average yearly decline, in feet	Wells	Average yearly decline, in feet	Wells	Average yearly decline, in feet	Wells	Average yearly decline, in feet
Northern part of Bailey	24	0.6	23	2.5	28	3.0	27	3.5
Castro	12	1.2	15	1.3	23	2.7	18	3.8
Deaf Smith	40	1.0	38	1.3	42	2.8	33	4.1
Western part of Floyd	35	1.5	26	4.3	43	5.2	43	4.8
Hale	62	1.1	53	2.4	58	4.2	78	4.9
Lubbock	33	.6	31	1.7	80	4.1	74	3.4
Swisher	24	.8	23	1.2	52	3.7	37	3.6
Hockley	5	.5	7	1.1	22	3.2	26	3.9
Lamb	17	.3	22	1.5	35	2.9	36	3.8
Parmer	(1)	(1)	(1)	(1)	10	1.1	9	3.9

[1] Record incomplete.

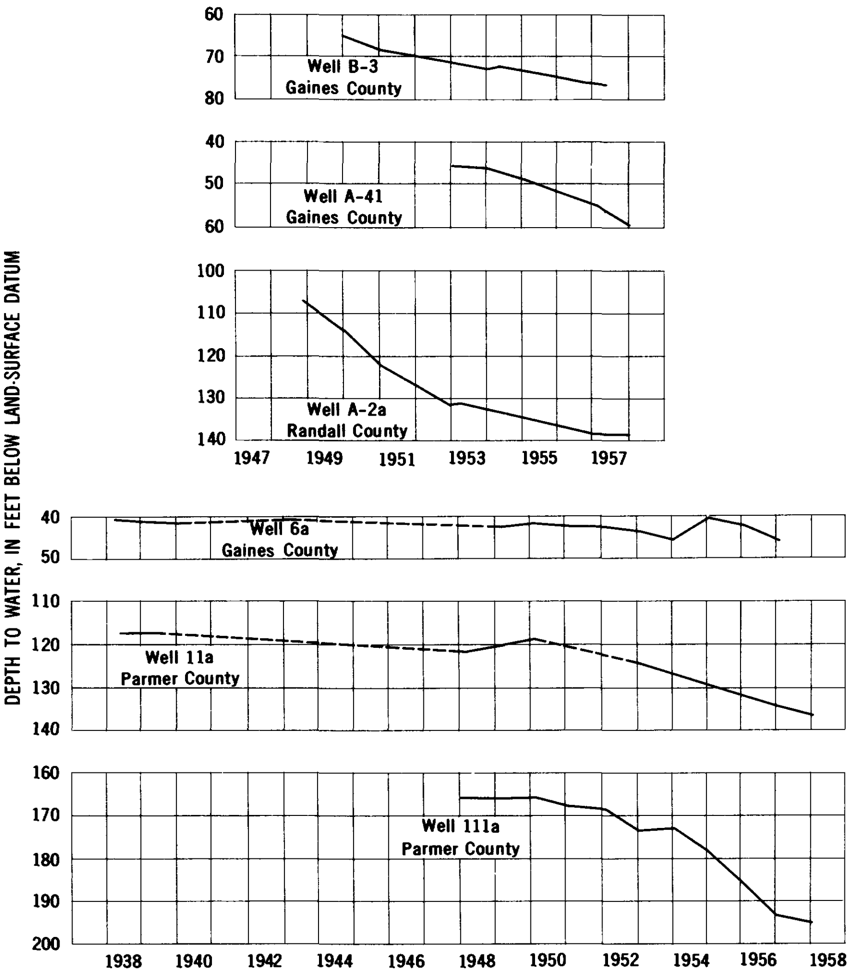

FIGURE 8.—Hydrographs of wells in Gaines, Parmer, and Randall Counties, Tex.

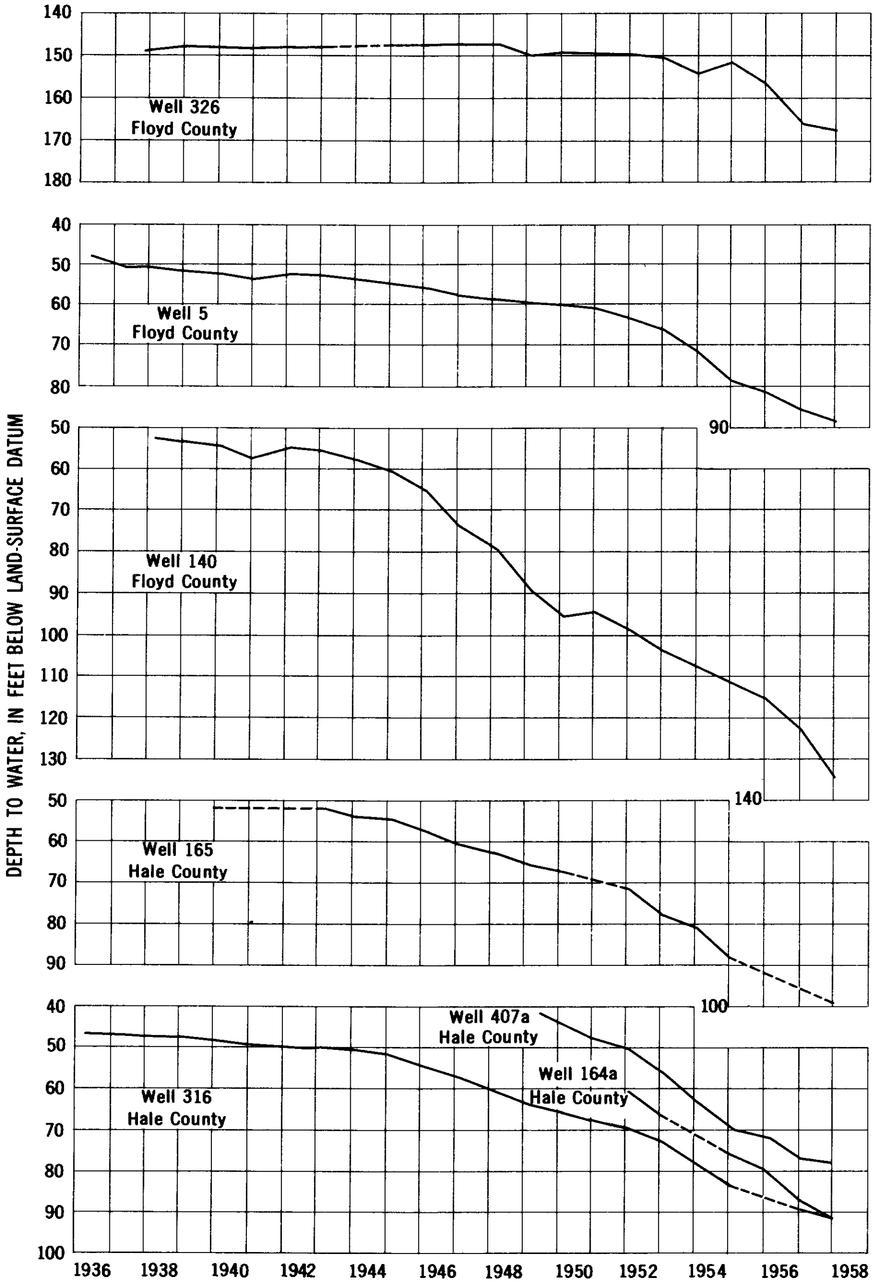

FIGURE 9.—Hydrographs of wells in Floyd and Hale Counties, Tex.

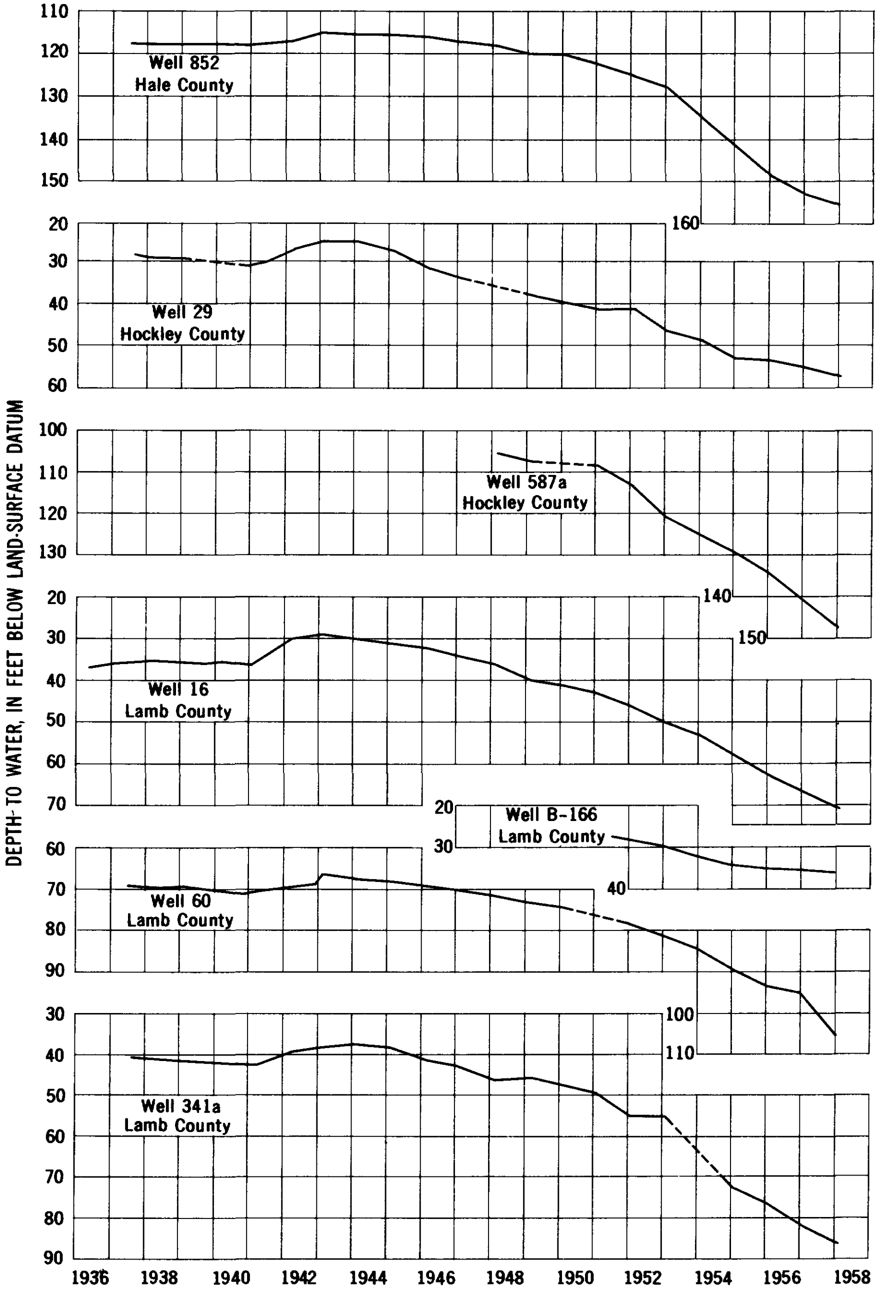

FIGURE 10.—Hydrographs of wells in Hale, Hockley, and Lamb Counties, Tex.

