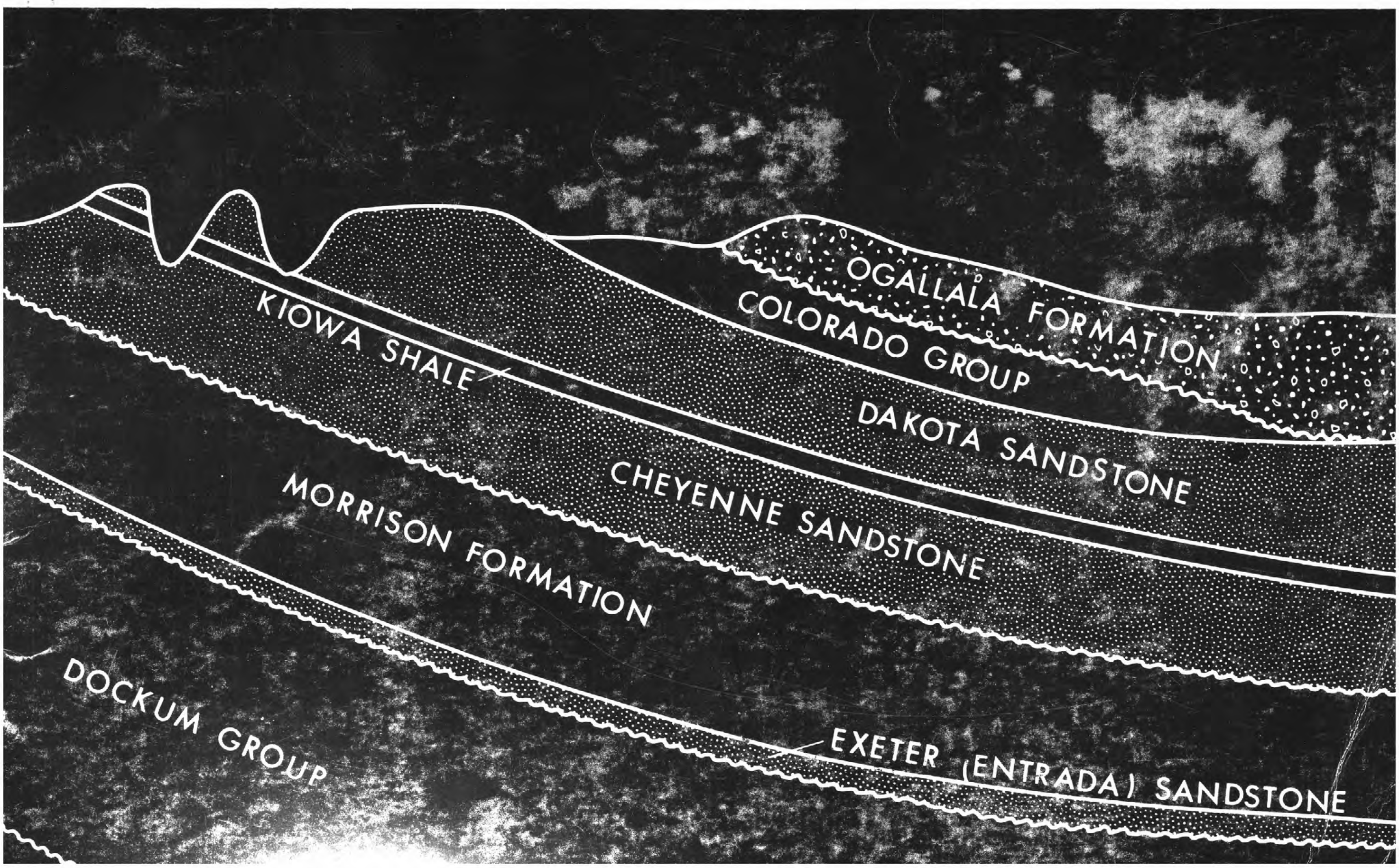
34-87

GEOHYDROLOGY OF THE OKLAHOMA PANHANDLE, BEAVER, CIMARRON, AND TEXAS COUNTIES

U. S. GEOLOGICAL SURVEY

WATER RESOURCES INVESTIGATION 25-75

Prepared in cooperation with
OKLAHOMA WATER RESOURCES BOARD



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16. Abstracts The Ogallala aquifer is the principal source of ground water in the Oklahoma Panhandle. Based on an estimated average storage coefficient of 0.1, the quantity of water stored in the Ogallala aquifer was computed at approximately 50 million acre-feet (6.17×10^{10} metres cubed). Local overdevelopment of this water resource has resulted in water-level declines of more than 40 feet (12 metres) from 1966 to 1972. The amount of ground water in storage has been reduced about 2 percent. Aquifer tests indicate that transmissivity ranges from 500 to 11,800 feet squared per day (46 to 1,100 metres per day), the storage coefficient ranges from 0.002 to 0.11, and hydraulic conductivity ranges from 2.1 to 55 feet per day (0.6 to 16.8 metres per day).

Other aquifers that locally yield sufficient water for irrigation are the Dakota and Cheyenne Sandstone. Water levels in these aquifers have not shown the pronounced declines that have occurred in the Ogallala aquifer.

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April 1976

UNITED STATES DEPARTMENT OF THE INTERIOR

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English units used in this report may be converted to metric units by the following conversion factors:

English	Multiply by	Metric
inches (in)	25.4	millimetres (mm)
feet (ft)	.3048	metres (m)
miles (mi)	1.609	kilometres (km)
square feet (ft^2)	.0929	square metres (m^2)
acres	.004047	square kilometres (km^2)
square miles (mi^2)	2.590	square kilometres (km^2)
acre-feet (acre-ft)	1,233	cubic metres (m^3)
gallons per minute (gal/min)	.06309	litres per second (l/s)
gallons per minute per foot [(gal/min)/ft]	.207	litres per second per metre [(l/s)/m]
feet per mile (ft/mi)	.1894	metres per kilometre (m/km)

