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GEOLOGY AND GROUND-WATER RESOURCES OF THE NORTHERN HIGH PLAINS OF TEXAS, PROGRESS REPORT NO. 1

by

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and the
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ABSTRACT

This is the first report on the progress of an investigation of the geology and ground-water resources of the Northern High Plains in Texas, an area of 9,300 square miles which includes the Texas Panhandle north of the Canadian River. With the exception of small amounts of surface water and of water from springs used by livestock, all the water used in this region is obtained from wells.

The climate of the Northern High Plains in Texas is semiarid. The topography is typical of the High Plains region--relatively flat plains sloping gently eastward separated by "breaks" or areas of valley slopes along the principal streams. The altitudes range from 4,735 feet above mean sea level in northwestern Dallam County to 2,167 feet in the valley of the Canadian River in eastern Hemphill County.

Most of the land in the Northern High Plains is used for ranching. Dry-land farming was well established in the 1920's and irrigation from wells in the shallow-water areas began in the 1930's. The drought from June 1951 to December 1956 greatly accelerated the development of irrigation. The number of irrigation wells and the acreage under irrigation in the Northern High Plains increased from 150 wells and 37,000 acres in December 1952 to 1,206 wells and 324,000 acres in December 1959. The amount of water pumped yearly is related to the annual precipitation, and the use of water per well during 1958 probably is representative of near average use. The withdrawals in the Northern High Plains during 1958 have been estimated at 420,000 acre-feet, of which 383,000 acre-feet, or more than 90 percent, was used for irrigation; 30,000 acre-feet was used by industry; and 7,000 acre-feet was used by municipalities.

The Ogallala formation of Tertiary age, the principal aquifer in the region, is from 0 to about 700 feet thick and underlies the surface of the plains areas and part of the breaks areas. The Ogallala was deposited upon a somewhat irregular land surface composed of older rocks of Cretaceous, Jurassic, Triassic, and Permian ages. The Ogallala formation is composed of gravel, sand, silt, and clay; the thickest sections of the formation occur in the old stream channels cut into the pre-Ogallala surface. The water occurs under water-table conditions, and the differences in the thickness of the water-saturated material are closely related to the differences in the thickness of the Ogallala formation. With the exception of the Cretaceous sandstones in northwestern Dallam County, water is obtained in relatively small amounts from the older rocks.

Near the Texas-New Mexico boundary, the water in Cretaceous sandstone is under artesian pressure. Sediments of Quaternary age on the surface of the plains areas and along the streams contain only minor amounts of water, but the sand and gravel of the stream terraces and the sand dunes on the plains and along the streams are locally important as areas favorable to natural recharge of ground water to the underlying formations.

The water available for development is represented largely by the amount of storage in the ground-water reservoir because the rate of replenishment is small compared to the potential withdrawal rate. Approximately 160,000,000 acre-feet of ground water was available from storage in 1958 in the Northern High Plains.

The average annual decline in static water levels from the winter of 1956 to the winter of 1960 ranged from 0.4 to 1.4 feet. These small declines reflect the relatively light pumpage for irrigation in the Northern High Plains.

In general, the water from the Ogallala formation is of good chemical quality except that it is hard and some of it has a high silica content. With the exception of one irrigation well, all the sampled water is suitable for irrigation of the crops grown in the region.

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INTRODUCTION

Location

The Northern High Plains in Texas, commonly known as the North Plains, as used in this report constitutes an area of 9,300 square miles, including all the Texas Panhandle north of the Canadian River (Figure 1). The Northern High Plains is a provincial term used to designate a part of the High Plains section of the Great Plains province. The area includes two water districts--the North Plains Ground Water Conservation District No. 2, extending from Hartley to Ochiltree Counties and including approximately 4,950 square miles; and the Dallam County Underground Water Conservation District No. 1, which includes 258 square miles in northwestern Dallam County (Plate 1).

Purpose and Scope

This report is a progress report setting forth the results of the investigation to date. The report has three main purposes: (1) to furnish up-to-date information on the development and availability of ground water; (2) to describe the progress and results of the cooperative ground-water studies; and (3) to describe the areas and problems that need further study.

The current investigation, which began in January 1956, is being done by the U. S. Geological Survey in cooperation with the North Plains Ground Water Conservation District No. 2 and the Texas Board of Water Engineers. The investigation was made under the administrative supervision of A. N. Sayre and P. E. LaMoreaux, successive chiefs of the Ground Water Branch of the Geological Survey, and under the immediate supervision of R. W. Sundstrom, district engineer in charge of ground-water investigations in Texas. Chemical analyses of ground-water samples were made in the laboratory of the U. S. Geological Survey in Austin, Texas.

Previous Investigations

Johnson (1901, 1902) made the first studies of the underground water of the High Plains, and Gould (1906, 1907) made the first studies of the geology and ground-water resources of the Texas Panhandle. Patton (1923) included the

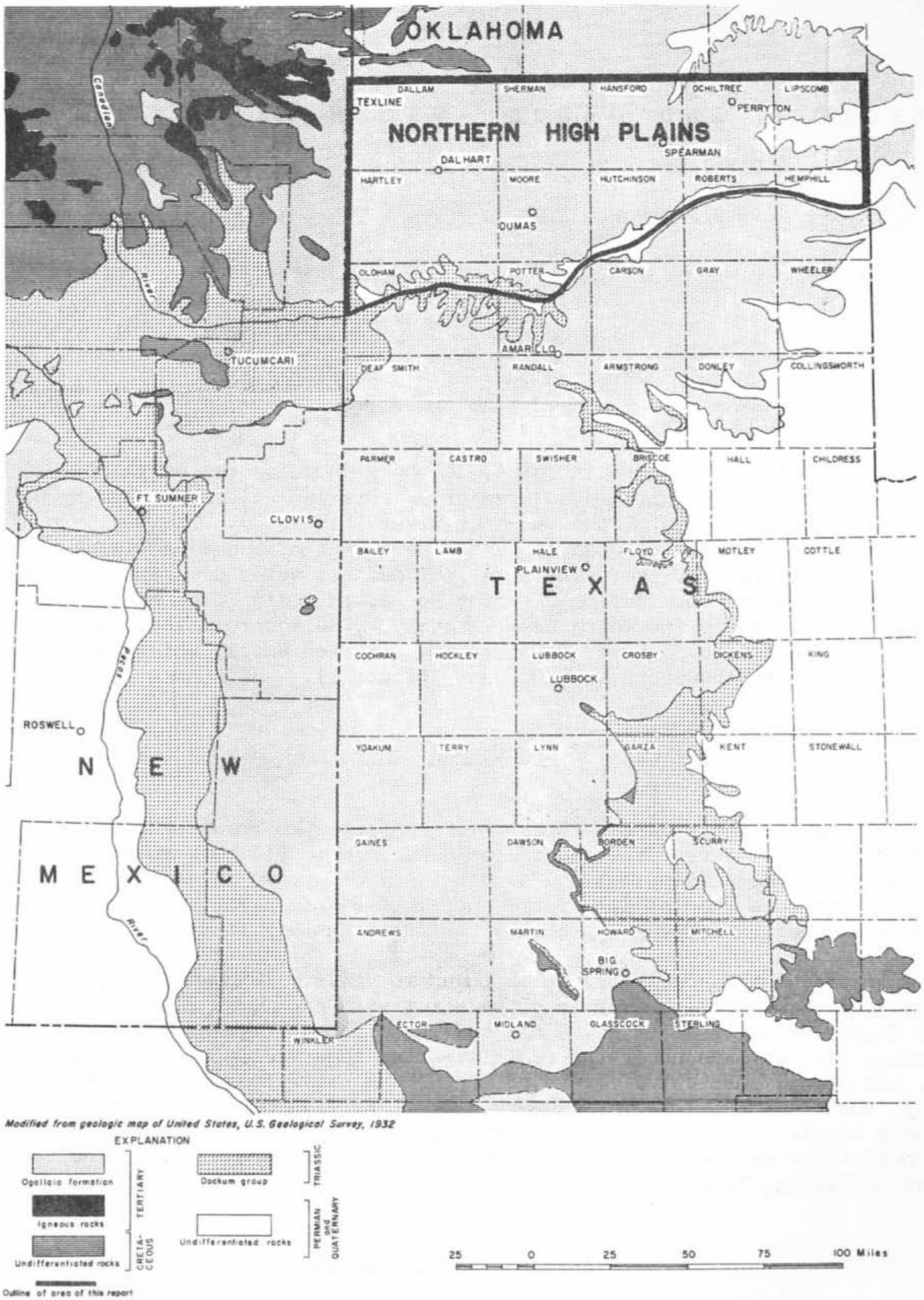


FIGURE 1.— Geologic map of the High Plains in Texas and adjacent areas, showing location of the Northern High Plains in Texas

logs of water wells and a discussion of ground water in his report on the geology of Potter County. Reed and Longnecker (1932) made a detailed study of the Ogallala formation in Hemphill County. Theis, Burleigh, and Waite (1935) made a ground-water reconnaissance of the High Plains including Texas in 1933-34.

Since 1936 the U. S. Geological Survey, in cooperation with the Texas Board of Water Engineers, has made inventories of water wells and measured water levels in observation wells in the Northern High Plains. Records of water wells have been published for the following counties: Dallam (Follett, 1937), Hansford (Broadhurst, 1936), Hartley (Follett and Harrison, 1938), Ochiltree (Davis, 1939), Oldham (Shafer and Follett, 1938), Potter (Smyers, 1938), and Roberts (Follett and Foster, 1940). In addition to well records, these reports contain measurements of water levels, well logs, water analyses, and maps showing well locations. The water-level measurements made from 1937 to 1941 have been published by the U. S. Geological Survey (issued annually) and summarized by Follett (1954a, 1954b, 1957) and Rayner (1959). The water-level measurements made in Hansford, Hartley, Hutchinson, Moore, Ochiltree, and Sherman Counties for 1956-60 have been published by the North Plains Ground Water Conservation District No. 2 (1958, 1959, 1960).

Ground-water conditions in parts of Moore County have been described by Sundstrom (1942a, 1942b).

The Northern High Plains in Texas is included in the area covered by the report on public-water supplies in western Texas by Broadhurst, Sundstrom, and Weaver (1951). The report includes chemical analyses of public supplies and data on the amount of water used.

Five reports on areas adjacent to the Northern High Plains in Texas containing information applicable to studies in this area are (1) Artificial-recharge experiments at McDonald well field near Amarillo, by Moulder and Frazor (1957); (2) Geologic studies of Union County, New Mexico, by Baldwin and Muehlberger (1959); (3) the report on the geology and ground-water resources of the east-central part of Union County, New Mexico, by Baldwin and Bushman (1957); (4) Geology and ground-water resources of Texas County, Oklahoma, by Schoff (1939); and (5) Geology and ground-water resources of Cimarron County, Oklahoma, by Schoff (1943).

Other geologic reports which include discussions of the Northern High Plains are Evans and Meade's (1944) report on the Quaternary of the Texas High Plains, Roth's (1949, 1955) discussions of the paleo-geology of the Texas Panhandle, and McKee and other's (1956) folio of paleotectonic maps of the Jurassic system including the northwestern corner of the report area, and Totten's (1956) report on the general geology and petroleum production of the Texas and Oklahoma Panhandles.