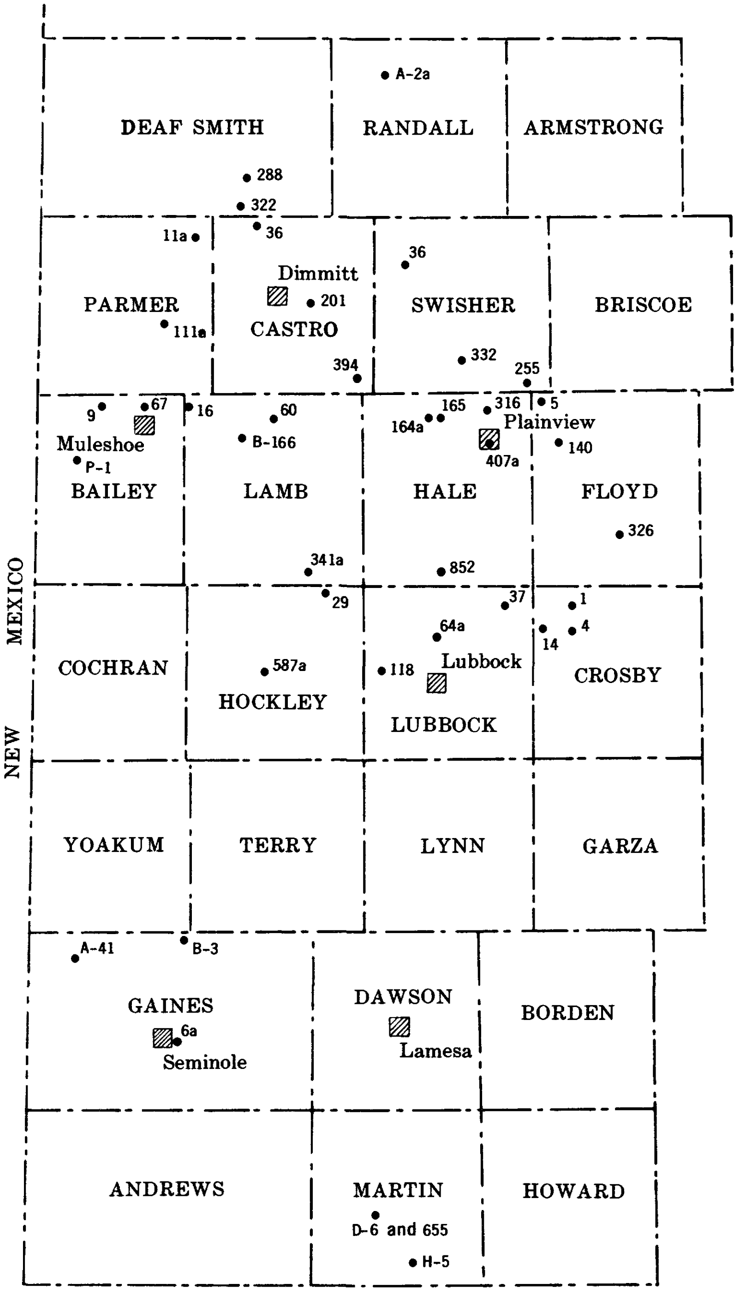

FIGURE 11.—Map showing locations of wells for which hydrographs are shown in figures 4–10.

DEPTH TO WATER

The depth to water in the Ogallala formation in the Southern High Plains ranged from less than 50 feet to more than 250 feet below land surface at the beginning of 1958. The depth to the ground water is, in general, affected by several conditions, including: the topography of the land surface, the proximity to areas of recharge or natural discharge, the proximity to areas of withdrawal of water through wells, and by the configuration of the bedrock surface. Depths to water in the Southern High Plains in 1958 are contoured on plate 6.

The shallow depth (less than 50 feet in places) to ground water in parts of the sandhills area of Lamb and Bailey Counties is probably due at least in part to recharge in the sandhills. It is also due to the topography inasmuch as many of the wells are in the valleys or low points. Furthermore, most of the wells in the sandhills are remote from areas of heavy pumping.

Ground water in the Southern High Plains moves generally in an east-southeast direction, and high areas on the bedrock surface may act as underground dams that cause the ground water to accumulate on the west and northwest sides of these highs. The shallow depth to water north of Floydada in Floyd County is caused at least in part by a high area on the bedrock surface. The shallow-water area between Canyon in Randall County and Hereford in Deaf Smith County is probably caused by the high area on the bedrock surface in southwestern Randall County.

NATURAL RECHARGE

The principal sources of ground-water recharge to the Ogallala formation in the Southern High Plains of Texas are underflow from the Ogallala in New Mexico and precipitation that falls on the land surface in Texas. The amount of recharge, if any, that might result from the return of part of the water applied for irrigation is unknown

The amount of water moving into the Texas part of Southern High Plains by underflow probably is small but fairly constant from year to year.

The amount and rate of recharge from precipitation depend on the amount, distribution, and intensity of the precipitation, the amount of moisture in the soil when the rain begins or snowmelt starts, the temperature, vegetative cover, and the permeability of the intake materials at the site of infiltration. Because of wide variations in, as well as lack of information on, the above-cited factors, it is difficult to determine the amount of recharge that enters the ground-water reservoir in the Ogallala formation in the Southern High Plains. Barnes and others (1949, p. 26–27) have suggested that studies made by White, Broadhurst, and Lang (1946) indicate that the average annual recharge would be only a fraction of an inch in an area of about 9,000 square miles roughly in the central part of the area considered in this report. From studies made in New Mexico and Texas, Theis (1937, p. 564–568) has suggested that the average annual recharge from precipitation in the Southern High Plains is less than half an inch. With the information available now, it is impossible to determine if the average annual recharge throughout the entire Southern High Plains is the same as the above estimates; however, it is probably about the same.

Much of the surface of the Southern High Plains is underlain by caliche. In some places the caliche is indurated and relatively impermeable and prevents seepage of surface water into the underlying rocks. However, in other places the caliche is absent or its character and composition is different. Solution channels or bore holes made by rodents occur in the rock and the rock may be fractured. In such places the caliche might not be a hindrance to the infiltration of surface water into the underlying soil. Barnes and others (1949, p. 24) have said, "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 subsoils. The principal areas in which direct infiltration can occur are the sandy zones in Bailey, Lamb, Lubbock, and Hockley Counties."

Depressions or sinks ranging from a few feet to 50 feet or more in depth and from a few hundred feet to a mile in diameter are of common occurrence in the Southern High Plains. During periods of heavy rainfall, surface runoff collects in these depressions. In some of the ponds, the water disappears in a short time, in others it remains for months.

Regarding infiltration from the depression ponds, White, Broadhurst, and Lang (1946, p. 387) have indicated that the water level rose in nearby observation wells after heavy rains had filled the depressions. Deposits of clay and silt, containing thin layers of caliche, occupy the bottom of most of these depressions. In cross section the deposits are crescent shaped, that is, they are thick in the center of the depression and thin out toward the perimeter. The deposits range in thickness from 0 to more than 50 feet. The results of tests of the porosity and permeability of some of these deposits are given in table 5 on page 67. The tests show that the sediments have a very low permeability (capacity to transmit water), but their porosity is such that they will store a considerable quantity of water. After the ponds become dry, fractures and crevices frequently develop in the deposits. Commonly, a sandy belt surrounds the perimeter of the depressions above the point where the deposits of clay and silt feather out.

As noted above, the permeability of the clay and silt in the bottoms of the depressions is very low, and it is unlikely that much water percolates through them. To account for the rise in the water level in the nearby wells, the process of infiltration is probably somewhat as follows: The desiccation fractures or cracks in the clay and silt deposits provide a passageway for the downward movement of water for a time when the pond is being filled. After the water has remained in the pond for a period of time, the clay swells and seals the cracks. If the water level in the ponds rises above the point where the clay and silt feather out around the perimeter of the depressions, then some water would infiltrate through the sandy belt which commonly surrounds the perimeter above the clay and silt.

Perhaps infiltration into the sandy zone above the clay and silt was observed by White, Broadhurst, and Lang (1946, p. 387) when they reported, "In some of the ponds the rate of decline was small and apparently was due mostly to losses from evaporation. In others it was at first quite rapid, amounting in some cases to 2 inches or more a day for 10 days or so after the rains, and then gradually slowed down." If the rapid loss occurs after the initial filling, following a long dry period, some of the early loss of water may be through the dessication fractures or crevices before the clay swells and seals the cracks.

The amount of water lost by evaporation and the amount of water that collects in the depressions is discussed on pages 56 to 71.

In general, very little water from streamflow is available for recharge in the Southern High Plains. During periods of normal rainfall, parctically no runoff collects in the stream channels. However, after exceptionally heavy rains, the streams may, in some places, carry large quantities of water. For example, in May 1937 the discharge of Running Water Draw at Plainview reached a peak of 1,200 cfs (cubic feet per second) but the maximum flow 15 miles below Plainview was only 80 cfs (White, Broadhurst, and Lang, 1946, p. 387). Apparently a large part of the water was absorbed by the soil and a part probably percolated downward to the water table. Flows of such magnitude occur very infrequently and it is rare indeed that water flows over the escarpment of the Southern High Plains.

A form of recharge which is detrimental to the fresh water in the ground-water reservoir in the Ogallala formation has been reported to occur in several places in the Southern High Plains. For many years it has been common practice to dispose of oil-field brine in surface pits. Salt water has apparently invaded some irrigation wells, and Broadhurst (1957b, p. 1) has indicated that seepage of salt water from the surface disposal pits has polluted the water in the ground-water reservoir in some places. This method of disposal of oil-field brines is being abandoned by most oil companies, owing principally to the efforts of the High Plains Underground Water Conservation District No. 1.