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ABSTRACT

The Ogallala aquifer, which consists of semiconsolidated clay, sand, and gravel, is the principal source of ground water in the Oklahoma Panhandle. This aquifer commonly yields 500 to 1,000 gallons per minute (32 to 63 litres per second) and may yield as much as 2,500 gallons per minute (158 litres per second). Based on an estimated average storage coefficient of 0.1, the quantity of water stored in the Ogallala aquifer was computed at approximately 50 million acre-feet (6.17×10^{10} cubic metres). Local overdevelopment of this water resource has resulted in water-level declines of more than 40 feet (12 metres) from 1966 to 1972 in some areas of concentrated well development. The amount of ground water in storage has been reduced about 2 percent during this period.

Aquifer tests indicate that transmissivity ranges from 500 to 11,800 feet squared per day (46 to 1,100 metres squared per day), the storage coefficient ranges from 0.002 to 0.11, and hydraulic conductivity ranges from 2.1 to 55 feet per day (0.6 to 16.8 metres per day). In addition to these tests, 802 specific-capacity tests were used to extend transmissivity data.

Recharge to the Ogallala aquifer is primarily from precipitation and may be as much as 1 inch (25 millimetres) per year in areas where catchment and percolation are most favorable. Discharge is primarily from pumping and a small amount of natural discharge.

Aquifers of limited importance are the Dakota Sandstone and the Cheyenne Sandstone Member of the Purgatoire Formation which provide water to irrigation wells in the southwestern part of Cimarron County. Irrigation wells generally are completed jointly in these aquifers and yields of 300 to 500 gallons per minute (19 to 32 litres per second) are common. Water levels in these aquifers have not shown the pronounced declines that have occurred in the Ogallala aquifer. Permian red beds provide only small quantities of water to domestic and stock wells.