Since 1953 the Texas Agricultural Extension Service has published annual reports on the development of irrigation in the Texas High Plains by Thurmond (1952, 1953, 1954), Jones and Thurmond (1955), Black (1956), and Sherrill (1957, 1958, 1959). Bloodgood, Patterson, and Smith's (1954) report on evaporation studies in Texas includes two stations pertinent to the Northern High Plains--Amarillo and Dalhart.

A field office of the U. S. Geological Survey was maintained in Dumas from 1952 to 1954, and investigations of ground water were conducted in Moore, Hartley, and Dallam Counties. The data collected form part of this report.

In 1959 the Geological Survey, in cooperation with the Texas Board of Water Engineers, made a reconnaissance of the ground-water resources of the Canadian River basin in Texas. The fieldwork in the Northern High Plains part of this investigation consisted of testing 125 wells, collecting samples of water from 22 municipal wells, measuring the depth to water in about 100 wells, and determining the altitude of several dozen control points with an altimeter. Maps were prepared showing the locations of the irrigation, industrial, and municipal wells; the thickness of fresh-water saturated material; and the depth to water in irrigable areas. Estimates were made of the volume of water pumped during 1958 and the volume of water available from storage in 1958. Most of this information has been incorporated in this report.

Acknowledgments

Appreciation is expressed for the personal assistance given during the investigation by Mr. J. W. Buchanan, Manager, and other officials of the North Plains Ground Water Conservation District No. 2, and for help obtained from Mr. W. A. Gray, secretary of the Dallam County Underground Water Conservation District No. 1.

Most of the information on irrigation wells was obtained from the well logs and other data supplied to the water districts by the drillers and pump companies. Logs of oil and gas wells, logs of seismic "shot holes," and information on the geologic formations at shallow depths were obtained from the oil companies and the well-logging service companies.

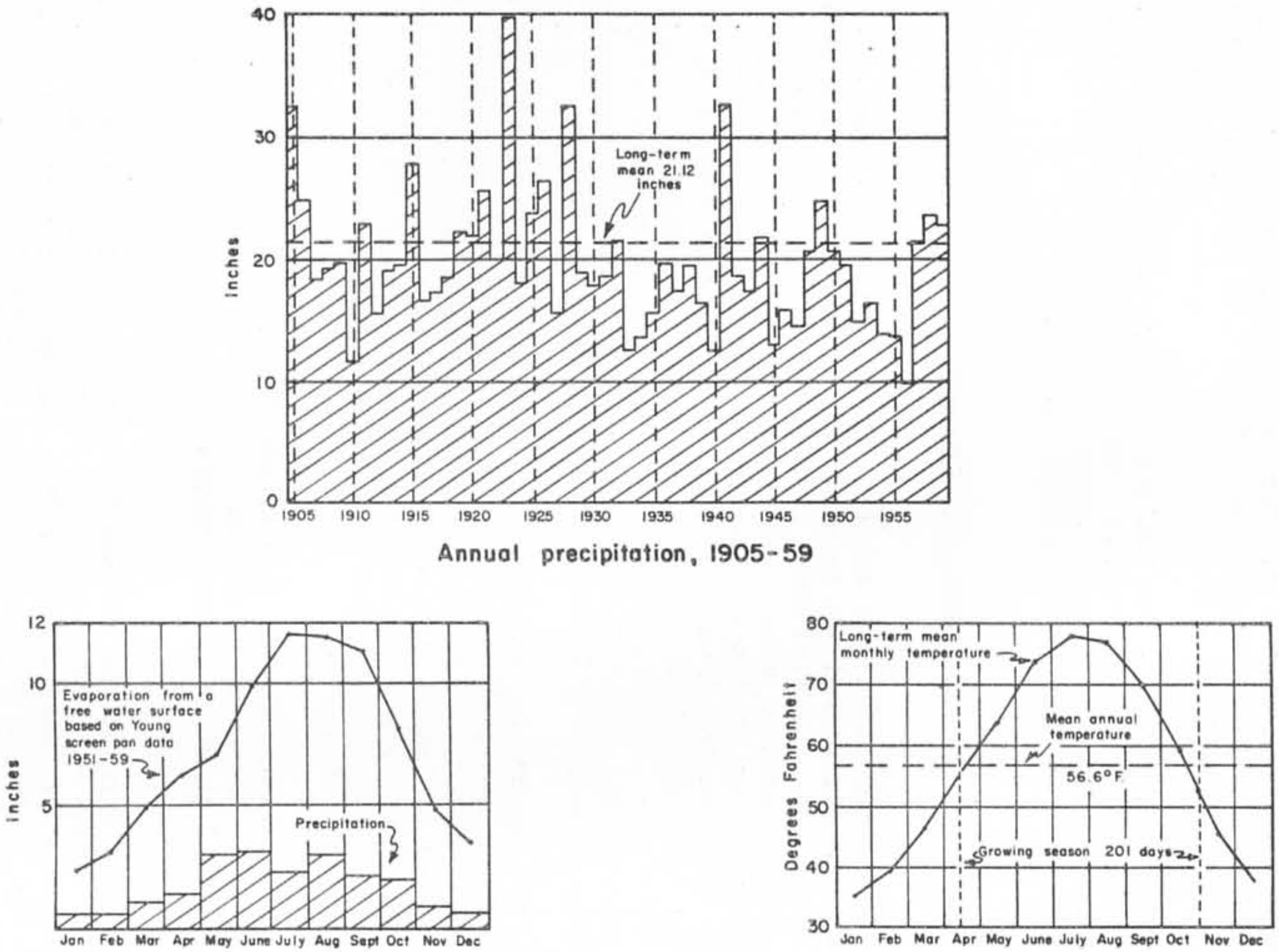
Acknowledgment also is made for the information furnished by officials of the cities, the industries, and the State and Federal agencies, especially the Soil Conservation Service of the U. S. Department of Agriculture, and the county agricultural agents. An important part of the investigation is the compilation of data obtained from many different sources, and the cooperation of organizations and individuals interested in the ground-water resources of the Northern High Plains has helped considerably with the work now in progress.

GEOGRAPHY

Climate

The climate of the Northern High Plains in Texas is characterized by low humidity, a wide range in temperature and precipitation, and frequent to occasional windstorms. Although dry-land farming is and has been practiced extensively, crop failures may occur during drought periods.

The climate at Amarillo, Texas, documented by records collected continuously since 1905, is typical of the area north of the Canadian River (Figure 2). The long-term mean annual precipitation at Amarillo is 21.12 inches. Most of the precipitation occurs during the growing season which usually averages 201 days starting in mid-April and extending to the first part of November. A part of the precipitation in winter occurs as snow which annually averages 18.7 inches. Precipitation ranges widely from year to year, from nearly 40 inches in 1923 to slightly less than 10 inches in 1956. Most of it occurs during local thunderstorms. The annual averages for different stations in the



Annual precipitation, 1905-59

Average monthly evaporation and long-term mean monthly precipitation

Mean monthly temperature

FIGURE 2. - Precipitation, temperature, and evaporation at Amarillo

(From records of U.S. Weather Bureau and Texas Board of Water Engineers) region are similar although for any particular year there may be wide variations from place to place. Records for some years show that a few areas may have above-normal precipitation when most of the others have several inches below average. In other years the precipitation pattern may be reversed.

The mean annual temperature at Amarillo is about 57°F. The mean monthly temperature ranges from a low in January of about 35°F to a high in July of about 78°F. The temperature range during the day commonly is as much as 30°F. The highest recorded temperature at Amarillo was 108°F in June 1953 and the lowest was minus 16°F in February 1899.

The high summer temperatures, low humidity, and strong breezes are responsible for a high rate of evaporation. The evaporation from a free-water surface, based on observation in a Young screen-type evaporation pan at Amarillo, averaged about 86 inches for the 9-year period, 1951-59.

Topography and Drainage

For purposes of description, the Northern High Plains is divided into two topographic types--the plains and the breaks. The plains area, including about 5,300 square miles, slopes eastward about 10 feet per mile and is poorly drained. The breaks area, which includes about 4,000 square miles, has been highly dissected and has a rolling to rugged topography. The breaks area is drained from the south by the Canadian River and its tributaries and from the north by the tributaries of the North Canadian (Beaver) River in Oklahoma. The delineation of the breaks area is shown on Plate 1. Most of the breaks country is unsuitable for cultivation, although there are several irrigation wells on the flood plain and valley slopes of Palo Duro Creek in Hansford County.

The runoff from the breaks area contributes flow to the streams, whereas, the plains area contributes practically no runoff. Nearly all the precipitation on the plains is evaporated, absorbed by the soil, or collected in several hundred small depressions or lakes scattered throughout the area. Water ponded in the lakes ultimately evaporates or percolates into the ground. Most of the lakes are circular in outline and range from 0.1 mile to more than 1 mile in diameter, averaging about 0.3 mile.

The Northern High Plains ranges in altitude from a high of 4,735 feet above mean sea level in northwestern Dallam County to a low of 2,167 feet in the valley of the Canadian River in eastern Hemphill County where the river enters Oklahoma.

The flow in the two principal streams draining the area--the Canadian and the North Canadian Rivers--is from runoff in New Mexico, Oklahoma, and Texas, and from springs and seeps issuing chiefly from the Ogallala formation. Punta de Agua Creek is the principal tributary in Texas contributing an appreciable amount of runoff to the Canadian River. The principal tributaries to the North Canadian River are Coldwater Creek, Palo Duro Creek, and Wolf Creek. The springs and seeps sustain the base flow of the Canadian River during the winter, but large evaporation and transpiration losses consume most and sometimes all of the base flow during the summer. The average annual flow of the Canadian River, as measured at a gaging station near Amarillo, is about 340,000 acre-feet for the periods 1924-25, 1938-57, and near Canadian is about 450,000 acre-feet for the period 1938-57 (Texas Board of Water Engineers, 1958, pages 38-39).

Agricultural and Industrial Development

Although most of the land in the Northern High Plains is used for ranching, the amount of cultivated land has increased since about 1900 when nearly all of it was used for ranching. The completion of the Fort Worth and Denver Railroad across the Northern High Plains in 1888 opened the region to farming; and by the early 1920's dry-land farming was well established, wheat and grain sorghum being the principal crops. The size of the area under cultivation was increased considerably by 1926 by the rapidly expanding use of the gasoline tractor.

Irrigation from wells started in the shallow-water areas in northwestern Dallam County and along Palo Duro Creek in Hansford County. By 1937 there were 16 irrigation wells and about 2,000 acres were under irrigation in the Northern High Plains. The drought from June 1951 to December 1956 greatly accelerated the development of irrigation; and by December 1959 there were 1,206 irrigation wells and about 324,000 acres were under irrigation.

Practically all the industrial development in the Northern High Plains is related to the petroleum industry--the production and refining of oil, the production and transmission of natural gas, the extraction of helium from natural gas, the manufacture of carbon black and petro-chemicals, and the use of natural gas as industrial fuel. The large Panhandle gas field includes northern Potter County, most of Moore and Sherman Counties, and part of western Hansford County. The Panhandle oil field extends over much of western Hutchinson County and small parts of the adjoining counties. Most of the development of the Panhandle gas and oil fields occurred between 1926 and 1937. Since 1955 several other oil and gas fields have been found in Hansford and Ochiltree Counties.