ARTIFICIAL-RECHARGE STUDIES

By B. N. Myers

SCOPE AND METHODS

In recent years much thought has been given to the conservation of the present supply of ground water in the Southern High Plains and to ways and means of increasing the recharge to the aquifer. Inadvertent artificial recharge by isolated attempts to drain playa lakes on the Southern High Plains have been reported as early as 1918. The motivating factor of these early attempts was the desire to use the fertile soil in the lake bottoms to grow crops, and little thought was given to recharging the aquifer. Since 1948 several attempts have been made at artificially recharging the ground-water reservoir by drilling wells in or near playa lakes and draining water from them into the ground. Some of these attempts have been reported as successful, others as failures; however, very few records of the operations have been kept.

The artificial recharge potential in the Southern High Plains was investigated by the U.S. Geological Survey in cooperation with the Texas Board of Water Engineers and the Harvest Queen Mills at Plainview.

The purpose of the recharge study was to estimate the amount of water available from storm runoff into the playa lakes which might be stored in the ground for future use, to conduct experiments on injecting this water into the aquifer through drilled wells, to collect and analyze climatological data in the area, to study the effect of injecting surface water into an aquifer, and to determine the permeability and porosity of the material in the bottom of the lakes.

The area selected for study includes approximately 1,470 square miles in southeastern Castro County, southwestern Swisher County, northeastern Lamb County, and western Hale County (fig. 12). It is drained by 1,348 playa lakes, 1 intermittent stream, and branches of 2 others. Most of the land in the area is used for agriculture, a large part of it being irrigated. In the southwest part of the area there are some sand dunes and other types of soil unsuitable for irrigation.

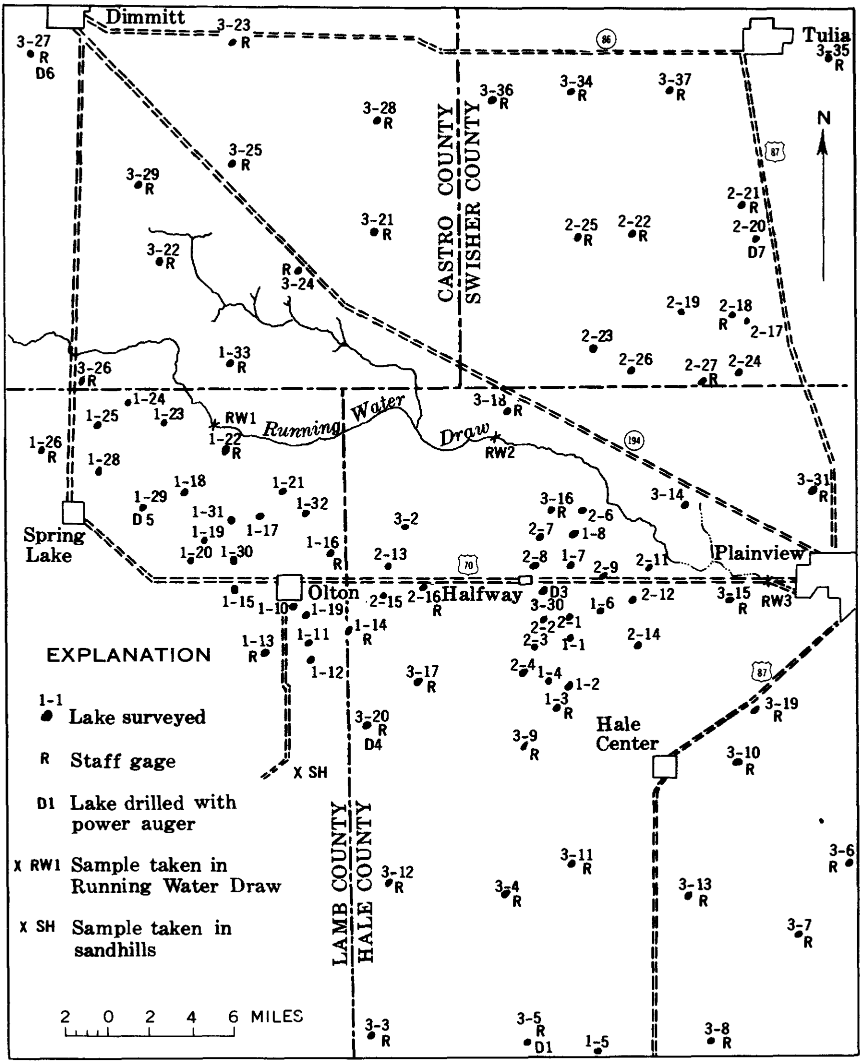

FIGURE 12.—Location of sample lakes, Castro, Swisher, Lamb, and Hale Counties, Tex.

The land surface of the area is typical of much of the Southern High Plains in that it slopes to the south and east about 8 to 10 feet per mile.

The fieldwork was started in the summer of 1956 by making topographic surveys of a number of lakes in the area, of which 50 of these were selected according to size, geographic location, and soil conditions to be representative of all the lakes in the area. Staff gages were installed in the selected lakes and in 1957 periodic readings were begun of the elevation of the water surfaces of the 50 selected lakes.

The bottoms of 13 lakes and Running Water Draw were drilled, and 56 samples of water-bearing materials were sent to the hydrologic laboratory of the U.S. Geological Survey at Denver, Colo., for tests of their physical and hydraulic properties.

A Young screen-evaporation pan and a recording rain-gage were installed at Halfway in Hale County for daily measurements of evaporation and rainfall. Rainfall data were collected also at other points in the area. Evaporation records were obtained from weather stations at Lubbock and near Amarillo, and a plot of cumulative evaporation at the two stations was made for comparison with the evaporation at Halfway (fig. 13).

A recharge well and three observation wells were drilled on the experiment farm of the Texas Research Foundation at Halfway. The recharge well was equipped with a pump and motor and was connected to the lake through a floating intake, a settling and filter basin, and several feet of 15- and 8-inch diameter pipe. Connections were also made with another irrigation well on the farm through an underground irrigation-distribution system which permitted water to be pumped from one well to the other. This system afforded a means of testing the rate of injection at the recharge well by using native ground water. Meters were installed on intake and discharge pipes at the recharge well and were used to measure the rate and amount of water being recharged and discharged. The three observation wells, located 5, 50, and 100 feet distant from the recharge well, were used to observe the profile of the water surface during recharge operations.

Other phases of the recharge investigation included classifying all lakes in the 4-county area by size, determining the drainage area of the 50 sample lakes, and attempting to correlate the amount of water caught in certain lakes with others of comparable drainage areas. Corelations were attempted only when rainfall intensities and amounts were approixmately the same over the area.

RECHARGE TESTS

In December 1957, a test using the native ground water from a nearby irigation well was started at the High Plains Research Foundation farm to determine the effects of recharging an aquifer. Water was pumped through the underground irrigation-distribution line into the recharge well at the rate of 800 gpm. The test was run for 18 days; the pump was shut down for short periods only long enough to service the pumping equipment. The total water injected into the recharge well during the test was 63.7 acre-feet. No effects of clogging were noted while the water was being injected, and the recharge well was still taking water readily when the test was stopped. During the

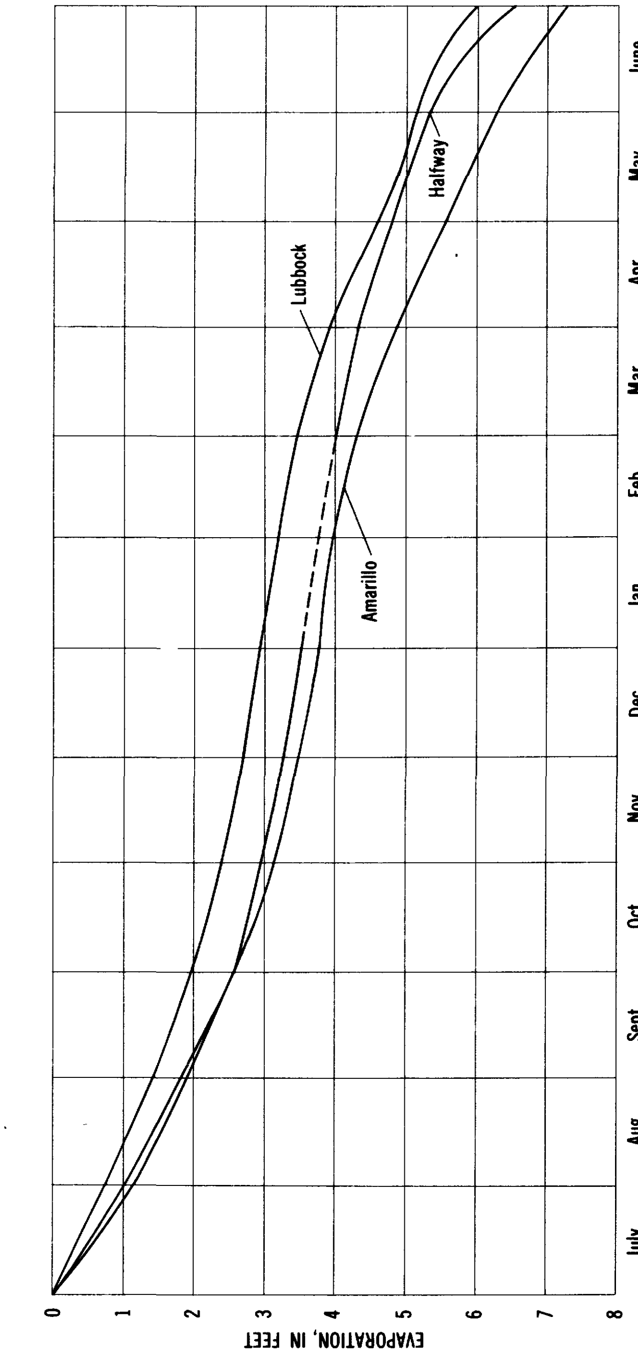

FIGURE 13.—Cumulative evaporation at Lubbock, Halfway, and Amarillo, July 1957 to July 1958.

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test, water levels in several other irrigation wells 1/4 to 1/2 mile distant were measured periodically. No increase in the altitude of water levels in these wells could be detected.

In May 1959 the lake on the High Plains Research Foundation farm caught more than 25 acre-feet of water. Drainage of the lake through the recharge well began and in approximately 7 days the lake was completely drained. Dr. T. C. Longnecker, the farm director, estimated that about 23 acre-feet of water had been injected into the aquifer. The average rate of recharge was approximately 780 gpm, but on test trials the rate of recharge was increased to 1,200 gpm. The recharge well was pumped periodically for short periods during the 7-day interval to remove silt that accumulated in the formation and well.