Water in the Ogallala aquifer, Dakota Sandstone, and Cheyenne Sandstone Member generally has a dissolved-solids concentration of less than 500 milligrams per litre. The dissolved-solids concentration in water from the Permian red beds generally exceeds 500 milligrams per litre and locally exceeds 2,000 milligrams per litre.

INTRODUCTION

Purpose and Scope of Investigation

Increased use of ground water in the Oklahoma Panhandle since the 1930's has created the need for a detailed study of the aquifers in order to estimate the amount of ground water in storage and to determine the effects of pumpage on the availability of ground water. Abundant ground water has enabled farmers and ranchers to drill wells for domestic and stock use almost anywhere in the area with assurance of adequate supplies. Cities and towns throughout the area depend on ground water to meet their growing needs, and since the mid 1960's vast amounts of water have been pumped to irrigate crops. In order to use the resources wisely it is necessary to have a better understanding of its physical regime and extent.

This investigation defines the geology and areal extent of the water-bearing deposits, evaluates the hydraulic characteristics of the aquifers, shows the effect of increased ground-water withdrawal on water levels of the area, and describes the chemical quality of the water and its relation to the aquifers. These data can provide a framework for developing water-management plans by local officials if they are desired by the water users of the Panhandle.

Location and General Features of the Area

The Oklahoma Panhandle in extreme northwestern Oklahoma has an area of 5,680 mi^2 (14,711 km^2) (fig. 1).

The Panhandle is an eastward-sloping plateau with its highest point in the extreme northwestern part of Cimarron County at an altitude of 4,978 ft (1,517 m) and its lowest point at the Cimarron River on the eastern edge of Beaver County at an altitude of about 1,990 ft (607 m). The average slope of the major upland area is about 14 ft/mi (2.6 m/km).

The Panhandle consists mostly of upland plains with some stream-flood plains and intermediate slopes. Large areas on the upland plains are comparatively flat, featureless, and undissected. Much of the surface has very broad gentle swells or hills, shallow depressions, and some dune-covered areas.

Depressions, which dot much of the plains in Cimarron and Texas Counties and parts of Beaver County, range from a few feet to several miles across and range in depth from a few feet to about 40 ft (12 m). Numerous theories have been presented to explain these closed depressions, including subsidence caused by the solution of gypsum and salt, which are common in the Permian rocks underlying the area, or by the compaction of underlying sediments. Many of the depressions contain small ephemeral lakes.

Sand dunes are most prominent along the northern slopes of the major rivers where prevailing southerly winds blow sand from the flood plains onto the north slope of the valleys. However, a large upland dune area occurs in