The population of the principal cities, according to the 1960 census, are as follows: Dumas, 8,477; Dalhart, 5,160; Perryton, 7,903; and Spearman, 3,555.

The Northern High Plains is served by three railroads: Fort Worth and Denver, Rock Island, and Santa Fe; two transcontinental highways, U. S. Route 54 and U. S. Route 87; and two commercial airports at Dalhart and Dumas.

Ground-Water Conservation Districts

In the Northern High Plains two ground-water conservation districts--the North Plains Ground Water Conservation District No. 2 and the Dallam County Underground Water Conservation District No. 1--have been validated by the State Legislature. The general nature of the work done by the districts is the conservation, protection, recharging, and prevention of waste of the underground water within the boundaries of the districts.

The North Plains Ground Water Conservation District No. 2 was organized in December 1954 and validated in March 1955. This district (Plate 1) covers all or parts of six counties and includes 4,950 square miles, or about 50 percent of the Northern High Plains. The landowners in the district are represented by 35 elected officials--5 members of the board of directors and 30 county committeemen, 5 from each county. The district is very active in its work. It employs a manager, a technician, and a secretary; and the office is in the North Plains Savings and Loan Building in Dumas.

The district's requirements on the spacing of wells promotes the efficient development of its water resources; and its records of well-completion data, well logs, and well measurements are important sources of information.

The Dallam County Underground Water Conservation District No. 1 was organized in December 1950 and validated in April 1959. This district (Plate 1) includes 258 square miles in northwestern Dallam County. The landowners in this district are represented by 5 elected officials--all members of the board of directors.

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES

The distribution of the outcrops of the principal geologic formations in the Texas High Plains and adjoining areas is shown in Figure 1. The plains topographic subdivision is underlain by the Ogallala formation. Older rocks of Triassic and Permian age crop out in the canyon of the Canadian River in Oldham, Potter, southeastern Moore, and Hutchinson Counties. The breaks topographic subdivision along the Canadian River and its tributaries includes the outcrops of both the older rocks and the Ogallala formation. Most of the breaks areas along the tributaries of the North Canadian River are made up of outcrops of the Ogallala formation.

The Ogallala formation is the principal water-bearing formation (aquifer) in the Northern High Plains. The relation of the Ogallala formation to the underlying rocks, the thickness of the Ogallala, and the water table are shown in Plate 2. Table 1 shows the thickness of the various geologic formations and gives brief descriptions of their character and water-bearing properties.

Permian System

The Permian rocks, shown together with the Quaternary rocks on the geologic map (Figure 1), are the oldest exposed in the Northern High Plains. They crop out in the canyon of the Canadian River in western Oldham County, Potter County, southeastern Moore County, Hutchinson County, and Hemphill County. The thickness of the Permian strata in the subsurface ranges from about 3,000 feet in western Sherman County to more than 5,400 feet in Lipscomb County. The upper two-thirds of the Permian rocks in the Northern High Plains consists of salt, gypsum, anhydrite, red shale, and sandstone; the lower one-third is composed of limestone, dolomite, and shale. The Alibates lentil of the Quartermaster formation, the Blaine gypsum, and the Glorieta sandstone of local usage, the key beds in the upper part of the Permian strata, are shown on geologic section A-A' (Plate 2). Because the water in the Glorieta sandstone is highly mineralized, the possibility of using this formation as a reservoir for the disposal of saline water produced by the petroleum industry should be investigated. Small amounts of generally saline water are obtained from the Permian rocks.

Table 1. Geologic formations and their water-bearing properties, Northern High Plains

System	Series	Group	Stratigraphic unit	Approximate thickness (feet)	Character of rocks	Water-bearing properties
Quaternary	Pleistocene and Recent			0 - 100+	Sand, silt, clay, and gravel of alluvial origin dune sand and lake clay.	Yields small amounts of water. Forms important areas of natural recharge locally.
Tertiary	Pliocene		Ogallala formation	0 - 700	Sand, silt, clay, gravel, and caliche.	Principal source of water in Northern High Plains in Texas.
Cretaceous			Graneros shale	0 - 44	Dark-gray shale.	Yields no water to wells.
			Dakota sandstone	0 - 181	Yellow to brown sandstone and gray shale.	Supplies irrigation and municipal wells in northwestern part of Dallam County.
			Purgatoire formation	0 - 59	Dark-gray shale and light-colored to white sandstone.	do
Jurassic				0 - 217	Green and red shale, white to brown lenticular beds of sandstone.	Yields small amounts of water to stock wells in central Dallam County.
Triassic		Dockum		0 - 1,000	Dark-gray and variegated shale, red, brown, or gray sandstone. About half sand and half shale.	Yields small amounts of water to stock wells in parts of eastern Dallam County.
Permian				3,000-5,400+	Salt, gypsum, anhydrite, red shale, and sandstone in upper two-thirds; limestone, dolomite, and shale in lower one-third.	Yields small amounts of water, generally saline.

Triassic System

Dockum Group

The beds of the Dockum group, generally considered to be Late Triassic in age, lie on the eroded surface of the Permian rocks. In the Northern High Plains, the Triassic rocks are composed of about half sandstone and half shale. The sandstone is red, brown, or gray; the dominant color of the shale is dark red. The triassic rocks are from 300 to 1,000 feet thick in Dallam and Hartley Counties and are absent in most of the remainder of the region. About 100 feet of Triassic rocks have been reported in wells in parts of Sherman and western Hansford Counties.

More than 100 feet of red fresh-water-bearing sand, red clay, and shale have been reported in logs in the lower parts of rocks penetrated by many irrigation wells in Moore, Sherman, and Hansford Counties, and in northwestern Hutchinson County. These red sediments overlie red beds of Permian age and are probably Triassic in age. The water is satisfactory for irrigation; and the analyses of water samples from wells K-3 and R-6, north of Gruver in Hansford County (Table 5 and Plate 1) are almost identical to samples from irrigation wells supplied entirely from the Ogallala formation. The local distribution of the red fresh-water-bearing sand and the good quality of the water indicate that the red sediments occur as isolated hills covered and surrounded by sediments of Ogallala age, and the source of the water is the Ogallala formation.

In western Dallam and western Hartley Counties, the Triassic rocks are overlain by Jurassic rocks. Elsewhere in the Northern High Plains, they are overlain by the Ogallala formation of Pliocene age.

The sandstones of Triassic age yield small quantities of water to stock wells in parts of eastern Dallam County.

Jurassic System

As much as 217 feet of green and red shale and white to brown lenticular beds of sandstone of Jurassic age have been reported in oil-test wells in an area of about 625 square miles in western and central Dallam County. Similar strata have been reported in the logs of water wells drilled in an adjoining area of about 75 square miles in the northwestern part of Hartley County. The Jurassic rocks overlie the Triassic; they are, in turn, overlain by Cretaceous rocks in the northwestern part of Dallam County and elsewhere by the Ogallala formation of Pliocene age. The sandstones of Jurassic age yield small quantities of water to stock wells in central Dallam County.

Cretaceous System

Rocks of Cretaceous age underlie an area of about 150 square miles in the northwestern part of Dallam County and are overlain by the Ogallalla formation of Pliocene age. The Cretaceous rocks consist of white, and yellow to brown sandstone, and gray to dark-gray shale comprising the Purgatoire formation, Dakota sandstone, and Graneros shale, in ascending order. A total thickness of

284 feet of Cretaceous rocks has been reported by Baldwin and Bushman (1957, page 36) in an irrigation well $3\frac{1}{2}$ miles south of Texline and a few yards east of the Texas-New Mexico boundary (Plate 1).

The sandstones in the Dakota sandstone and Purgatoire formation are the principal aquifers in the Cretaceous formations. They supply water of good chemical quality to the two municipal wells at Texline and a few irrigation wells near the city. Cretaceous rocks also supply several irrigation wells in Union County, New Mexico, adjacent to the Texline area and more than 150 irrigation wells in southeastern Colorado.

Tertiary System

Ogallala Formation

The Ogallala formation was named for the town of Ogallala, Nebraska, (Darton, 1898, pages 732-742). The Ogallala of Pliocene age underlies the surface of the plains areas and was deposited on the eroded surfaces of the Cretaceous, Jurassic, Triassic, and Permian rocks. The Ogallala sediments were eroded from the "ancient" Rocky Mountains, more than 100 miles west of the Texas Panhandle, and were transported by streams to this area and farther to the east. The earliest sediments of Ogallala age, composed mainly of gravel and coarse sand, filled the valleys cut in the pre-Ogallala surface by the larger eastward-flowing streams. After these valleys were filled, deposition continued until the Ogallala sediments covered all the ancient land surface; the action of the wind helped distribute the finer sediments. Then conditions changed and the streams cut valleys into the Ogallala--in some places completely through the formation into the older rocks. As erosion continued in the headwaters of the Canadian River and other streams north of the Texas Panhandle, the Ogallala formation was removed from the area between the Rocky Mountains and the High Plains so that now the formation in this region extends only a few miles into New Mexico.

The Ogallala is composed of light-colored sand, silt, clay, and gravel; white limy material called caliche is found near the top of the formation. The formation is thicker in the old valleys cut into the pre-Ogallala surface, the variations in the thickness of the water-saturated material shown on Plate 4 being closely related to the thickness of the Ogallala formation. The maximum thickness of the Ogallala in the Northern High Plains is about 700 feet in southwestern Ochiltree County.

Because the sediments were deposited by streams, their character varies both vertically and laterally. The sand, silt, and clay are distributed irregularly throughout the formation. Generally, however, the gravel is more abundant in the basal part of the formation, especially in the old stream channels cut into the pre-Ogallala surface.

The Ogallala formation is the principal source of ground water in the Northern High Plains. In addition to being the source for nearly all the municipal and industrial water supply in the Northern High Plains, the Ogallala formation furnished water to more than 1,200 irrigation wells in 1959. The average production of 125 irrigation wells measured in 1959 was about 700 gpm (gallons per minute), and this figure is representative of the large-capacity wells pumping from the Ogallala formation. The estimated volume of water pumped during 1958 for irrigation, industrial, and municipal uses in the Northern High Plains was about 420,000 acre-feet.

Quaternary System

Pleistocene and Recent Series

Evans and Meade (1944, page 486) classified the Pleistocene and Recent sediments of the Texas High Plains into three types: (1) lake or pond deposits, (2) stream-valley deposits, and (3) wind deposits. The lake or pond deposits are predominantly nearly impermeable clay, which retards the infiltration of surface water. The sand and gravel of the stream-valley deposits and the sand dunes on the plains and along the streams are hydraulically connected with the Ogallala formation and are locally important as areas favorable to the natural recharge of ground water. The Quaternary sediments in the Northern High Plains are thin, ranging from 0 to slightly more than 100 feet in thickness.

Reed and Longnecker (1932) mapped the stream terraces along the Canadian River in Hemphill County and identified three terrace levels, described according to their elevations above the flood plain of the river: 40 feet, 65 to 90 feet, and 195 to 220 feet. They also mapped the extensive area of sand dunes in Hemphill County north of the Canadian River. This area of sand dunes extends across the southern part of adjacent Lipscomb County. Other extensive areas of sand dunes are in western Hartley County and in Dallam County.

Small amounts of water for livestock and domestic supplies in the valleys are obtained from the sand and gravel of Quaternary age.