On June 24, 1959, the lake caught approximately 30 acre-feet of water. Because high winds kept the sediment from settling out of the lake water, 50 pounds of settling compound was spread over the lake surface from an airplane. Little if any clearing of the water was noted, and, the water being rapidly consumed by evaporation, it was decided to proceed immediately with the injection of the muddy water but at the low rate of about 250 gpm. After 2 days of recharging at this rate, no undue clogging was noticeable, so the rate of recharge was increased to 850 gpm. The well was pumped and surged at least for 1 hour each day to remove as much of the accumulated silt as possible.

During the time the lake was being drained, more rain fell and the lake caught more water. The recharging operation was continued and a total of 45.3 acre-feet of water was injected into the aquifer. A total of approximately 7 acre-feet of water was pumped back into the lake during the period of daily redevelopment of the well; that is, the net total of actual recharge was 38.3 acre-feet. This quantity of water plus the 23 acre-feet estimated by Dr. Longnecker to have been recharged in May made a total of approximately 61 acre-feet of water which was recharged during 1959.

The computed evaporation loss during the recharging test indicates that about 5 1/2 acre-feet of water was lost before the lake was drained. This loss suggests that between 80 and 90 percent of the water caught in the lake can be stored in the ground for future use.

Samples of water were obtained periodically during the recharge operation and also more frequently during the redevelopment of the well. The samples were analyzed for sediment content. During the period of daily redevelopment of the well, an abnormal amount of formation sand was pumped from the well. Computations based on the quantitative analysis of the sediment samples caught while redeveloping the recharge well indicated that 6.2 cubic yards of silt and clay and 16.4 cubic yards of formation sand were pumped out of the aquifer during the recharging operation.

If the specific conductance is used as a measure of the parts per million of dissolved solids in the water, an estimate can be made of the percentage of the mixture of native ground water and the recharged water that was pumped during the redevelopment of the well. The estimates are based on the following formula:

$$V_1C_1+V_2C_2=C_3(V_1+V_2)$$

where,

V_1=volume of water going into the well as recharge;

V_2=volume of ground water mixing with recharge water;

V_1+V_2=total or 100 percent of the mixture coming from the well while pumping;

C_1=dissolved-solids content of the recharge water, estimated from the specific conductance;

C_2=dissolved-solids content of the native ground water, estimated from the specific conductance;

C_3=dissolved-solids content of the mixture of native ground water and recharge water, estimated from the specific conductance.

Samples of the native ground water, recharge water, and a mixture of the two obtained as the well was pumped were analyzed in the laboratory of the U.S. Geological Survey in Austin, Tex. Averages of the percentages computed by the above formula indicated that approximately 88 percent of the water which was pumped while redeveloping the recharge well each day was recharge water or water that had been injected into the aquifer from the lake. This figure does not mean that the percentage of lake water remains that high until all recharge water is pumped out of the ground. As more of the mixed water is pumped, the percentage of native ground water becomes larger.

Artificial recharge experiments conducted at Amarillo, Tex., have indicated that 78 to 90 percent of the recharge water could be recovered, and that the maximum recovery could be obtained if pumping began immediately after recharge was stopped (Moulder and Frazor, 1957, p. 22).

Several organizations and many individuals have been interested in recharge experiments in the Southern High Plains. According to Sherrill (1959, p. 6–7), 124 recharge wells were in operation in 1959. The High Plains Underground Water Conservation District No. 1, under the supervision of W. L. Broadhurst, chief hydrologist, has constructed a recharge well for experimental purposes; the district has conducted several experiments with its own well and has also participated in experiments on wells owned by others. Several members of the faculty of the Texas Technological College at Lubbock have been interested in the study of recharge, and recently the Department of Animal Husbandry and Agricultural Engineering of that institution has constructed a recharge well and other facilities to experiment with the filtering of the recharge water and with artificial recharging procedure. The Texas Highway Department is reported to be considering experimenting with recharge wells to drain water along the highway right-of-way. Such wells, if successful, would not only recharge the ground-water reservoir but also could lower highway construction and maintenance costs.

The recharge wells owned by the individual well owners are constructed to meet the conditions and needs of the owner and they have been used with varying degrees of success. Most of the wells are dual-purpose wells, that is, they can be used either for recharge or production.

One recharge well in Hale County was drilled adjacent to a lake, and an intake ditch was dug from the lake to the well. The well was connected by about a half mile of underground concrete pipe to another well on higher ground. Water was carried in the ditch from the lake to the nearby well where the water was injected through the well into the aquifer. If desired, the pump in the well adjacent to the lake could be in operation while water was draining from the lake and as the water from the lake drained into the well, the water could be pumped to the well a half mile away. There, the water could be injected into the aquifer or it could be diverted into an underground distribution system for immediate application to the land. The well adjacent to the lake also was equipped so that as the lake water drained to the well, the water could be pumped directly into a sprinkler system for immediate application to crops on the sloping land adjacent to the lake.

At an installation in Floyd County, a surface pump was used at the lake to pump water into a concrete underground distribution system connected to several wells. The lake water could either be applied to the crops from the distribution system or injected into the ground-water reservoir through the wells.

In Lamb County a 20-inch-diameter uncased well was drilled in the center of one of the lakes. The well was filled with 2-inch rock and a mound of 1-inch rock was placed over the well to act as a filter. A 30-acre lake was drained twice by this installation but additional data are not available to indicate further successful use.

The High Plains Underground Water Conservation District No. 1 has conducted several recharge tests at their experimental well in southwestern Floyd County. In one test, the lake water was filtered through cotton burrs before the water was injected into the aquifer. The filtering test was not successful. Broadhurst (1957a, p. 3) has reported the results of a test made during April and May of 1957 as follows: "It is significant to note that during the first 24 hours the well took water at the average rate of 920 gallons a minute, that during the second and third days the rate was about 770 gallons a minute, and that during the fourth day the rate was 620 gallons a minute, showing that the silt was gradually clogging the sand." The injection of water was stopped after 4 days of continuous recharging and the well was pumped for 4 hours at a rate of about 1,000 gpm, during which time a large quantity of silt and sand was removed from the well. The injection of water was again started and during this part of the test the well was pumped periodically to remove the silt from the well. Regarding this part of the test, Broadhurst (1957a, p. 3) has said, "Again it is significant to note that whereas the rate of recharge during the first 4 days of the experiment decreased from 920 gallons a minute to 620 gallons a minute, with pumping only once a day to remove silt, the rate of recharge was maintained at a rate of about 920 gallons a minute until the lake was drained."

Some of the wells owned by individuals reportedly have been recharged at the rate of 1,000 gpm or more. The usual procedure is to recharge for a period of time, perhaps 24 hours, then pump the well for a short period of time, perhaps 1 hour, to remove the silt and clay. Then, the recharging is again started.

LAKE SURVEYS

The assumptions made in the study and analysis of the data from the lake surveys were (a) that the amount of water gained or lost from the selected sample lakes was representative of the average gain or loss from all lakes in the study area; (b) that the evaporation rate from an evaporation pan, corrected by the pan coefficient, was applicable to all lakes to determine the lake water evaporation; and (c) that the rapid losses in and around the edges of the lakes, following storms, were only a small part of the total water available for artificial recharge.

Precipitation records gathered in the 3-county area are listed in table 3. The difference in the amount of total yearly rainfall reflects the difference in the amounts of water available for recharge.

TABLE 3.—*Precipitation, in inches, at selected stations in Castro, Hale, and Swisher Counties, Tex., 1957–58*

Station	January	February	March	April	May	June	July	August	September	October	November	December	Total	Yearly normal
1957														
Plainview	0.23	1.10	1.16	5.33	5.03	4.77	0.32	3.22	0.63	3.07	1.59	0.57	27.02	21.28
Tulia	.19	.85	1.55	2.57	4.79	3.99	.83	3.30	.47	4.91	1.34	.12	24.91	22.20
Hale Center, 14 miles northwest	.24	.73	1.17	3.03	4.07	6.64	.43	.78	.82	3.06	1.43	.10	22.50	----------
Hart	.12	1.00	1.72	2.20	2.84	2.76	.10	1.98	1.39	4.46	1.41	.10	20.08	----------
Dimmitt	.27	1.36	2.43	1.68	2.53	4.39	2.96	1.04	.83	2.28	1.25	.12	21.14	19.00
1958														
Plainview	2.38	0.26	2.25	2.56	2.05	2.38	1.46	1.40	2.42	0.64	0.47	0.16	18.43	[1] 21.28
Tulia	1.37	.25	2.22	2.38	1.99	2.04	1.60	2.60	2.37	.46	.41	.14	17.83	[2] 22.20
Hale Center, 14 miles northwest	1.30	----------	----------	1.95	.26	----------	----------	----------	----------	----------	----------	----------	----------	([3])
Hart	1.51	.26	1.68	1.76	.56	1.82	2.09	1.82	2.97	.08	1.04	.15	15.74	([3])
Dimmitt	1.72	.34	2.38	2.11	1.24	1.94	3.16	1.70	2.20	.31	.85	.23	18.18	[4] 19.00

[1] Period of record 1892–1958.
[2] Period of record 1896–1958.
[3] Yearly normal not available.
[4] Period of record 1923–1958.

Table 4 shows the number of lakes classed according to size, the average catch in acre-feet for each size lake, the total catch for all lakes, the average evaporation loss for each size lake, the total evaporation loss for all lakes, and other losses as transpiration and seepage for the years 1957 and 1958.

The total amount of water in the lakes that is available for artificial recharge depends on several factors such as the amount and intensity of rainfall, the rate of evaporation, the rate of natural recharge, and the condition of the soil on the upland and in the basins. A study of table 3 shows that the intensity and amount of rainfall were greater in 1957 than in 1958. If the water caught in the lakes in 1957 could have been spread over the study area, it would have covered the area to a depth of 2.54 inches, whereas the 1958 catch would have covered the area to a depth of only 0.47 inch; the total recorded rainfall for 1957, however, was only 33 percent above the 1958 total.

TABLE 4.—*Summary of lake surveys, Castro, Swisher, Hale, and Lamb Counties, Tex., 1957–58*

Summary factor (acre-feet)	Size range of lakes (acres)									
	0–25		25–50		50–75		>75		Total	
	1957	1958	1957	1958	1957	1958	1957	1958	1957	1958
Lakes surveyed, total	853	853	442	442	47	47	6	6	1,348	1,348
Catch per lake (average)	100	17.1	217	41.5	320	73.5	400	107	-------	------
Total catch	85,300	14,586	96,356	18,343	15,040	3,454	2,400	642	199,096	37,025
Evaporation loss per lake (average)	63.5	10.5	149.3	24.2	168.1	63.9	[1] 168.1	[1] 63.9	-------	------
Total evaporation loss	54,165	8,956	65,991	10,696	7,900	3,003	1,008	383	129,064	23,038
Other losses [2]	31,135	5,630	30,365	7,647	7,140	451	1,392	259	70,032	13,987

[1] Assumed.
[2] Transpiration, soil moisture replenishment, and recharge.