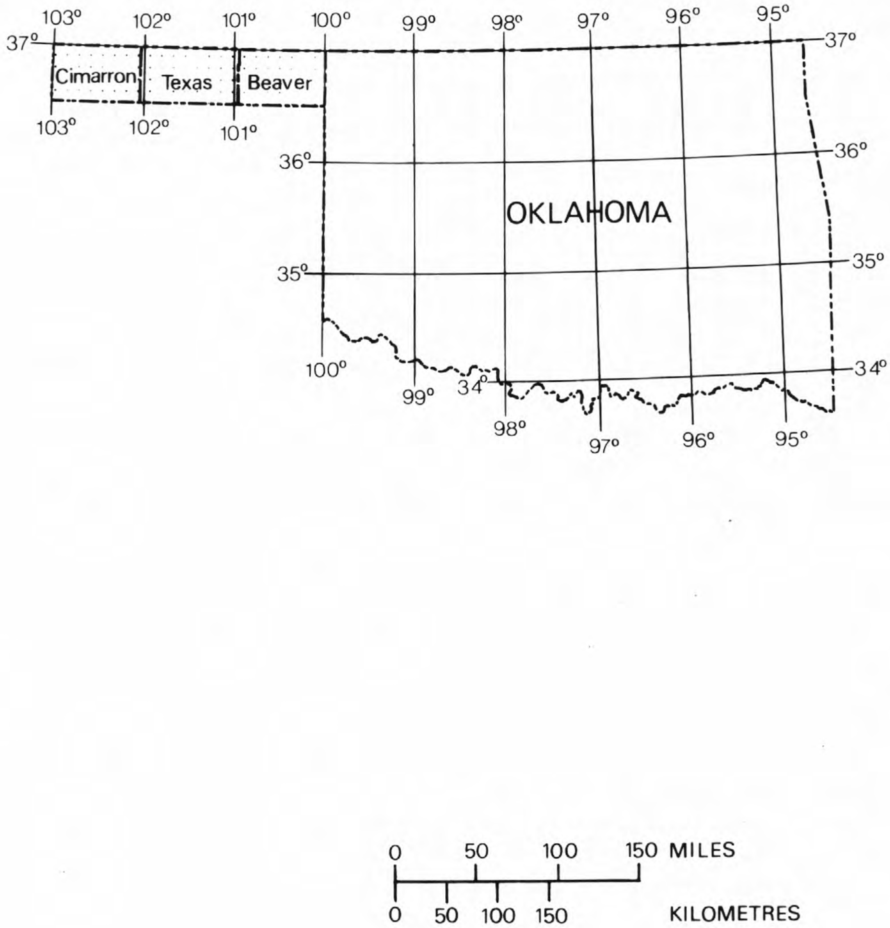

Figure 1.--Location of the Oklahoma Panhandle.

northeast Texas County and northwest Beaver County. Many of the upland dunes are more or less stabilized by vegetation, but near the rivers some are barren of vegetation and are actively shifting.

The northwestern part of Cimarron County exhibits a varied and striking topography. The Cimarron River and its tributaries flow through steep-walled canyons. Numerous buttes, capped by sandstone, occur along the entire length of the upper part of the Cimarron and also in the valleys of West Carrizo and Gillenas Creeks. The most conspicuous feature of the area is Black Mesa which is approximately 6 mi (10 km) wide and 50 mi (80 km) long. The mesa trends northwest through Colorado and New Mexico, and the eastern tip, less than 4 mi (6.4 km) long, extends into Cimarron County. On the south side the mesa rises about 600 ft (183 m) above the level of the Cimarron River and on the north side about 400 ft (122 m) above a small tributary to West Carrizo Creek. The mesa is capped by a basalt flow that has preserved the softer underlying rock.

Surface drainage is provided by the drainage system on the Beaver and Cimarron Rivers. The Beaver River drainage heads in New Mexico and enters Oklahoma in southwestern Cimarron County as Currumpa and Cinequilla Creeks which join in T. 2 N., R. 2 E., to form the Beaver River. The Cimarron River drainage also heads in New Mexico, entering Cimarron County as the Dry Cimarron, and becomes the Cimarron River at its confluence with Carrizozo Creek in T. 5 N., R. 1 E.

Previous Investigations

Several studies have been made of the geology and ground-water resources of the Oklahoma Panhandle; the most recent studies are three atlas reports of the reconnaissance type. These reports update information concerning well location, water availability, and water quality. The first atlas by Wood and Hart (1967) reported on Texas County, the second by Morton and Goemaat (1973) reported on Beaver County, and the third by Sapik and Goemaat (1973) reported on Cimarron County. Two recently published studies reporting on deeper hydrologic and geologic data are by Irwin and Morton (1969), and by Morton (1973).

Additional reports concerning the geology and ground-water resources of the Oklahoma Panhandle and adjacent areas are listed in the Selected References on page 51.

Well-Numbering System

The well and test-hole numbers in this report give the location of wells and test holes according to the U.S. Bureau of Land Management system of land subdivisions, as follows: township, range, section, and position within the quarter-quarter-quarter section. This method of well location is shown in figure 2.