OCCURRENCE OF GROUND WATER

The Ogallala formation is the principal water-bearing formation in the Northern High Plains in Texas. Ground water occurs in the formation under unconfined, or water-table conditions--that is, the water does not rise in wells above the level at which it is found in the formation. The water table is the surface at which unconfined water stands in unpumped wells and is also the top of the water-saturated part of the formation. Springs and seeps occur in valleys that have been cut through the water table. The depth to water in wells in the Ogallala formation ranges from less than 50 feet below the surface in the valleys to about 400 feet in parts of the plains areas (Plate 3). The average depth to water in wells in the Northern High Plains is about 210 feet, and in large parts of the plains areas the depth to water is between 150 and 200 feet.

The water in wells tapping the permeable Cretaceous beds in northwestern Dallam County rises above the level at which it is found and, consequently, is said to occur under artesian conditions. In some places the water rises above the level of saturation in the overlying Ogallala formation. The Cretaceous beds are inclined or dip to the east and beds of dense clay and shale overlying the permeable sandstone tend to confine the water under artesian pressure. Additional studies are needed to show the extent and characteristics of the water-bearing beds in the Cretaceous and older formations.

Natural Recharge

The source of water to the Ogallala formation is precipitation on its surface in Texas and New Mexico. Part of the water that falls in New Mexico moves eastward into Texas as underflow. The source of the artesian water in the older formations is precipitation in an area in northeastern New Mexico where the formations are at or near the surface. Contrary to common belief, the recharge area for fresh-water-bearing deposits in Texas does not extend to the Rocky Mountains.

The amount of precipitation that becomes recharge is a small part of the total. Measuring the actual amount is a problem yet to be solved; however, it probably averages only a fraction of an inch per year. The areas where the opportunities for recharge are most favorable are the areas where the surface soils are most permeable and where runoff accumulates in some of the topographically low areas. The sandhill areas in western Dallam and Hartley Counties and southern Lipscomb and northern Hemphill Counties appear to be favorable for recharge. The small drainageways cut into the Ogallala also are favorable areas for recharge. Overland runoff concentrates in the drainageways and part of it is lost underground through the coarse sandy material forming the bottoms of the drainageways. Further study is needed to determine whether the lakes substantially recharge the ground-water reservoir. The accumulations of poorly permeable silt deposits in the bottoms of the lakes may prevent most of the water from percolating into the ground. Most of the water held near the surface is ultimately consumed by evaporation or is transpired by plants.

Movement of Ground Water

Ground water moves slowly from areas of recharge to areas of discharge. Under natural hydraulic gradients water moves in the Ogallala only a few inches per day in the direction of the slope of the water table. In general the water table slopes toward the east at the rate of about 10 feet per mile and is approximately parallel to the general slope of the land surface (Plate 2). However, the water table slopes at greater rates toward the centers of areas of heavy pumping and toward valleys cut below the water table. Altitudes of wells are required before a contour map that shows the configuration of the water table can be made.

Water may move from one geologic formation to another. For example, in Dallam County the artesian pressure in the sandstones of Cretaceous age is released where the beds come in contact with the Ogallala formation. Thus, water moves from the Cretaceous beds into the Ogallala.

Natural Discharge

Water is discharged naturally from the Ogallala formation along the streams and drainageways that have cut into or through the zone of saturation. Some of the water is discharged from springs and becomes streamflow; a larger part is discharged from seeps and is consumed by plants and evaporation.

Some of the water being discharged as springs and seeps from the Permian rocks along the Canadian River in the breaks areas is water that has moved from the Ogallala formation into the Permian rocks. Most of the fresh water found in the Permian rocks is believed to be water that has recharged the Permian in this fashion.

The amount of water discharged by wells has increased each year as more and more wells are used for irrigation. Ultimately, the well discharge will reduce noticeably the natural discharge, but no appreciable reduction has occurred so far.

USE OF GROUND WATER

History

The earliest developments of irrigation by the white settlers in the Northern High Plains were small tracts irrigated by water from springs and streams. Gould (1906, page 47) described several developments along Palo Duro Creek in Hansford County, including one tract of 35 acres; he also described the irrigation of 150 acres of alfalfa and garden in northwestern Dallam County using water from Coldwater Creek (1907, page 53). The flow of Coldwater Creek at this locality, about one-half mile downstream from Buffalo Springs, was reported at that time to be approximately 5 cubic feet per second, or about 2,250 gpm.

The earliest developments of irrigation using water from wells were in Dallam and Hansford Counties in the early 1930's. Three irrigation wells in the Valley of Palo Duro Creek in Hansford County were reported by Broadhurst (1936), and 13 irrigation wells in the shallow-water area in northwestern Dallam County were reported by Follett (1937). These 16 wells were used to irrigate an estimated 2,000 acres.

The drought extending from 1951 to 1956 (Figure 2) greatly accelerated the development of irrigation. In 1950 there were 120 irrigation wells in use to irrigate about 15,000 acres in the Northern High Plains; by December 1952 there were 150 wells used to irrigate 37,000 acres; and by December 1956, 987 wells were used to irrigate 284,000 acres (Thurmond, 1952, 1953, 1954; Jones and Thurmond, 1955; and Black, 1956). The above-average precipitation from 1957 to 1959 was one factor in slowing down the rate of irrigation development, but by December 1959 there were 1,206 irrigation wells used to irrigate 324,000 acres in the Northern High Plains (Sherrill, 1957, 1958, 1959). The number of irrigation wells and the acreage under irrigation in the Northern High Plains from 1950 to 1959, by years, are shown in Figures 3, 4, and 5.

As previously mentioned, practically all the industrial development in the Northern High Plains is related to the petroleum industry which started with the development of the Panhandle oil and gas fields between 1926 and 1937. In the early 1940's, industrial development and the industrial use of ground water were accelerated by the construction of two petrochemical plants for military needs. Most of the industrial development has been in Moore and Hutchinson Counties, and the municipal use of ground water also increased in this area. The recent oil and gas developments in Hansford and Ochiltree Counties have increased the population and consequently the municipal use of ground water in Spearman and Perryton.