Hydrographs of the water surface were plotted for the individual sample lakes. When the cumulative evaporation curve was plotted on the same sheet with the hydrographs of the lakes, it was evident that a large part of the lake water was lost by evaporation. Figure 14 is a plot of cumulative evaporation and the recession part of the hydrograph for lake 3–7. The lake contained approximately 18 acre-feet of water on July 1, 1957; another 2 acre-feet was added by subsequent rains before September 11, making a total of 20 acre-feet. For the same period the cumulative total evaporation was 16.8 acre-feet. This total indicates that about 83 percent of the water was lost by evaporation from lake 3–7. The computed average evaporation loss for the sample lakes was from 60 to 65 percent of the observed total water caught in the lakes. Much of this water could have been conserved if it had been used quickly for recharge.

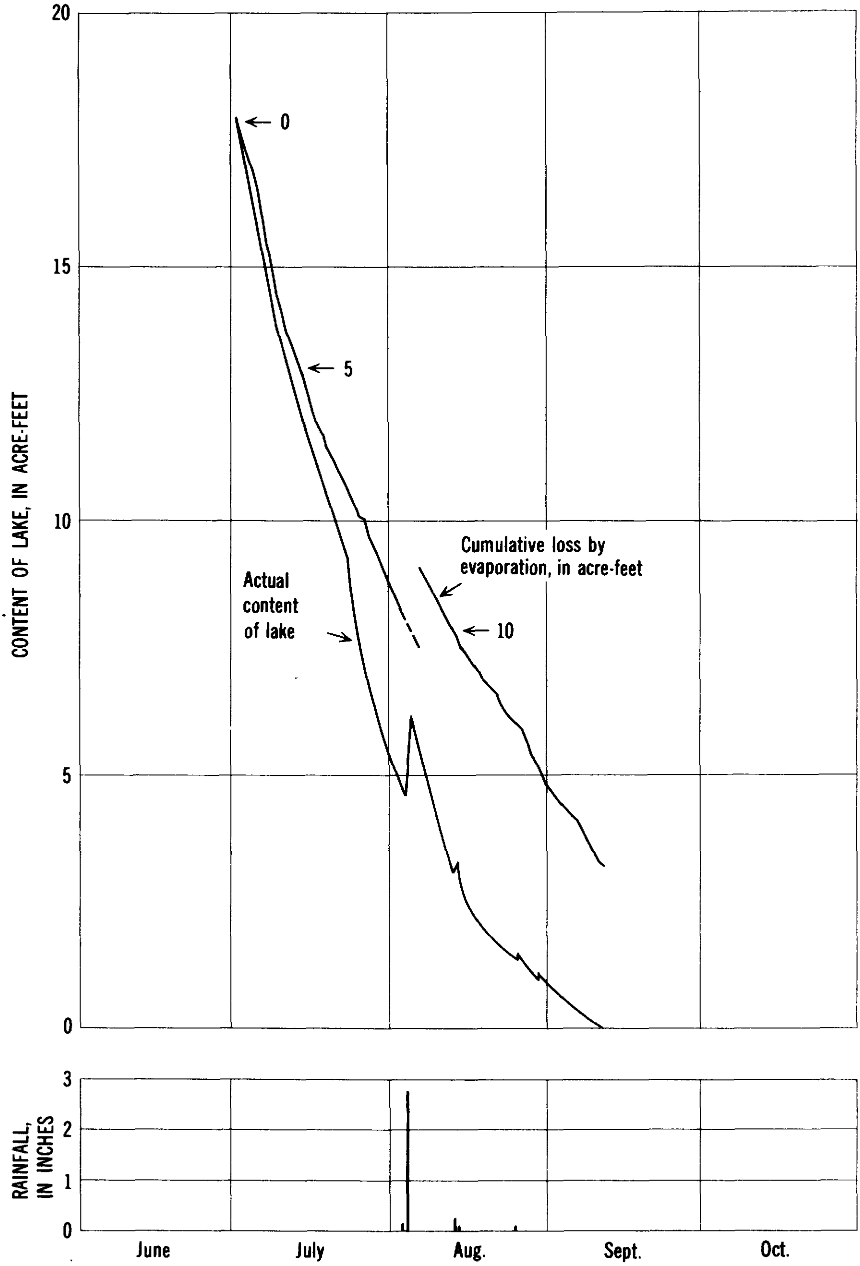

FIGURE 14.—Graphs showing loss by evaporation, content of lake, and rainfall, lake 3–7, Hale County, July 1 to Sept. 11, 1957.

Samples of material obtained from the lake bottoms indicate that the porosity ranges from 33 to 55 percent; this range means that the water content of the silt and clay when completely saturated is from 33 to 55 percent of the total volume of the sediment which has collected in the lakes.

Because the permeability of the material in the lake bottoms is very low, very little of the lake water can be expected to pass through the sediment which has collected in the lakes; evaporation and transpiration, therefore, account for most of the water losses. Table 5 gives permeability and porosity data for bottom samples taken from four representative lakes in the study area. Table 6 gives the sample logs of the material penetrated in the same lakes.

TABLE 5.—*Analysis of sample material from four selected lakes in the Southern High Plains of Texas*

[For locations of lakes, see fig. 12]

Sample	Depth at which sample was taken (feet)	Field description of material	Porosity (percent)	Permeability (gpd per sq ft under 100 percent gradient)
		Lake 3-27		
1	3.5	Clay, silty	40	0.0002
2	4.6	Silt, clayey	36.7	.6
3	11.1	Silt, clayey	33.1	.002
		Lake 3-20		
1	1.2	Clay	42.0	0.0009
2	5.1	Clay	38.6	.0005
3	7.8	Silt, clayey	34.7	.0002
		Lake 3-10		
1	1.2	Clay	46.7	0.0004
2	4.7	Clay	43.9	.0001
		Lake 3-30		
1	5.0	Clay, silty	45.6	0.0002
2	7.8	Clay, silty	44.8	.0002
3	11.7	Clay, silty	50.5	.0003

TABLE 6.—*Sample logs of test holes in four selected lakes in the Southern High Plains of Texas*

[For locations of lakes, see fig. 12]

	Thickness (feet)	*Depth (feet)*
Lake 3-10		
Hole 1:		
Clay, brownish-gray, calcareous; very fine to coarse nodules of caliche	3	3
Clay, brown, calcareous	3	6
Clay, yellowish-gray, calcareous; very fine to coarse nodules of caliche	23	29
Clay, yellowish-gray, calcareous; very fine to pebble-size nodules of caliche	6	35
Clay, silty, light-olive-gray calcareous; nodules of caliche	4	39
Clay, silty, olive-gray and yellowish-gray variegated, calcareous; nodules of caliche	7	46
Silt, clayey, very pale orange, highly calcareous	7	53
Silt, sandy, pinkish-gray, highly calcareous; some pebble-size nodules of caliche	2	55
Hole 2:		
Clay, black, calcareous	5	5
Clay, brownish-gray, calcareous	5	10
Clay, yellowish-gray, calcareous; few coarse nodules of caliche	6	16
Silt, clayey, yellowish-gray, calcareous	4	20
Silt, clayey, pale greenish-yellow, calcareous	6	26
Silt, very pale orange, calcareous	8	34
Silt, white, highly calcareous	1	35
Hole 3:		
Clay, brownish-black, calcareous; coarse nodules of caliche	4	4
Silt, clayey, yellowish-gray, calcareous; coarse nodules of caliche	6	10
Clay, silty, greenish-gray and pale greenish-yellow, variegated, calcareous; large caliche nodules	3	13
Clay, silty, pale-olive, slightly calcareous	2	15
Silt, clayey, very pale orange, highly calcareous	3	18
Lake 3-20		
Hole 1:		
Silt, sandy, clayey, dusky yellowish-brown	6	6
Silt, sandy, clayey, pale greenish-yellow and white, variegated (white part due to very high caliche content)	4	10
Clay, silty; same color as preceding unit but with less white	3	13
Silt, sandy, very pale orange, highly calcareous; nodules of caliche	2	15
Same as preceding unit but more nodules of caliche	3	18
Hole 2:		
Clay, silty, brownish-black; some small nodules of caliche. Clay itself has little or no caliche	7	7
Clay, sandy, silty, brownish-gray and very pale orange, variegated, highly calcareous; some small nodules of caliche	1	8
Silt, sandy, yellowish-gray, highly calcareous; medium to coarse nodules of caliche	8	16

TABLE 6.—*Sample logs of test holes in four selected lakes in the Southern High Plains of Texas*—Continued

[For locations of lakes, see fig. 12]

	Thickness (feet)	Depth (feet)
Lake 3-20—Continued		
Hole 2—Continued		
Silt, clayey, pale greenish-yellow, highly calcareous; medium to coarse nodules of caliche	9	25
Clay, silty, pale greenish-yellow, highly calcareous; medium to coarse nodules of caliche; very hard caliche layer 25.5 to 26 ft.	3	28
Clay, very pale orange, highly calcareous; medium to coarse nodules of caliche; hard caliche layer 34.5 to 35 ft	14	42
Clay, silty, yellowish-gray, highly calcareous; fine nodules of caliche; very hard caliche layers 44.5 to 45.2, 46 to 46.5, and 52 to 53 ft	13	55
Hole 3:		
Clay, silty, brownish-black, small nodules of caliche. Little or no caliche in clay itself	3	3
Silt, sandy light olive-gray and brownish-gray variegated, slightly calcareous; very few small nodules of caliche	4	7
Clay, silty, pale greenish-yellow; large, white, extremely calcareous spots and many medium coarse nodules of caliche throughout	5	12
Clay, pale greenish-yellow, highly calcareous	6	18
Silt, sandy, clayey, light greenish-gray, highly calcareous; very hard caliche layers at 39 to 39.5, 42 to 42.7, and 47 to 47.5 ft	30	48
Silt, very sandy, very pale orange, highly calcareous; very hard caliche layer at 50 ft	2	50
Lake 3-27		
Hole 1:		
Clay, silty, brownish-gray	3	3
Silt, clayey, light-brown, sandy, calcareous, medium to coarse nodules of caliche	½	3½
Clay, silty, pale yellowish-brown, calcareous	2½	6
Clay, silty, yellowish-gray, calcareous	8	14
Silt, clayey, very pale orange, calcareous, sandy; few medium to coarse nodules of caliche	4	18
Clay, silty, yellowish-gray, calcareous; brown, yellow, and black stained subangular fragments of caliche, 1/16 in. to ¼ in. in diameter	6	24
Clay, silty, pale yellowish-brown, calcareous, pale olive and moderate reddish-orange streaks and caliche fragments similar to those above but not so numerous	3	27
Silt, sandy, moderate reddish-brown, slightly calcareous	11	38
Silt, sandy, moderate reddish-brown; spots of brighter reddish-brown sandy silt	2	40
Hole 2:		
Clay, brownish-black	5	5
Clay, light olive-gray, calcareous; medium to coarse nodules of caliche	3	8
Clay, silty, very pale orange, calcareous	2	10