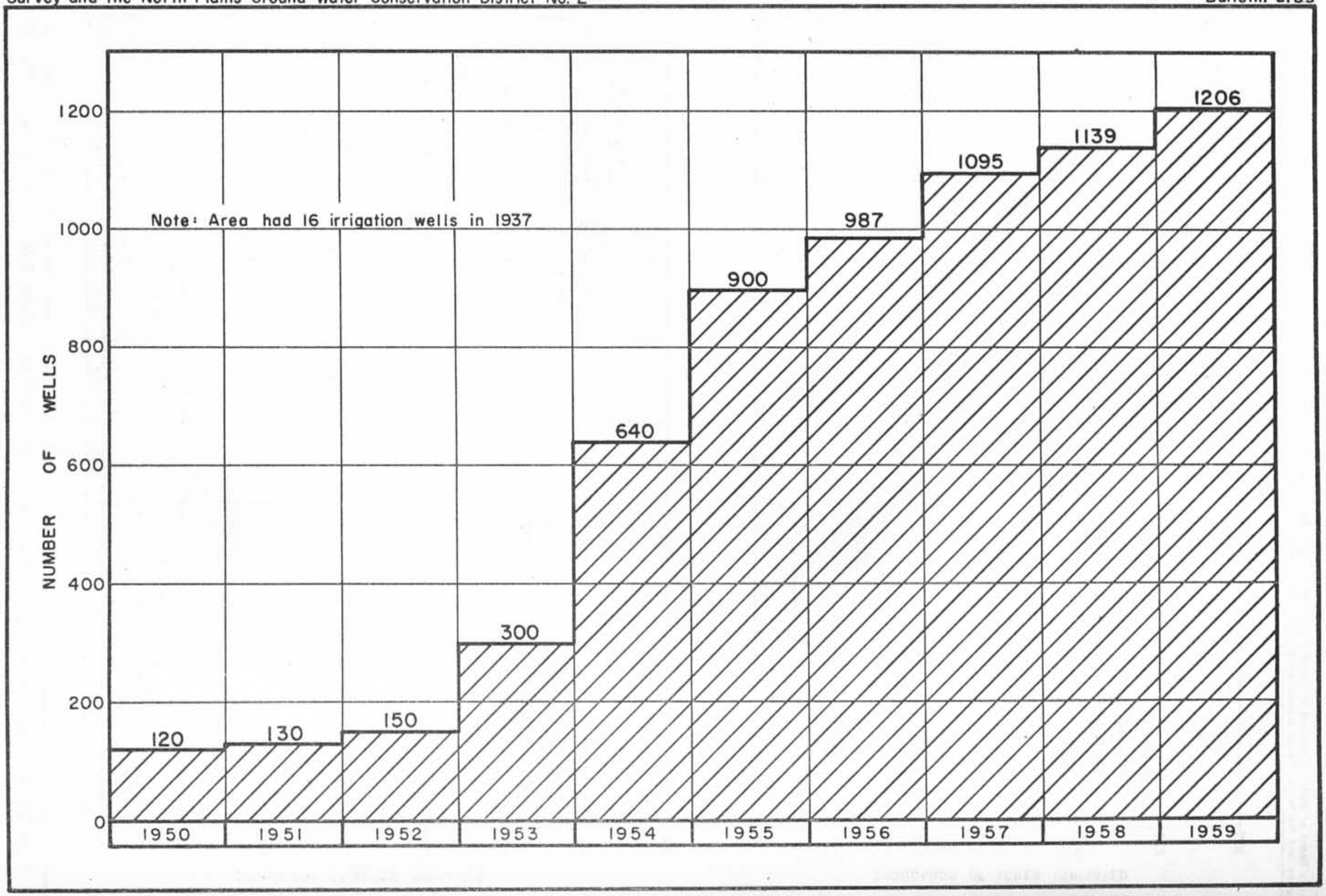


FIGURE 3.—Irrigation wells in Northern High Plains in Texas, 1950-59

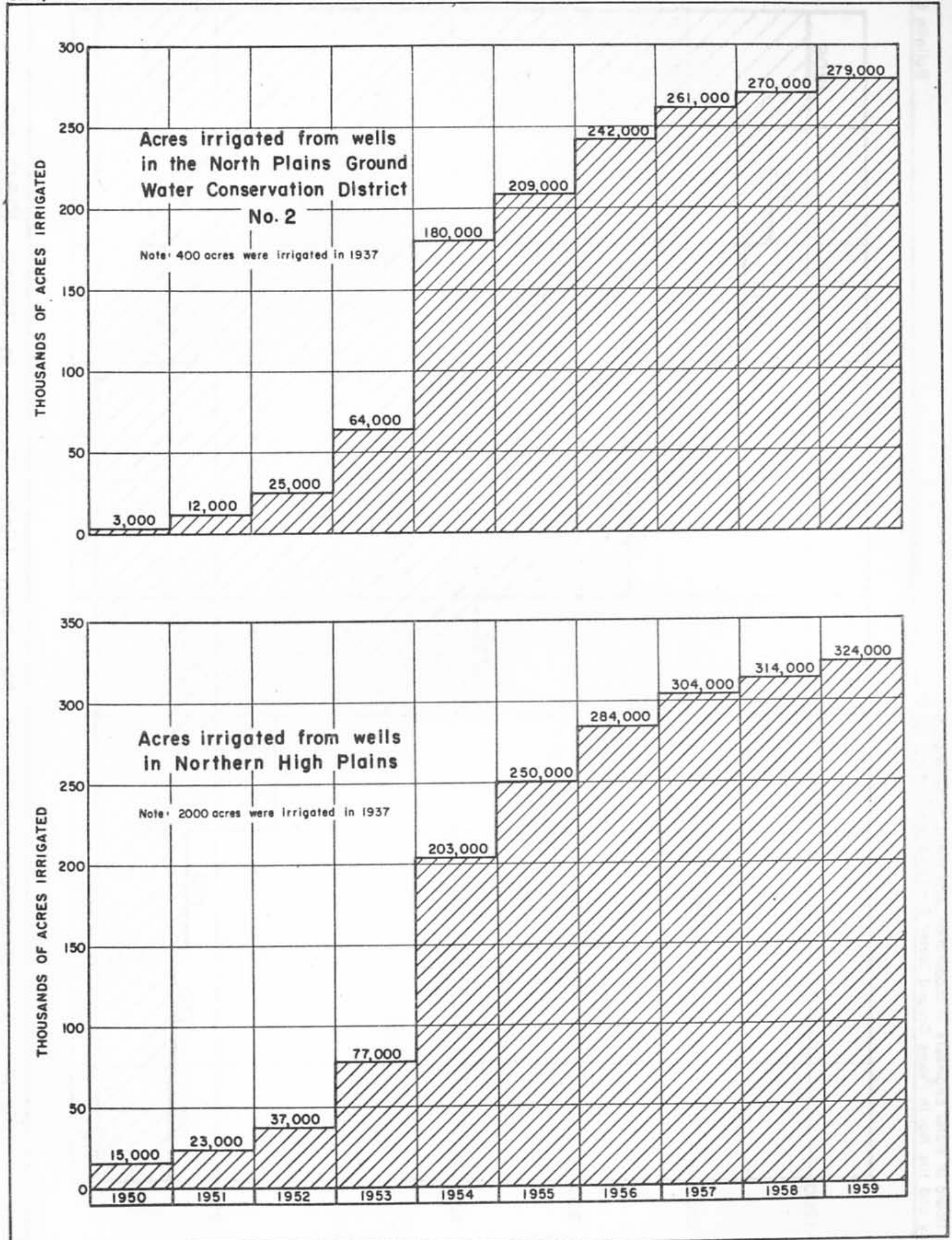


FIGURE 4. - Acres irrigated from wells in Northern High Plains in Texas, 1950-59

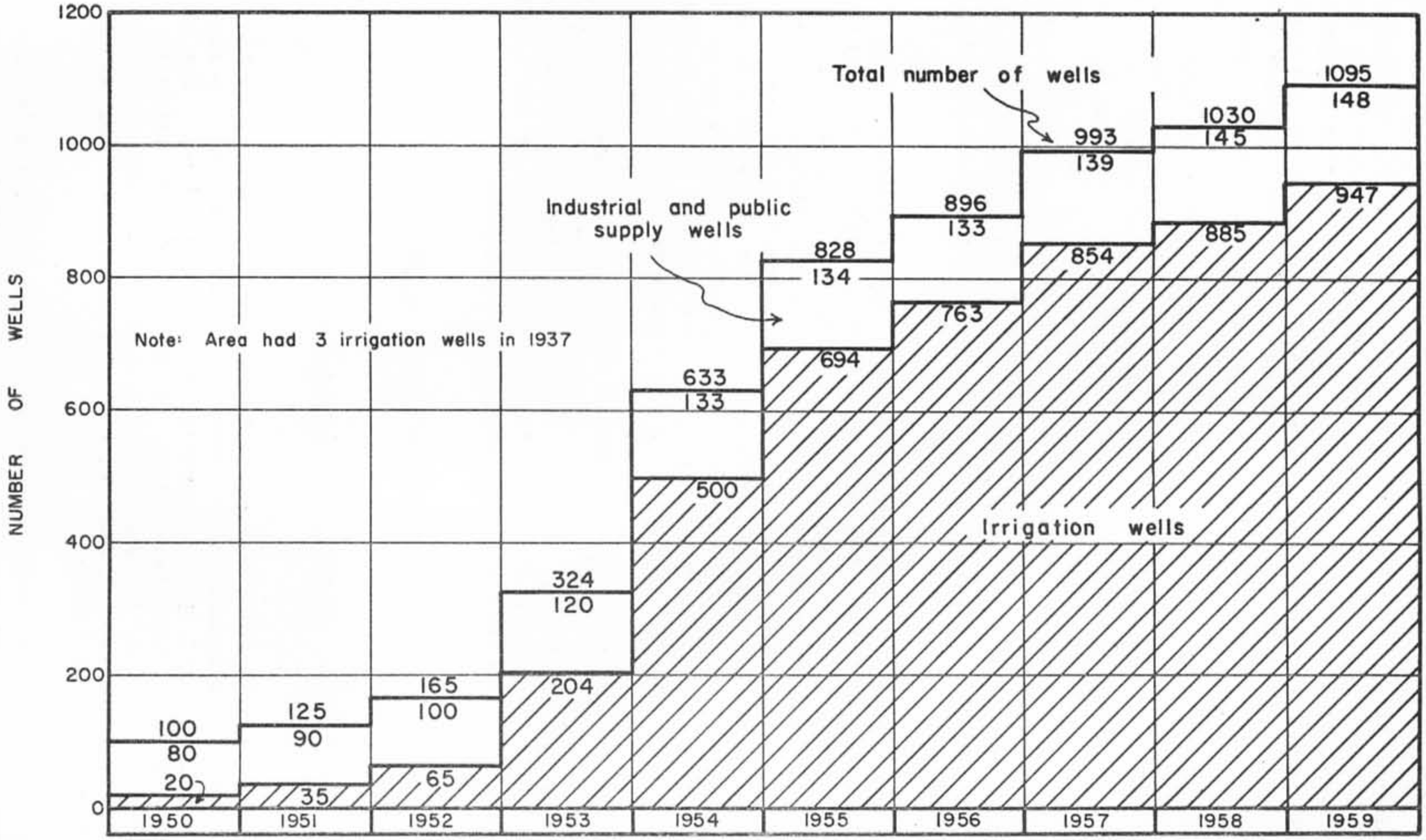


FIGURE 5.—Irrigation, industrial and public supply wells in North Plains Ground Water Conservation District No. 2, 1950-59

Withdrawals in 1958

The total use of ground water for irrigation, industrial, and municipal purposes in the Northern High Plains in 1958 was about 420,000 acre-feet (Table 2). By far the largest use was for irrigation. The withdrawals for irrigation in 1958, based on measurements of the use from about 10 percent of the irrigation wells, is estimated to be about 383,000 acre-feet. The use of water averaged about 1.22 acre-feet per acre of irrigated land and about 336 acre-feet per well. The amount of water pumped yearly is dependent largely on the annual precipitation, and the use of water per well in 1958 probably is representative of near-average use as the precipitation during 1958 was about average. The low water requirement of 1.22 acre-feet per acre irrigated occurred because 96 percent of the acreage in 1958 was planted in winter wheat and grain sorghum (Sherrill, 1959), which require small amounts of water compared to alfalfa and cotton. The pumpage for industrial and municipal uses in 1958 was about 37,000 acre-feet, nearly 30,000 acre-feet for industrial purposes and about 7,000 for municipal use. The number of wells and the withdrawals of ground water in 1958 for irrigation, municipal, and industrial uses, by counties, in the Northern High Plains are shown on Table 2.

The concentration of irrigation development in the Northern High Plains is shown by the density of irrigation wells in Plate 1. Most of the irrigation development falls within the boundaries of the water districts and within the plains areas. Irrigation development outside the water districts generally is scattered. The largest area of concentrated development is in northern Moore, southern Sherman, and northwestern Hutchinson Counties, where the density of wells is as much as four per square mile. The greatest density in the Northern High Plains, however, is in a smaller area in northwestern Dallam County where there are as many as six irrigation wells per square mile.

Ground-water withdrawals for irrigation in Moore, Dallam, Hutchinson, Hansford, and Sherman Counties accounted for about 82 percent of the total withdrawals in the Northern High Plains in 1958. Withdrawals for industrial use in Hutchinson and Moore Counties accounted for about 7 percent of the total, and withdrawals for all municipal use were less than 2 percent.

AVAILABILITY OF GROUND WATER

Amount of Water in Storage

The water available for development is represented largely by the amount of water in storage in the ground-water reservoir because the rate of recharge is undoubtedly small compared to the potential rate of withdrawal. The thickness of saturated material is a rough measure of the availability of water in storage. In general, the greater the thickness, the greater is the amount of water available. Plate 4 shows the approximate thickness of saturated material throughout most of the Northern High Plains.

The map should be used with caution in locating new wells because the type of material below the water table is not indicated and because interpretations between control points may be substantially in error. Although in most places enough of the saturated material consists of sand and gravel capable of yielding large quantities of water, in a few small areas nearly the entire saturated

Table 2.--Number of irrigation, municipal, and industrial wells, and withdrawals of ground water in 1958, Northern High Plains

	Number of wells					Withdrawals in thousands of acre-feet			
County	Irrigation	Municipal	Industrial	Both Public Supply and Ind.	Total	Irrigation	Municipal	Industrial	Total (rounded)
Dallam	237	10	0	0	247	80	1.02	0	81
Hansford	226	8	10	0	244	65	.66	.79	66
Hartley	66	5	0	0	71	13	.07	0	13
Hemphill	4	2	0	0	6	.5	.01	0	1
Hutchinson	92	3	6	24	125	47	1.00	17.60	66
Lipscomb	13	9	1	0	23	2.5	.29	T	3
Moore	236	11	61	0	308	101	1.48	11.16	114
Ochiltree	75	9	5	0	89	24	1.07	T	25
Oldham	0	2	0	0	2	0	.51	0	1
Potter	0	0	7	0	7	0	0	.10	--
Sherman	190	3	3	0	196	50	.26	.01	50
TOTALS	1,139	62	93	24	1,318	383	6.37	29.66	420

T = less than 10 acre-feet

section is composed of silt and clay. Wells completed in this clayey material yield insufficient quantities for irrigation, municipal, and industrial supplies but may be adequate for domestic and stock supplies. In some areas where the control points are closely spaced, the map shows abrupt changes in saturated thickness, and other areas in which such changes may occur are not evident because the control points are widely spaced. Additional studies are needed to refine the map and to delineate the areas containing principally clayey materials.

The amount of water available from storage is dependent on the specific yield of the material. Specific yield is the ratio, expressed in percentage, of the volume of water a formation will yield by gravity to the volume of material drained. Although estimates have not been made of the specific yield of the water-bearing materials in the Northern High Plains, estimates made in the Southern High Plains are probably applicable owing to the similarity of the deposits in the two areas. A specific yield of 15 percent is commonly used in calculations of storage in the Southern High Plains (Leggat, 1954, page 5), and on this basis about 160 million acre-feet of water was available from storage in the Northern High Plains in 1958. This figure should be considered the maximum because it is probably not practical to recover all the water. As the water levels decline, the yields of the wells will decrease, so that for irrigation use it may be uneconomical to develop perhaps the lower 20 to 50 feet of the saturated section.

Table 3 shows the estimated volume of water available by counties in the Northern High Plains in 1958. The data also have been classified according to the amount of water available beneath the plains and breaks areas of the counties. About 40 percent of the 160 million acre-feet of water available underlies the breaks area, and much of the breaks area is unsuitable for irrigation. The water under the breaks area is, however, available for industrial or municipal development.

Wells and Their Performance

The depths of the large-capacity wells in the Northern High Plains range from 300 to more than 500 feet in the plains areas, and are less than 100 feet in the "breaks" areas. The wells are drilled with rotary drilling rigs, and it is a common practice to drill a small-diameter test hole at each well location. If the driller and landowner decide that the thickness and texture of the sand and gravel below the water table in the test hole are suitable, the test hole is reamed to a diameter of 30 to 32 inches. Sixteen-inch casing whose lower end is perforated with vertical slots for a sufficient distance to extend from the water level to the bottom of the well, is then placed in the center of the well. "Pea size" gravel, 1/8 inch to 1/4 inch in diameter, is then placed in the annular space between the casing and the wall of the well filling the space to the land surface. Finally, the drilling mud is removed and the well is developed by pumping and surging.

All the large-capacity wells are equipped with deep-well turbine pumps which are operated by motors or engines at the surface. The wells are classified by the diameters of the column pipes and about 80 percent of the wells in the Northern High Plains are equipped with 8-inch column pipes. According to Sherrill (1959) about 50 percent of the irrigation pumps in the Northern High Plains are powered by natural gas; 41 percent by butane; 8 percent by electricity; and 1 percent by gasoline or diesel fuel.

Table 3.--Estimated volume of water available from storage, Northern High Plains, 1958 (thousands of acre-feet)

County	Plains	Breaks	Total
Dallam	21,000	0	21,000
Hansford	12,000	6,000	18,000
Hartley	21,000	9,000	30,000
Hemphill	0	6,000	6,000
Hutchinson	4,000	6,000	10,000
Lipscomb	300	24,000	24,000
Moore	10,000	2,000	12,000
Ochiltree	10,000	6,000	16,000
Oldham	0	200	200
Potter	0	500	500
Roberts	0	6,000	6,000
Sherman	16,000	3,000	19,000
TOTAL	94,000	69,000	163,000

The yields and drawdowns of more than 10 percent of the irrigation wells in the Northern High Plains were measured during the investigation. The yields of 125 wells ranged from about 200 to 1,200 gpm, and averaged about 700 gpm. The drawdowns (differences between static water levels and pumping levels) ranged from about 17 feet to 170 feet, and averaged about 40 feet. The specific capacity, defined as the yield of the well in gallons per minute per foot of drawdown, is a useful index of the ability of a well to yield water. The measured specific capacities ranged from about 3 to 63 gpm per foot, and averaged about 20 gpm per foot of drawdown. About 35 percent of the wells tested were in areas where the static water levels were between 150 and 250 feet, and the yields of these wells ranged from 700 to 1,000 gpm.

FLUCTUATIONS OF WATER LEVELS

Measurements of the fluctuations of water levels in wells form an integral part of any investigation of the ground-water resources of a region. In an area such as the Northern High Plains, changes in water levels indicate primarily changes in storage in the ground-water reservoir. The rate of depletion or recharge of the reservoir can be determined by studying records of water levels. In order to obtain a long-term record of water levels, observation wells are chosen in which the water levels may be measured periodically.

Water levels are measured by inserting a steel tape line between the casing and the column pipe of the pump, usually through a hole made for this purpose in the base of the pump gear head. The lower part of the tape line is covered with carpenters' chalk, and, after the tape line is removed, the depth to water is obtained by subtracting the length of wet tape from the measurement previously held at the top of the hole in the pump base, or some other reference point. The depth to water is then corrected to the land-surface datum by subtracting the height of the reference point above the ground.

Many of the irrigation wells in the Northern High Plains are pumped intermittently throughout the year. Grain sorghums are irrigated during the spring and summer; and wheat is irrigated during the fall, winter, and spring. The best opportunity for measuring the static water levels in irrigation-observation wells is during January and February when most of the pumps have not been in operation for periods of from 4 to 8 weeks. Because of the extensive development of irrigation, most of the measurements made since 1955 have been in irrigation wells during the winter.

Periodic measurements of static water levels in observation wells in the Northern High Plains were started in 1936 and continued until December 1941. Most of the observation wells measured before 1941 were in the irrigated areas in northwestern Dallam County. Only a few measurements were made during World War II and immediately following until 1950 when a number of new observation wells were added to the network.

During the winter of 1955, measurements were made in 95 irrigation wells, or about 15 percent of the total number of irrigation wells in use; and during the winter of 1956, the number was increased to 185 wells, or about 20 percent of the total. The network of observation wells was extended during the winter of 1957 into the newly irrigated areas, and this required measurements in more than 300 wells, or about 30 percent of the total. This percentage has been maintained since then, and measurements were made in 360 wells during the winter of 1960. This figure of 30 percent appears to be rather large for a sample of measurements, but allowances must be made for the occasional pumping of observation wells during the winter. For example, measurements were available for both the winter of 1959 and the winter of 1960 in only 250 wells, or about 20 percent of the total number of irrigation wells. The objective is to obtain long-term records in about 10 percent of the wells in the irrigated areas. As more wells are drilled, the present number of wells measured will approach the desired 10 percent coverage.

The average annual changes in static water levels, in feet, in irrigation-observation wells based on winter measurements from 1956 to 1960 are shown in Table 4. In this table, a minus sign (-) indicates a decline of water level and a plus sign (+) indicates a rise of water level. The large declines between the winter of 1956 and the winter of 1957 were caused by heavy pumping during the drought in 1956, and the small declines and few rises in the following years reflect the above-average precipitation in 1957, 1958, and 1959. The small average annual declines from 1956 to 1960, ranging from about 0.4 foot to 1.4 feet, reflect the wide distribution of the irrigation wells and the light pumpage in the Northern High Plains.

Some indication of recharge in the Northern High Plains is obtained from changes in water levels after the heavy rainfalls in 1941 and 1949 (Figure 2). Water levels in 16 observation wells were obtained prior to January 1942 and after 1950. The 16 observation wells were 1 to 4 miles from irrigation wells, and the water levels in 14 of these wells rose from 1.6 feet to 7.4 feet, or an average of about 3.0 feet, during the period 1940 to 1950 or 1951; in 2 wells near streams the water levels rose 3.1 and 9.5 feet, respectively, during the same interval. Although the data are too meager to evaluate the recharge quantitatively, they indicate that the net effect of the two wet years was substantial.

QUALITY OF GROUND WATER

Ground water contains varying amounts of dissolved minerals which determine its suitability for municipal, industrial, and irrigation uses. In the Northern High Plains the ground water in the Ogallala formation, the Cretaceous rocks, and part of the water in the Jurassic and Triassic rocks is suitable for most uses, whereas water from the underlying Permian rocks is more saline and is unsuitable for most uses.

The chemical analyses of water from 79 wells in the Northern High Plains are shown in Table 5; the locations of the wells sampled are shown on Plate 1. The wells are numbered by counties in a grid system of 5-minute rectangles of longitude and latitude; each rectangle is given a letter (or letters) which is followed by the number of the well within the quadrangle. All the wells for which records are available have been assigned numbers; however, only the numbers of the wells from which samples were collected are shown on Plate 1. The wells sampled range in depth from 120 to 619 feet, and with the exception of four wells, Dallam County L-4 and L-5 and Hansford County K-3 and R-6, the wells sampled obtain water from the Ogallala formation. The two Dallam County wells are supplied by the Dakota sandstone of Cretaceous age, and the two Hansford County wells are supplied by the Ogallala formation of Pliocene age and by red sand that probably is of Triassic age.

Water samples were collected from 32 public-supply wells and 47 irrigation wells and are considered representative of most of the fresh water in the Northern

Table 4.--Average change in water levels, in feet, in observation wells, Northern High Plains, 1956-60

County	1956 to 1957		1957 to 1958		1958 to 1959		1959 to 1960		1956 to 1960	
	Number of wells	Average change	Number of wells	Average change	Number of wells	Average change	Number of wells	Average change	Number of wells	Average change per year
Dallam	16	-1.8	23	-0.5	36	+0.1	35	-0.1	17	-0.5
Hansford	20	-1.7	46	.0	37	-.5	35	-.6	23	-.8
Hartley	10	-1.7	13	-.1	17	-.2	21	-.1	14	-.4
Hutchinson	9	-1.8	19	+.1	18	-1.0	19	-.8	11	-1.0
Lipscomb	--	--	--	--	4	+.9	4	-.6	--	--
Moore	20	-2.8	40	-.3	50	-.8	59	-1.0	26	-1.4
Ochiltree	9	-1.1	24	+.5	23	-.1	21	-.6	5	-.4
Sherman	21	-2.3	38	+.3	47	-.8	56	-.5	25	-.9

High Plains. The analyses supplement those included in the report by Broadhurst, Sundstrom, and Weaver (1951) and in the various county well-inventory reports previously mentioned (see References Cited).

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, pages 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. Wilcox (1955, page 15) stated that the system of classification of irrigation waters proposed by the Laboratory staff "...is not directly applicable to supplemental waters used in areas of relatively high rainfall." Thus, the system of classification probably is not directly applicable to the Northern High Plains where the average annual precipitation is almost 20 inches. Wilcox (1955, page 16) indicates that generally water may be used safely for supplemental irrigation if its conductivity is less than 2,250 micromhos per centimeter at 25°C and its SAR is less than 14. In 75 of the water samples in Table 5, the conductivity ranged from 392 to 796; and in three wells it ranged from 1,100 to 1,940. The conductivity of the water sample from Moore County well G-3 was 4,670 micromhos per centimeter at 25°C. This irrigation well is near an oil field salt-water disposal pit, and the possibility that the high salinity may be caused by pollution from the pit is being investigated (summer 1960) by the North Plains Ground Water Conservation District No. 2. The SAR in 78 of the water samples in Table 5 ranged from 0.1 to 7.7 and was 10 in Moore County well G-3.

Several factors other than chemical quality are involved in determining the suitability of water for irrigation purposes. The type of soil, adequacy of drainage, crops grown, climatic conditions, and quantity of water used all have important bearing on the continued productivity of irrigated acreage. Almost all the sampled water in Table 5 is suitable for irrigation of the crops grown in the Northern High Plains, and only one well (Moore County well G-3) is known to produce water unsatisfactory for irrigation. In general, water produced from the Ogallala formation probably is suitable for irrigation; but water from older formations is more variable in quality and should be analyzed before being considered for this purpose.

Suitability of Water for Public Supply

Water used for municipal and domestic supplies should be colorless, odorless, palatable, and wherever possible be within the limits required by the U. S. Public Health Service (1946, pages 371-384) for drinking water used on interstate carriers. The following limits have been placed on some of the most common minerals found in solution:

Iron (Fe) and manganese (Mn) 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.

With the exception of the water samples from two irrigation wells (Moore County well G-3 and Ochiltree County well F-2) the water sampled meets most of the requirements suggested by the U. S. Public Health Service. The fluoride content ranged from 0.4 to 2.4 ppm in the 69 samples analyzed; and in 32 samples, it exceeded the suggested limit of 1.5 ppm. The iron content ranged from 0.00 to 2.2 ppm in the 38 samples analyzed; and in 7 samples, it exceeded the suggested limit of 0.3 ppm.