TABLE 6.—*Sample logs of test holes in four selected lakes in the Southern High Plains of Texas*—Continued

[For locations of lakes, see fig. 12]

	Thickness (feet)	Depth (feet)
Lake 3-27—Continued		
Hole 2—Continued		
Clay, light-brown, calcareous	4	14
Clay, light-olive and light-brown, variegated, calcareous, some brownish-orange streaks	6	20
Clay, moderate yellowish-brown; some brownish-orange and black streaks	5	25
Clay, sandy, silty, variegated, highly oxidized, brown, green, orange, and black, greenish-brown color predominating	5	30
Similar to preceding unit but with less green; reddish-brown color predominating	3	33
Silt, very sandy, light-brown	7	40
Silt, very sandy, moderate reddish-brown	3	43
Hole 3:		
Clay, brownish-gray	7	7
Clay, light olive-gray calcareous; small nodules of caliche	2	9
Clay, pale yellowish-gray; small nodules of caliche	11	20
Clay, light olive-gray, calcareous	5	25
Clay, pale-olive, slightly calcareous; some brownish-orange streaks	13	38
Clay, silty, dusky-yellow, and pale greenish-yellow variegated, slightly calcareous; some brownish-orange and black streaks	3	41
Clay, sandy, silty, pale yellowish-brown, slightly calcareous	4	45
Silt, clayey, light olive-gray, calcareous	7	52
Silt, sandy, moderate yellowish-brown, calcareous	1	53
Sand, clean, very pale orange	½	53½
Lake 3-30		
Hole 1:		
Clay, brownish-black, calcareous, very few nodules of caliche	10	10
Clay, dark yellowish-brown and light-brown, variegated, calcareous; some nodules of caliche	4	14
Clay, pale-olive and dark yellowish-brown, variegated, calcareous; very few nodules of caliche	6	20
Clay, silty, pale-olive and light-brown, variegated, slightly calcareous	4	24
Silt, sandy, light olive-gray, slightly calcareous	30	54
Sand, silty, grayish-orange, very fine grained	—	54
Hole 2:		
Clay, brownish-black	3	3
Clay, silty, olive-gray	5	8
Clay, light olive-gray	3	11

Tests have been shown that water from the playa lakes can be injected into the ground-water reservoir of the Ogallala formation in the Southern High Plains. If the recharge well is pumped within a reasonable length of time after recharging is completed, a large percentage of the water can be recovered through the same well.

It is estimated that during 1957 when the rainfall was above normal, the 1,348 lakes within the area of the recharge study caught nearly 200,000 acre-feet of water. In 1958 when the rainfall was below normal, the same lakes caught approximately 37,000 acre-feet of water. These figures suggest that for a year of normal rainfall the water available for recharge from the depression ponds within the 4-county area of study would range from 37,000 to 200,000 acre-feet. This amount is about 5 percent and 25 percent of the quantity of water normally pumped for irrigation and other purposes in the same area.

Some of the hazards involved in artificially recharging the ground-water reservoir through wells are the possibility of clogging the well screen or formation by suspended matter in the recharge water, the possible pollution of the ground water by the direct addition of contaminated water; and the possible clogging of the well screen or formation by chemical precipitates caused by the incompatability of the recharge water with the native ground water and the constituent parts of the formation being recharged.

DEVELOPMENT OF GROUND WATER

The early settlers in the Southern High Plains obtained their water supply from springs along the eastern escarpment and from the intermittent and water-table lakes in the interior of the Plains. The first wells for domestic and stock use were probably dug or drilled in the 1880's. Haley (1953, p. 96) reports that by 1900 the XIT Ranch, which consisted of more than 3 million acres of land in the Panhandle of Texas, part of which was in the Southern High Plains, had 335 windmills in use. At that time the ground-water reservoir in the Southern High Plains was probably virtually in balance—that is, the amount of water lost by natural discharge and the amount withdrawn by wells were probably about equal to the natural recharge.

Irrigation from wells in the Southern High Plains of Texas was reportedly started near Plainview, Hale County, in 1911. The fact that water was available at a shallow depth, 50 feet or less, undoubtedly was a controlling factor in the location of the first irrigation wells. Drilling subsequently was started in the Hereford and Muleshoe districts where water was also available at shallow depths, and by 1914 about 140 wells had been completed in the three districts. The number of acres irrigated each year and the number of irrigation wells in use each year in the Southern High Plains are shown on figure 15.

Development of the ground-water supply progressed slowly until January 1937 when 600 irrigation wells were in use. During 1937 the number of wells nearly doubled, and during the succeeding 6 years

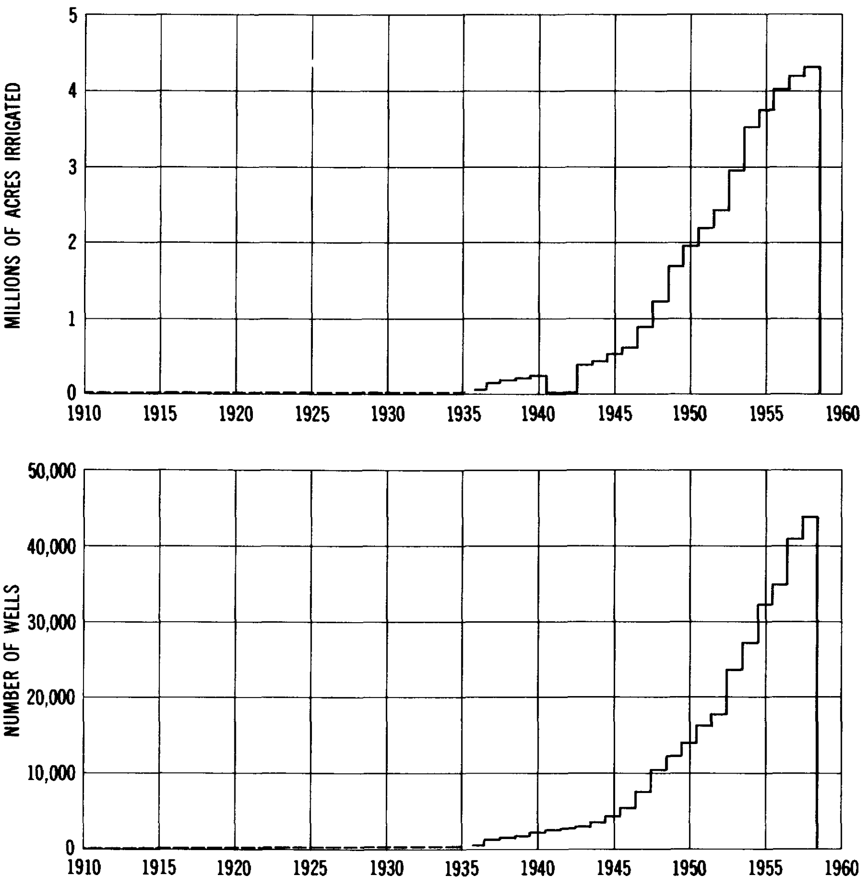

FIGURE 15.—Graphs showing number of irrigation wells and acres irrigated in the Southern High Plains of Texas, 1910–58. (Data for 1949–58 based on irrigation survey reports of Texas A. & M. College Extension Service.)

new wells were added at rates ranging from 120 to 480 wells per year. New wells were being drilled outside of the older, more or less isolated areas, and by 1943-44 the areas were beginning to merge into one big irrigated area. From 1943 to 1950, about 11,000 wells were drilled, and as of January 1951 about 14,000 irrigation wells were in use. By this time the area between Amarillo on the north and Tahoka in Lynn County on the south was extensively developed for irrigation. In the southern counties such as Terry, Gaines, and Martin, scattered areas were being developed for irrigation.

Precipitation was slightly below normal in 1951, and in 1952 it was only about 55 percent of normal at the five stations as shown in figure 2. During these 2 years, about 3,850 wells were drilled. Near-drought conditions continued during 1953 and 1954 and 9,400 wells were drilled; an estimated total of 27,300 wells were in use in the Southern High Plains at the end of 1954.

Drilling continued at an accelerated pace during 1955 when 5,000 wells were drilled. In 1956 the drilling rate slackened and about 2,700 wells were drilled. In 1957 and 1958 about 6,000 and 3,300 wells were drilled; a total of about 44,000 wells were in operation in 1958.

In 1950 the area commonly referred to as the principal irrigated area extended northward from Tahoka in Lynn County to the vicinity of the Potter-Randall county line and from the New Mexico State line almost to the eastern escarpment. During the period 1950-58, additional wells were drilled in the older areas and new acreage was continually being placed under irrigation.

Development of irrigation in the southern part of the Southern High Plains did not start as early as in the northern part, except possibly in small scattered areas. Sherrill (1958, p. 2–3) reported that in 1958, 600 irrigation wells were in use in Dawson County, 900 wells in Gaines County, and 1,200 wells in Terry County. In 1951, Thurmond (1951, p. 1) reported the number of wells in use in the same counties as being 9, 275, and 100, respectively.

Much of the development for irrigation in Armstrong and Donley Counties also has been in recent years. Sherrill (1958, p. 2) reported that, in 1958, 150 wells were in use in Armstrong County, and 175 in Donley County. In Armstrong County about one-third of the wells in use in 1958 were in the extreme southwestern part of the county south of the Prairie Dog Town Fork of the Red River, and the remainder were in the northern part of the county north of the river.

The yields of the wells in the Southern High Plains are dependent, at least in part, on the saturated thickness of deposits tapped and, in general, as the water levels continue to decline, the yields of the wells will decline. The areas where ground water has been withdrawn for the longest period of time are the areas of greatest decline of the water table. Declines in yield due to the development have been reported as early as 1951 in some places (Leggat, 1954a, p. 16-17). For example, the average yield of 10 wells in Swisher County decreased from 828 gpm in 1938 to 680 gpm in 1951. In Hale County the average yield of 14 wells decreased from 989 gpm to 786 gpm during the same period. In Deaf Smith County the average yield of 15 wells decreased from 836 gpm in 1938 to 671 gpm in 1951, and in Floyd County the average decrease for 11 wells was from 753 gpm to 668 gpm.