Probably one of the most objectionable characteristics of the water from the standpoint of public supply is its hardness. All the samples analyzed were hard. Except for the sample from Moore County well G-3, the hardness ranged from 169 to 288 ppm; and most of the samples contain more than 200 ppm and would be classified as very hard.

The nitrate content of 78 of the water samples ranged from 0.0 to 16 ppm, but one sample contained 50 ppm. Hem (1959, pages 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 as 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, page 239) summarized recent investigations of the relation of nitrate in water to health, especially the health of infants, which indicate that nitrate in amounts of more than 44 ppm may be a health hazard.

Suitability of Water for Industrial Use

The quality requirements of water used in industry vary widely according to the products manufactured and the processes involved. The uniform quality and constant temperature of ground water may be desirable factors in selecting water for industrial use. The temperature of the water in most of the wells in the Northern High Plains ranged from 62°F to 65°F.

Most of the water from the Ogallala formation in the Northern High Plains is suitable for industrial use except that the water is hard and some of it has a high silica content. As previously stated all the samples analyzed were hard to very hard, and the water would require softening for many industrial uses.

Silica forms a hard adherent scale in boilers, and Moore (1940, page 263) has suggested the following allowable concentration of silica in water for boilers operating at various pressures:

Less than 150 psi (pounds per square inch), 40 ppm.

150 - 250 psi, 20 ppm.

250 - 400 psi, 5 ppm.

More than 400 psi, 1 ppm.

The silica content in the samples analyzed ranged from 12 to 53 ppm; 3 samples contained less than 20 ppm, 23 samples contained 20 to 30 ppm, 36 samples contained 31 to 40 ppm, and 17 samples had more than 40 ppm. According to Moore's classification, about 80 percent of the water sampled could be used in boilers operating at less than 150 psi, and only 4 percent could be used where the pressures were greater than 150 psi.

Treatment of Water

The hardness of water is an important consideration in both municipal and industrial supplies. Soap consumption for washing and laundering operations increases as the hardness increases. Hardness in water also causes incrustation or scale in pipes, coils, and boilers. Compounds of calcium and magnesium are almost entirely responsible for the hardness of water. Hardness equivalent to the carbonate and bicarbonate is called carbonate hardness; the remainder of the hardness, usually sulfate, is called noncarbonate hardness. Total hardness is the sum of the carbonate hardness and the noncarbonate hardness.

The two principal processes for softening large quantities of water are the lime or lime-soda process, in which the calcium and magnesium are precipitated as calcium carbonate and magnesium hydroxide; and the zeolite process in which the calcium and magnesium in the water are replaced by sodium from the zeolite. In addition to softening, the lime-soda process reduces the mineralization of the water. The lime-soda process is the most economical for large softening plants, especially if the water is high in carbonate hardness. The zeolite process is most economical in small plants and commonly is used for household supplies.

The most widely used methods of reducing the iron content of water are by precipitation, by aeration, and removal by filtration. Iron may be removed also as part of the lime or zeolite processes used for softening water.

Continuous use of water containing fluoride in excess of 1.5 ppm by young children may cause permanent mottling of the teeth (Dean, Dixon, and Cohen, 1935, pages 424-442); however, the presence of fluoride in quantities less than this amount tends to reduce tooth decay (Dean, Arnold, and Elvove, 1942, pages 1155-1179). The excessive fluoride can be removed by filtering the water through a bed of activated alumina, a patented mineral known as "Defluorite," or specially prepared ground bone. Fluoride removal generally is not attempted if fluoride concentrations are only slightly above the recommended values.

FUTURE STUDIES

Plans for continuation of the present studies involve consideration of the following points:

Current information on the extent of ground-water development and its effects on the future availability of ground water is needed continually. Other studies are needed to solve specific problems and to refine the information contained in this report.

Continuing-type studies are needed to collect, compile, and analyze periodically the records of pumpage and water levels and relate them to climatological records. These data and studies are useful in showing trends of natural recharge and reservoir depletion. Pumping tests should be made to determine more closely than now known the water-bearing properties of the ground-water reservoir.

As more information becomes available, the thickness of saturated material should be mapped in greater detail and in areas not covered by this report; also maps could be made showing the thickness of the most permeable zones of the saturated material. Studies should be made of the volume of potable water in the Cretaceous and older rocks. This information is particularly needed in parts of Hartley and Dallam Counties where the water-saturated part of the overlying Ogallala formation is relatively thin. Additional geologic sections are needed to better illustrate the relation of the Ogallala formation to the underlying rocks.

The map of the depth to water should be further refined. Additional information on the water table could be obtained from a contour map based on elevations above sea level. This map would show the direction of movement of water and better delineate the effects of concentrations of heavy pumping. If sufficient data can be obtained, a contour map of the base of the Ogallala formation would show the old valleys cut in the pre-Ogallala surface which are the locations of the thicker and more permeable sand and gravels.

More information is needed on the location and extent of areas favorable to the recharge of ground water and on the volume of recharge added to the ground-water supplies by natural means. Studies should be made of the volume of surface water available for artificial recharge by wells. The amount of water that collects in lakes varies widely from year to year, and a long-term record is needed to determine accurately the average amount available.

The distribution of water samples collected as shown on Plate 1 indicates that more information is needed on the quality of water in the Northern High Plains. The water samples from the Ogallala formation indicate a rather uniform quality throughout the region, but more information is needed on the quality of the water in the Cretaceous and older rocks.

Because of the low rate of recharge and the slow movement of ground water under natural conditions, it is very important that the ground-water supplies be protected from pollution from industrial waste water. Bacterial pollution may be detected by bacteriological analysis of water samples, but proof of chemical pollution requires considerable detailed information on the original chemical quality of the water in question.

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Table 5.- Chemical analyses of water from selected wells in the Northern High Plains

(Analyses given are in parts per million except specific conductance, pH, percent sodium, and sodium-adsorption ratio)

Well	Owner	Depth of well (ft.)	Date of collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$		Percent sodium	Sodium-adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
																Total	Non-carbonate				
								Dallam County													
D-3	Flater Farm	-	May 2, 1950	40	-	39	28	39	243	80	7.8	-	3.5	-	366	212	14	28	1.2	465	8.2
F-19	Allen Smith	-	June 29, 1959	28	1/0.01	35	26	47 4.5	265	53	15	2.3	1.8	0.28	343	194	0	34	1.5	550	7.4
L-4	City of Texline	265	Apr. 29, 1959	12	1/ .00	40	23	30 4.2	256	38	8.5	1.2	.0	.03	283	194	0	25	.9	489	7.3
L-5	Southwestern Public Service Co.	297	Mar. 17, 1948	12	2.2	32	27	30 3.6	244	42	8.0	1.0	.0	.53	298	191	0	27	.9	506	7.2
N-57	E. R. McNabb	-	May 25, 1959	32	1/ .00	50	32	23 3.7	243	51	34	1.6	5.4	.21	352	256	58	16	.6	574	7.5
N-64	T. Q. Denman	348	June 30, 1959	28	1/ .01	42	24	23 4.7	252	30	12	1.6	6.1	.18	296	204	53	19	.7	481	7.3
BJ-4	Southwestern Public Service Co.	542	Mar. 17, 1948	30	.05	38	31	20 1.6	238	43	13	1.4	6.0	.35	302	222	28	17	.6	497	7.2
BJ-8	City of Dalhart	563	Apr. 28, 1959	32	2/ .00	37	29	22 4.8	240	41	8.5	1.6	6.4	.10	300	212	15	18	.7	483	7.7

1/ Total Iron (Fe) 0.01
2/ Total Iron (Fe) 0.00

Well	Owner	Depth of well (ft.)	Date of collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness Total	Hardness Non-carbonate	Percent sodium	SAR	Specific conductance	pH
								Hansford County													
B-1	John Wilkins	334	Oct. 17, 1956	36	-	41	27	32 5.2	239	70	10	2.0	8.4	.22	350	214	18	24	.9	538	8.0
E-4	Rock Island RR	484	June 23, 1948	35	1/.05	51	32	26 8.8	254	87	10	1.8	8.3	.43	385	259	51	21	.7	597	7.5
E-5	C. H. Clawson	350	Nov. 20, 1958	34	-	49	25	27 4.9	228	82	8.8	1.5	8.4	.13	353	226	38	20	.8	548	7.6
E-6	do	350	do	36	-	48	25	28 4.9	228	82	10	1.3	7.7	.11	355	223	36	21	.8	537	7.6
K-3	P. B. Higgs	556	do	31	-	42	21	38 5.2	243	58	8.5	1.6	12	.17	336	192	0	29	1.2	553	7.5
L-9	Ruby F. Woodring	429	do	32	-	45	24	39 5.6	246	72	12	1.8	9.8	.22	362	211	10	28	1.2	576	7.5
L-10	Max & Kirby Clawson	420	do	39	-	35	22	12 4.4	222	13	3.2	1.4	5.8	.08	245	178	0	12	.4	392	7.6
Q-5	Ben Harris	-	Oct. 23, 1956	32	-	47	21	35 5.3	253	54	10	1.8	13	.21	344	204	0	26	1.1	541	7.8
R-6	G. K. Wilmeth	486	Nov. 20, 1958	32	-	51	24	42 5.6	272	72	8.2	1.5	11	.18	381	226	2	28	1.2	589	8.0
R-7	Southwestern Public Service Co.	413	June 24, 1948	33	2/ .15	44	31	42 8.4	302	67	11	2.2	7.8	.19	396	238	0	30	1.2	625	7.5
R-8	Western Gas Service Co.	342	June 10, 1959	31	3/ .01	43	28	36 6.1	275	52	9.2	2.1	10	.37	358	222	3	25	1.1	562	7.4

Table 5.- Chemical analyses of water from selected wells in the Northern High Plains--Continued