Other factors affecting the increase in use of water in the Southern High Plains include the growth of industries associated with agriculture, an increase of oil production, and the increase in population.

The growth in population along with an increase in the per capita use of water has greatly increased the demand for public-water supplies. Because of the declining yields of wells in some of the older municipal well fields and the inability to acquire suitable nearby land for new well fields, some of the cities have had to develop well fields 50 miles or more from the city limits. The city of Amarillo obtains part of its water supply from a recently developed well field in Carson County, approximately 30 miles east of the city. The city also is reported to have acquired the water rights on a large tract of land in Hartley and Dallam Counties, north of the Canadian River about 70 miles from the city.

The city of Lubbock has developed a new well field on a large tract of land in the sandhills areas of Lamb and Bailey Counties. Since 1957, water has been transported by pipeline from this well field to the city, a distance of about 50 miles. The city of Midland is reported to be developing a new well field in northwestern Martin County and northeastern Andrews County, about 35 miles north of the city. New sources of municipal supplies are being sought by some of the smaller towns and cities also, especially in the southern part of the Southern High Plains where the zone of saturation is thin in many places.

The Southwestern Public Service Co. has developed a well field in the sandhills area of Lamb County to supply water for an electric generating plant. This well field is perhaps the largest in the Southern High Plains used solely for industrial purposes.

Because of insufficient data, reliable estimates of the proportion of water withdrawn for municipal, industrial, and irrigation purposes are not available. Leggat (1954b, p. 4) estimated that in 1953 about 2 percent of the total amount of water pumped was used for municipal and industrial purposes. Undoubtedly this percentage would be too low for 1958; the percentage pumped for industrial and municipal purposes for that year might be about 4 percent.

Plate 7, which was prepared in 1960, shows, where data are available, the approximate thickness of the saturated zone of the Ogallala formation in the Southern High Plains of Texas prior to large-scale development of ground water for irrigation and other purposes. The map shows the saturated thickness as of about 1936–40 in all the area except as follows: Briscoe County, 1946; Yoakum County, 1944; parts of Terry County, 1944. In these counties there was very little, if any, large-scale development prior to the years mentioned; for practical purposes, therefore, the map can be said to represent conditions in the late 1930's. The map was prepared in part by superimposing a map showing contours on the water table prior to the large-scale development of ground water (map not shown in this report) on a map showing contours on the base of the Ogallala formation (pl. 2) and then drawing lines through the points of equal saturated thickness as indicated by the intersections of the two sets of contours. Lines of saturated thickness were then drawn on the basis of the saturated thickness in individual wells as control points.

The accuracy of the map depends to a great extent on the quantity and quality of the available control data. For some areas the quantity and quality of the data were adequate, whereas for others only a few data were available. Because of insufficient data, some parts of the area included in this report were omitted entirely from the map. As was to be expected, the data were more numerous and reliable in the more heavily pumped areas.

In comparing plate 7 with plate 4 which shows the approximate thickness of the saturated zone of the Ogallala formation in 1958, some variations in the boundary lines of the areas of given saturated thickness may indicate, in a few places, a greater thickness of saturated material in 1958 than prior to large-scale development of ground water. Extreme caution should be used in interpreting such differences as indicating actual gains in water, such as those resulting from recharge, for it is quite possible, even likely, that the differences are due to deficiencies in control data.

The quantity of water available to wells prior to the large-scale development of ground water, which in general began in the late 1930's, in 11 of the most heavily developed counties of the Southern High Plains was calculated from plate 7. The difference between the amount of water available at that time and the amount of water available in 1958, as shown in table 7, is an estimate of the amount of depletion of the aquifer in each of the 11 counties from the time large-scale development began, in general in the late 1930's to 1958.

The information given in table 7 indicates that in the 11 counties listed, the depletion of the ground-water reservoir amounted to almost 26 million acre-feet from the time large-scale development of the ground water began, in general in the late 1930's to 1958. The amount of depletion is probably less than the amount of water pumped. These 11 counties are in what could be termed the "heavily pumped area" and they include much of the area where irrigation has been practiced for the longest period of time. Leggat (1954b, p. 4) indicated that 4.3 million acre-feet of water was used to irrigate 2.9 million acres of land in 1953. On this basis the duty of water was about 1.5 acre-feet of water per acre of irrigated land. This compares with an average duty of water of 1.2 obtained by Cronin and Wells (1960, p. 49) in Hale County in 1955. The duty of water for the entire Southern High

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TABLE 7.—*Estimated depletion of the Ogallala formation in 11 counties in the Southern High Plains, late 1930's through 1958*

County	*Estimated amount of depletion late 1930's–58 (acre-feet)*
Bailey	736,000
Briscoe [1]	765,000
Castro	2,117,000
Deaf Smith	3,081,000
Floyd	2,683,000
Hale	4,091,000
Lamb	3,408,000
Lubbock	3,148,000
Parmer	2,444,000
Randall	1,287,000
Swisher	2,204,000
Total	25,964,000

[1] Data for 1946, see p. 74.

Plains being assumed to be about that cited above, it can be calculated that during the years 1954 to 1957, about 20 million acre-feet of water was pumped. Leggat (1954b, p. 5) estimated that from 1938 to the end of 1953 about 16 million acre-feet of water had been pumped from the Ogallala formation in the Southern High Plains. Thus, it is estimated that from 1938 to 1957, about 36 million acre-feet of water has been pumped from the Ogallala formation in the Southern High Plains. The average yearly pumpage since 1954 is estimated at about 5 million acre-feet.

WATER IN STORAGE

Ground water is stored in the Ogallala formation in the void spaces between the grains of sand and particles of silt and clay, and it is possible to recover only a part of the water in storage. As the water table declines and the saturated deposits become dewatered, some of the water will be retained in the voids by capillarity. Because of increased pumping lifts and decrease in well yields, it may be impractical and perhaps economically unfeasible to recover some of the water which would otherwise be available to wells in the lower part of the aquifer.

The volume of water stored in the Ogallala formation underlying the Southern High Plains is the product of the volume of saturated material and the porosity (the ratio, expressed in percentage, of void space to total volume). Such an estimate of the total quantity of water in storage would be of little value in itself, because much of the water will not drain from the material and therefore will not be available to wells. The proportion of water in storage that will be available to wells is determined by the specific yield of the aquifer, and the quantity of water in storage that would be available to wells is computed by multiplying the volume of saturated material by the specific yield. The volume of saturated material was determined from the isopachous map (pl. 4) which shows by means of contours the approximate thickness of the water-bearing material.

The contact of the Ogallala formation with the underlying rocks can generally be determined readily from drillers' logs. However, in parts of Midland, Glasscock, Andrews, and Howard Counties, the similarity of the lithology of the Ogallala and underlying Cretaceous formations makes impossible their separation in well logs. In such places the depth to the Triassic rocks was computed and assumed to be the base of the ground-water reservoir of the Ogallala. Therefore, some of the water included in the estimate may be in rocks of both formations. The saturated-thickness map (pl. 4) shows that in the area considered in this report the thickest sections of the aquifer in the Ogallala formation are, in general, in the northern half of the area. Within the areas enclosed by the zero contours, it is possible that some ground water may be obtained from wells in places, but the quantity would probably be small.

On the basis of a specific yield of 15 percent, it is estimated that as of 1958 the Ogallala formation in the area considered in this report had about 160 million acre-feet of water in storage that would be available to wells. This quantity of water represents the ultimate recoverable from the Ogallala, if there is no recharge. Table 8 shows a breakdown, by counties, of the amount of water available.

QUALITY OF WATER

Ground water in the Southern High Plains is used for practically all purposes. The standards used for measuring the chemical quality of the water differ depending upon the proposed use.

The analyses of three representative samples of water from the Ogallala formation are shown in table 9. Samples 1 and 2 are from wells in the area where the Ogallala is underlain by Triassic rocks; sample 3 is from a well in the area where the Ogallala is underlain by Cretaceous rocks. In general, it seems that the geology of the rocks underlying the Ogallala acts as a control on the quality of the water because the analyses of 42 water samples indicate that in the area where the Ogallala is underlain by Cretaceous rocks and south of that area the ground water has a markedly different mineral content than in the area where the Ogallala is underlain by Triassic rocks.

TABLE 8.—*Availability of ground water in the Ogallala formation in the Southern High Plains of Texas, 1958*

County	Volume of water in storage (acre-feet)	County	Volume of water in storage (acre-feet)
Andrews	2, 150, 000	Hockley	5, 200, 000
Armstrong	2, 850, 000	Howard	(2)
Bailey	6, 630, 000	Lamb	9, 590, 000
Briscoe	2, 322, 000	Lubbock	6, 512, 000
Castro	15, 476, 000	Lynn	800, 000
Cochran	3, 570, 000	Martin	2, 330, 000
Crosby	7, 913, 000	Midland	900, 000
Dawson	3, 100, 000	Motley	(1)
Deaf Smith	13, 400, 000	Oldham	(2)
Donley	1, 125, 000	Parmer	14, 975, 000
Dickens	(1)	Potter	2, 650, 000
Floyd	13, 240, 000	Randall	4, 475, 000
Gaines	9, 600, 000	Swisher	9, 888, 000
Glasscock	(1)	Terry	3, 435, 000
Garza	(1)	Yoakum	3, 989, 000
Hale	15, 424, 000		
		Total	161, 544, 000

1 Not estimated; quantity probably small.
2 Not estimated; probably not more than 500,000 acre-feet.

SUITABILITY OF WATER FOR PUBLIC SUPPLY

Water used for municipal and domestic supplies should be colorless, odorless, palatable, and wherever possible should conform to the limits of the U.S. Public Health Service for use on interstate carriers (1946, p. 371–384). The following limits are recommended for some of the most common minerals found in solution:

Iron (Fe) and Manganese (Mn) together should not exceed 0.3 ppm.
Magnesium (Mg) should not exceed 125 ppm.
Chloride (Cl) should not exceed 250 ppm.
Sulfate (SO_4) should not exceed 250 ppm.
Fluoride (F) must not exceed 1.5 ppm.
Dissolved solids should not exceed 500 ppm. However, if such water is not available, a dissolved solids content of 1,000 ppm may be permitted.

Of 42 samples collected in 1955 and 1956 from various types of wells throughout the Southern High Plains, only two exceeded the limit for iron, one sample from Oldham County and one from Armstrong County. The standard for chloride content was met in all samples collected. Only four samples from Lubbock, Gaines, Martin, and Midland Counties exceeded the limit for sulfate content.