Well	Owner	Depth of well (ft.)	Date of collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)		Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$		Percent sodium	Sodium-adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
																	Total	Non-carbonate				
										Hansford County--Continued												
S-1	J. M. Ayres	398	Oct. 16, 1956	34	-	49	22	34	5.4	254	66	10	1.6	8.2	0.29	355	213	5	25	1.0	548	7.8
U-2	M. J. Groves	429	Oct. 18, 1956	34	-	48	23	37	5.2	254	66	14	1.8	7.6	.18	362	214	6	27	1.1	560	7.8
AA-9	City of Spearman	405	June 10, 1959	34	4/0.01	48	22	18	4.5	234	35	10	1.7	7.4	.00	310	210	18	15	.5	478	7.2
AA-10	do	405	June 23, 1948	42	.00	52	27	16	1.6	256	43	9.2	1.2	7.0	.32	325	241	31	13	.4	518	7.5
AH-1	D. A. Jackson	430	Oct. 11, 1956	44	-	49	31	191	4.1	270	99	242	1.8	4.2	.16	799	250	28	62	5.3	1,350	8.1
AL-4	Western Gas Service Co.	354	June 10, 1959	38	3/ .02	38	26	14	4.8	236	25	6.8	2.2	7.1	.15	280	202	8	13	.4	449	7.2
										Hartley County												
AE-2	Citizens Co-op	400	Apr. 28, 1959	32	.00	38	29	28	6.3	270	35	9.2	1.4	8.3	.22	320	214	0	22	.8	516	7.6
AR-3	W. H. Hamm	486	May 19, 1953	34	-	42	23	31	6.2	262	43	9.8	-	6.1	.19	324	200	0	25	1.0	522	7.7
BB-2	Western Gas Service Co.	400	Apr. 28, 1959	33	.00	43	19	12	4.4	204	19	9.8	.9	16	.07	257	185	18	12	.4	411	7.5
										Hemphill County												
D-1	Town of Glazier	220	Apr. 29, 1959	28	.04	86	11	24	2.6	272	16	25	.4	50	.09	392	260	36	17	.6	612	7.3
										Hutchinson County												
F-1	Buster W. Kirk	500	Oct. 25, 1956	49	-	40	27	12	4.5	243	27	8.8	1.8	6.2	.13	295	211	12	11	.4	456	7.7
H-1	C. E. Dunaway	362	Dec. 7, 1959	41	-	36	30	16	4.7	251	27	8.0	1.6	6.9	.09	294	214	8	14	.5	465	7.4
I-8	McCloy Bros.	420	Aug. 8, 1956	40	-	37	26	17	4.6	240	26	6.2	-	6.6	.17	282	199	2	15	.5	450	7.9
J-1	D. Chisum	-	Oct. 26, 1956	44	-	42	23	15	4.3	238	27	6.8	2.2	6.8	.11	288	199	4	14	.5	448	7.7
J-2	Community of Pringle	230	June 24, 1948	46	1/ .10	38	29	4.1	1.6	226	20	6.8	1.2	5.8	.31	273	214	29	4	.1	427	7.8

1/ Total Iron (Fe), 0.48
2/ Total Iron (Fe), 1.8
3/ Total Iron (Fe), .06
4/ Total Iron (Fe), .04

Table 5.- Chemical analyses of water from selected wells in the Northern High Plains--Continued

Well	Owner	Depth of well (ft.)	Date of collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)		Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$		Percent sodium	Sodium-adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
																	Total	Non-carbonate				
								Hutchinson County--Continued														
P-2	Phillips Petroleum Co.	544	June 9, 1959	28	2/ 0.02	44	30	28	6.2	252	76	6.0	1.8	7.3	0.32	352	234	27	20	0.8	553	7.3
Q-1	do	527	do	30	3/ .02	43	26	21	5.1	248	39	5.8	1.8	7.2	.22	301	214	12	17	.6	485	7.2
X-1	City of Stinnett	522	do	29	3/ .02	41	23	16	4.5	224	28	8.0	1.5	7.5	.18	275	197	13	15	.5	442	7.0
								Lipscomb County														
A-2	City of Booker	316	Apr. 28, 1959	45	.00	68	29	37	7.3	269	37	78	1.1	6.4	.21	472	288	68	21	.9	736	7.4
D-1	City of Darrouzett	300	do	53	.00	56	28	37	6.2	244	34	68	1.3	6.6	.26	434	254	54	23	1.0	671	7.5
F-1	-- Follett	369	Apr. 29, 1959	52	.00	48	23	45	5.7	260	23	53	1.1	4.5	.07	383	214	2	31	1.3	614	7.6
AI-1	City of Higgins	133	Apr. 28, 1959	44	.00	74	10	20	1.4	283	9.0	10	.6	14	.12	324	226	0	16	.6	504	7.2
								Moore County														
C-2	P. Schroetter	-	Mar. 18, 1953	28	-	42	27	15		237	31	8.8	1.4	6.5	-	277	216	22	13	.4	459	8.0
C-4	O. B. Thomas	501	Mar. 6, 1953	28	-	36	24	21		222	28	10	1.0	6.9	.11	264	188	7	19	.7	442	7.9
C-7	do	576	Feb. 26, 1953	30	-	38	26	22		237	32	9.5	1.2	6.1	-	282	202	8	19	.7	463	8.0
D-3	H. B. Lewis	342	Apr. 17, 1953	34	-	36	26	17		235	22	6.8	1.2	6.1	-	265	197	4	16	.5	434	8.2
E-1	--	360	Mar. 18, 1953	30	-	36	27	16		231	25	7.5	1.4	6.9	-	264	201	12	15	.5	442	8.2
E-4	-- Swett	342	July 2, 1953	31	.02	37	27	16	4.6	236	30	8.0	1.4	8.2	.24	279	203	10	14	.5	454	7.5
E-8	Cal Burkett	350	Feb. 24, 1953	30	-	36	27	18		240	24	6.2	1.0	8.2	-	268	201	4	16	.6	441	7.8
E-9	City of Sunray	300	May 7, 1959	29	1/ .00	40	24	16	4.8	222	28	12	1.2	8.5	.03	273	198	17	15	.5	459	7.5
E-10	Verlon Stevens	327	Mar. 14, 1953	32	-	38	26	19		236	28	8.5	1.0	6.8	-	276	202	8	17	.6	451	8.0
E-11	J. H. Burkett	414	Mar. 20, 1953	30	-	36	27	18		240	24	6.0	1.4	6.5	-	267	201	4	16	.6	444	8.1
G-3	Melvin Jones	388	Dec. 7, 1959	40	-	148	115	691	9.4	239	184	1,370	1.4	7.5	.10	2,680	842	646	64	10	4,670	7.7

1/ Total Iron (Fe), 0.52
2/ Total Iron (Fe), .06
3/ Total Iron (Fe), .04

Table 5.- Chemical analyses of water from selected wells in the Northern High Plains--Continued

Well	Owner	Depth of well (ft.)	Date of collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)		Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$ Total	Hardness as $CaCO_3$ Non-carbonate	Percent sodium	Sodium-adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
	Moore County--Continued																					
J-7	Jess Cooper	432	June 24, 1953	30	0.00	35	28	16	4.7	230	31	9.2	1.0	8.7	0.14	277	202	14	14	0.5	453	7.5
J-10	City of Dumas	400	May 16, 1959	30	2/ .04	35	30	19	5.3	242	34	7.2	1.1	12	.17	293	211	12	16	.6	484	7.4
K-2	-- McGregor	368	Apr. 20, 1953	30	-	36	27	21		235	31	9.0	1.2	8.3	-	280	201	8	19	.6	468	7.8
K-3	Cal Burkett	350	Mar. 13, 1953	34	-	36	27	24		238	34	9.0	1.2	9.7	-	292	201	6	21	.7	470	8.2
K-5	W. McGlothlin	387	Feb. 23, 1953	30	-	38	30	20		243	40	7.8	1.2	9.3	-	297	218	20	17	.6	489	7.9
L-1	Cal Burkett	350	Mar. 13, 1953	34	-	36	27	25		236	37	8.5	1.0	9.9	-	294	201	8	21	.8	477	7.9
L-3	Otto Barton	384	Aug. 17, 1953	34	-	35	28	19	4.9	238	31	9.0	-	9.9	.00	290	202	8	17	.6	484	7.9
M-5	J. Guleke	401	Apr. 16, 1953	38	-	34	28	19		238	26	6.2	1.8	7.2	.18	277	200	5	17	.6	449	7.8
O-2	Bob Brent	450	June 24, 1953	34	-	36	31	24	6.4	258	43	8.5	-	5.0	.27	315	218	6	19	.7	508	7.9
P-5	-- Beauchamp	437	Apr. 17, 1953	34	-	36	30	25	-	265	34	5.6	1.6	6.6	.30	305	214	0	20	.7	509	7.6
Q-5	F. Schuman	430	July 31, 1953	24	.04	41	25	34	7.0	281	43	6.8	-	6.9	.38	326	206	0	26	1.0	536	8.0
Q-7	City of Dumas	576	Mar. 17, 1948	16	.55	43	19	95	10	339	98	11	1.8	.0	.54	496	186	0	54	3.0	796	7.1
S-1	-- Bain	350	Mar. 20, 1953	37	-	36	33	17		250	39	5.8	1.8	5.9	-	300	226	20	14	.5	484	7.6
T-5	G. Bain	450	Oct. 8, 1953	22	-	44	31	48		297	77	7.2	1.6	5.5	-	384	238	0	31	1.4	623	7.7
W-1	Ed Stallwitz	455	Aug. 4, 1953	33	-	35	25	27		240	32	8.0	-	8.8	-	290	190	0	23	.9	461	7.8

1/ Total Iron (Fe), 0.04
2/ Total Iron (Fe), .14

Well	Owner	Depth of well (ft.)	Date of collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)		Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$ Total	Hardness as $CaCO_3$ Non-carbonate	Percent sodium	Sodium-adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
	Ochiltree County																					
F-1	Emmett Hummer	300	Aug. 29, 1956	43	-	42	27	83	7.0	231	67	95	-	6.9	.21	485	216	26	45	2.5	804	7.7
F-2	W. H. Fluitt	397	Aug. 10, 1956	44	-	57	33	296	7.5	234	174	385	-	4.5	.32	1,120	278	86	69	7.7	1,940	7.8
F-6	Ray Doerrie	300	Aug. 24, 1956	44	-	47	31	71	7.8	238	63	96	-	7.0	.26	484	244	49	38	2.0	813	7.7
K-2	City of Perryton	-	June 24, 1948	44	.00	40	27	25	5.2	242	12	32	2.4	7.0	.27	314	211	12	20	.7	538	7.5
K-3	do	420	do	46	.00	42	28	27	6.4	246	33	25	2.4	6.8	.52	338	220	18	20	.8	571	7.6
K-4	do	619	May 14, 1959	44	1/ .06	49	30	130	7.1	248	64	179	2.3	8.7	.14	636	246	43	52	3.6	1,100	7.3

Table 5.- Chemical analyses of water from selected wells in the Norhtern High Plains--Continued

Well	Owner	Depth of well (ft.)	Date of collection	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CaCO_3$ Total	Hardness as $CaCO_3$ Noncarbonate	Percent sodium	Sodium-adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)	pH
								Ochiltree County--Continued													
O-8	Waka Water Supply Co.	300	June 10, 1959	36	2/0.03	44	23	22 4.6	234	41	8.2	1.6	7.8	0.23	306	204	12	19	0.7	481	7.2
P-4	Farnsworth Water Service	305	May 15, 1959	42	3/ .04	42	23	38 5.3	228	34	39	1.9	5.8	.17	343	200	12	29	1.2	558	7.5

1/ Total Iron (Fe), 0.33
2/ Total Iron (Fe), .48
3/ Total Iron (Fe), .05

								Oldham County													
V-1	Boy's Ranch	120	June 30, 1959	24	.02	48	12	21 2.3	223	17	6.0	.7	4.8	.15	246	169	0	21	.7	416	7.3

								Sherman County													
I-5	Southwestern Public Service Co.	310	June 24, 1948	31	.00	36	36	14 5.2	244	48	10	1.2	9.5	.18	314	238	38	11	.4	520	7.6
I-6	Western Gas Service Co.	380	May 7, 1959	30	1/ .00	33	31	32 6.6	251	54	10	1.6	11	.08	332	210	4	24	1.0	537	7.6
AN-2	E. Brown	400	Mar. 18, 1953	32	-	40	27	8.6 -	250	13	3.8	.8	5.0	-	253	211	6	8	.3	425	7.7

1/ Total Iron (Fe), 0.03