The dissolved-solids content was more than 500 ppm in 25 of the 42 samples collected, and in five of the samples it was more than 1,000 ppm. All but three of the samples having an excess of 500 ppm of dissolved solids were from the area underlain by Cretaceous rocks (fig. 3) or to the south of that area.

TABLE 9.—*Chemical analyses of water from representative wells in the Southern High Plains of Texas*

[Analyses in parts per million except SAR, pH, and others as indicated]

	1 (June 20, 1955)	2 (Nov. 19, 1955)	3 (Aug. 16, 1956)
Silica (SiO_2)	39	55	65
Iron (Fe)	.00		.02
Manganese (Mn)	.00		.00
Calcium (Ca)	34	50	73
Magnesium (Mg)	42	36	81
Sodium (Na)	42	21	80
Potassium (K)	8.7	8.1	13
Bicarbonate (HCO_3)	331	280	295
Sulfate (SO_4)	41	34	220
Chloride (Cl)	27	36	165
Fluoride (F)	1.6	1.2	4.0
Nitrate (NO_3)	8.0	8.0	1.1
Sodium-adsorption-ratio (SAR)	1	.6	1.5
Boron (B)		.12	
Dissolved solids	404	386	889
Hardness, as $CaCO_3$	258	273	515
Noncarbonate hardness		44	273
Percent sodium	25	14	25
Specific conductance (micromhos at 25°C)	656	607	1,370
pH	7.8	7.8	7.8
Temperature (°F)	63	62	66

1. Irrigation well 3 miles north of Hereford, Deaf Smith County.
2. Irrigation well 31 miles southwest of Plainview, Hale County.
3. Irrigation well 10 miles south of Brownfield, Terry County.

Data collected by various agencies have demonstrated that fluoride in the drinking water of children reduces the incidence of tooth decay (Dean, Arnold, and Elvove, 1942, p. 1155–1179), but that concentrations exceeding 1.5 ppm may cause mottling of tooth enamel when the water is used continuously (Dean, Dixon, and Cohen, 1935, p. 424–442). The fluoride content was in excess of 1.5 ppm in 38 of the 42 samples collected. The fluoride content ranged from 1.1 to 3.0 ppm in 19 of 20 samples collected in the area where the Ogallala is underlain by Triassic rocks, but in 10 samples collected where the Ogallala is underlain by Cretaceous rocks, the fluoride content ranged from 3 to 5 ppm; seven samples had 4 ppm or more.

The hardness of water, the property that generally receives the most attention, is most commonly recognized by its effect upon soap consumption. Calcium and magnesium cause virtually all the hardness of ordinary water. These constituents are also the active agents in the formation of the greater part of the scale formed in steam boilers and in other vessels in which water is heated or evaporated.

The analyses of the 42 samples collected gave both the total and noncarbonate hardness. Carbonate hardness refers to the hardness in equivalence with carbonate and bicarbonate, and is almost completely removed by boiling. Sometimes this type of hardness is called temporary hardness. Water of high noncarbonate hardness usually contains large quantities of calcium and magnesium sulfates, chlorides, or nitrates in solution; it cannot be removed by boiling and is called permanent hardness.

A hardness classification commonly used by municipalities is as follows: less than 60 ppm, soft; 60–120 ppm, moderately hard; 121–200 ppm, hard; and more than 200 ppm, very hard.

The total hardness ranged from 182 to 640 ppm in the 42 samples analyzed, and three samples had slightly less than 200 ppm. In the area where the Ogallala is underlain by Triassic rocks, the total hardness ranged from 182 to 344 ppm and only five samples had noncarbonate hardness which ranged from 6 to 170 ppm. The remaining samples were from the area where the Ogallala is underlain by Cretaceous rocks and south of that area. These samples had total hardness ranging from 252 to 640 ppm, and all but one of the samples in this group had noncarbonate hardness ranging from 70 to 396 ppm.

The nitrate content of the 42 samples ranged from 0.4 to 33 ppm, except for one sample which contained 56 ppm. Hem (1959, p. 116–117) discussed the possible sources of nitrate in ground water which included the leaching of nitrate from the soil, especially in areas where soluble nitrate and gaseous ammonia are widely used in fertilizers, and the possibilities of organic pollution. He concluded that "* * * further investigations of the behavior of nitrate in ground waters are required, although an organic origin is probably indicated for most such occurrences." Hem (1959, p. 239) summarized recent investigations of the relation of nitrate in water to health (especially to the health of infants) which indicate that nitrate in amounts of more than 44 ppm may be a health hazard.

SUITABILITY OF WATER FOR IRRIGATION

A system of classification commonly used for judging the quality of a water for irrigation was proposed in 1954 by the U.S. Salinity Laboratory Staff (1954, p. 69–82). The classification is based chiefly on the salinity hazard as measured by the electrical conductivity of the water and the sodium hazard as measured by the sodium-adsorption-ratio (SAR). The relative importance of the dissolved constituents in irrigation water is dependent upon the degree to which they accumulate in the soil.

The SAR ranged from 0.6 to 4.0 in the 42 samples analyzed. In the same samples, the conductivity ranged from 476 to 1,750 micromhos per centimeter. In the area where the Ogallala is underlain by Triassic rocks the conductivity ranged from 476 to 892 and was less than 600 in 11 of the samples. In the area where the Ogallala is underlain by Cretaceous rocks and south of that area, the conductivity ranged from 743 to 1,750 micromhos and was more than 1,000 in 15 samples and 1,500 or more in 4 samples. The SAR and conductivity values indicate that the water is suitable for irrigation purposes.

Of the 42 samples collected, only one determination of boron was made. This was 0.12 ppm in sample 2 of table 9. Information from previous investigations indicates that boron does not constitute a problem in the water used for irrigation in the Southern High Plains.

The fact that ground water from the Ogallala formation has been used successfully for many years to irrigate crops in the Southern High Plains is an indication that the quality of the water meets the irrigation requirements.

SUITABILITY OF WATER FOR INDUSTRIAL USES

The quality standards for water used in industry vary greatly from one industry to another. The uniform quality and constant temperature of ground water may be prime factors in selecting water for industrial use, provided the mineral content of the water is within the specified limits. The temperature of the water as shown in the 42 samples ranged from 62° to 70° F.

Hardness and silica content are very important properties in the consideration of water for industrial use. Both properties are related to "boiler scale," an incrustation that forms on pipes, coils, and boilers. The scale reduces the flow of water through pipes and because of its insulating property may reduce heat-transfer properties of coils.

More (1940, p. 263) suggested the following allowable concentration of silica in water for boilers operating at various pressures:

Pressure (pounds per square inch)	*Silica (parts per million)*
<150	40
150–250	20
250–400	5
>400	1

Of the 42 samples analyzed, the silica content exceeded 40 ppm in 35 samples, 6 samples had a silica content between 30 and 40 ppm, and one sample contained 26 ppm. The data suggest that, in general, the silica content of the water in the Ogallala formation in the Southern High Plains is excessive for the use of water in boilers.

OUTLOOK FOR THE FUTURE

The estimated amount of water withdrawn from the Ogallala formation in the Southern High Plains each year so greatly exceeds even the most optimistic estimates of recharge that it must be concluded that ground water is being "mined," that is, it is coming from storage. Depth to water measurements show that since large-scale pumping was started about 1938, the water table has declined in practically all the Southern High Plains except in areas remote from pumping.

The pumping rate per unit draw down is largely a function of the thickness and permeability of saturated material. As the water table is lowered by the withdrawal of water and the saturated thickness is reduced, the yields of the wells decline and the pumping lifts increase. When it is no longer possible to increase the yields by deepening the wells or if the well penetrates the entire thickness of the Ogallala, then by lowering the pumps the yields will decline with further lowering of the water table. The lithology of the Ogallala varies both vertically and horizontally, and, in general, there is no reason to expect that the rocks in the lower part of the formation will contain and yield more water than the rocks in the upper part.

The length of time that any particular area of the Southern High Plains will produce water in sufficient quantities for large-scale irrigation is dependent chiefly upon the thickness of the water-bearing material underlying the area. Figure 7 shows that, in general, the thickest sections of saturated material are in the northern half of the area.

As the water level declines, it is important to regard the declines in water levels in terms of the thickness of the remaining saturated material. For example, a decline in the water table of 50 feet in an area where the remaining saturated thickness is 200 feet might not be as serious as a decline of 25 feet in an area where the remaining saturated thickness is only 50 feet. Areas where the saturated material is relatively thin can probably be expected to experience diminishing yields sooner than the areas where the saturated material is thicker. Even now (1958) the saturated thickness has been reduced as much as 50 percent or more in some areas where the saturated material was thin before large-scale pumping started about 1938. In such areas the yields of the wells have decreased appreciably.

The fact that the ground-water reserves are being depleted has been recognized, and methods of supplementing the water supply have been proposed. The Canadian River, the north boundary of the Southern High Plains, is the only perennial stream in the area. Plans are being discussed to divert water from this river to serve municipalities in the Southern High Plains. If some of the cities use river water, some ground water will be saved for irrigation and other uses, but the quantity will be small. The importation of water from other areas, although remotely possible, appears, infeasible. Materially increasing precipitation artificially by cloud seeding or other means is a remote possibility. If demineralization of saline water becomes practical, older geologic formations may be explored for water; however, the yields from the older formations probably would be small. If water is available in sufficient quantity for irrigation, its cost in relation to the value of the resulting products would be the decisive factor.

A more practical method for meeting the water-depletion problem is by improving water-conservation practices, through this method, at best will serve only to extend the life of large-scale agricultural production. Considering the economic value of irrigation, the extension of the water supply for even a few years is worthy of a concerted effort toward conservation.

The quantity of water that accumulates in the lakes and ponds of the Southern High Plains is not large by comparison with the estimated withdrawals. However, if all this water, which is now almost entirely lost by evaporation, were put to beneficial use either by direct application to the crops or by storing in the aquifer for future use, the life of the ground-water reservoir would be extended. Other conservation measures that may reduce the amount of water pumped include the reduction of ditch losses by distribution of water through underground pipes, the reduction or reuse of waste water from irrigated fields, and the production of crops requiring less water. Contour farming, terracing, and summer fallowing, have been recognized as effective land-practice methods of soil-water conservation. Well spacing to prevent mutual interference between wells is also a good practice.

Much of the present economy of the Southern High Plains is dependent on irrigation, which in turn is dependent on a diminishing supply of ground water. The only foreseeable means of extending the life of the ground-water reservoir is conservation of the present supply (a) by effective use, (b) by supplementation with water from lakes and ponds, and (c) by effective use of soil water. The life expectancy of the ground water, the life blood of the Southern High Plains, can be extended only by the efforts of everyone affected, both individually and collectively.

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