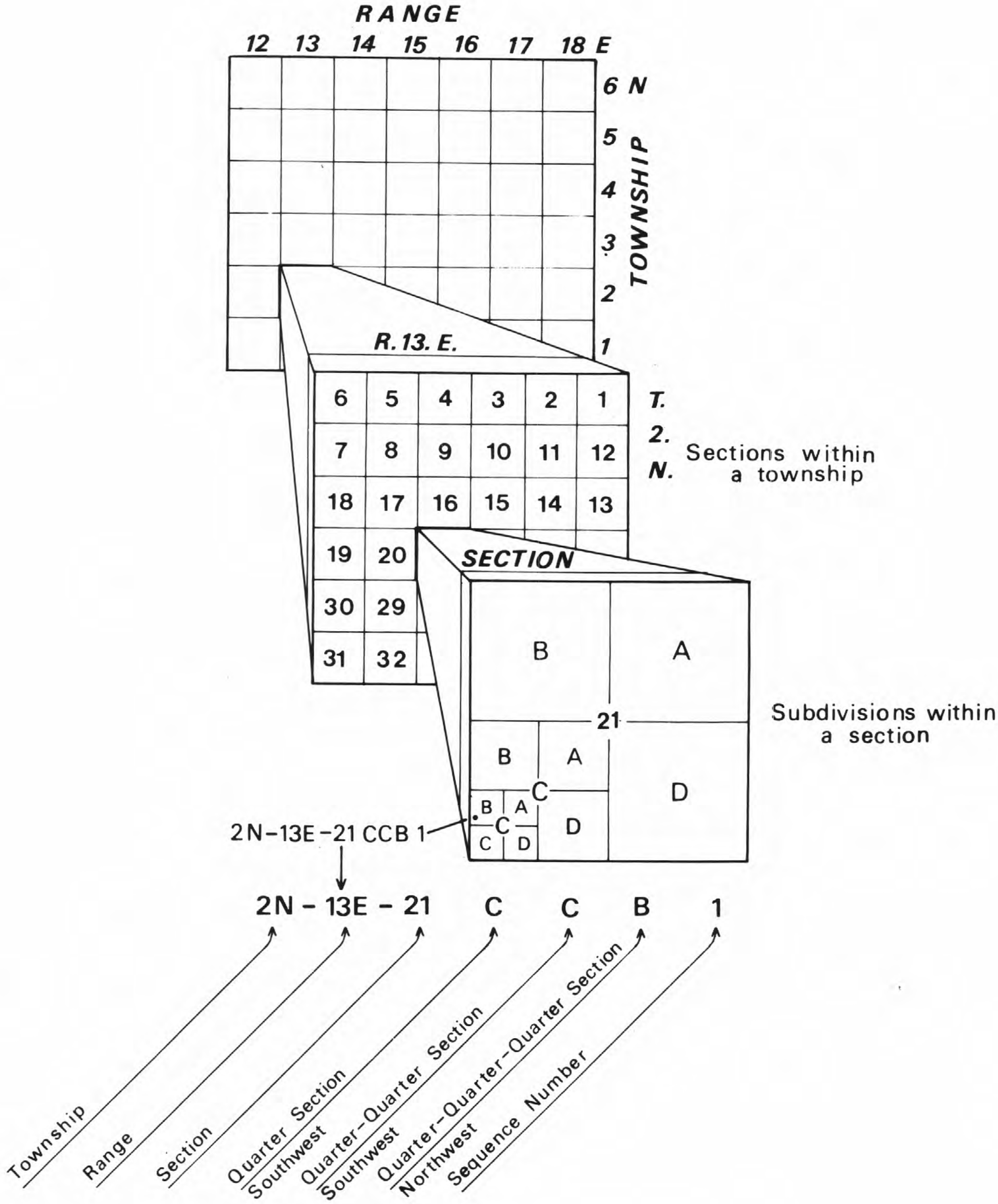

Figure 2.--Well-numbering system.

In some areas, locations of wells and test holes are known only to quarter section (160-acre or 0.65-square kilometre tract) or quarter-quarter section (40-acre or 0.16-square kilometre tract) as indicated by the well number.

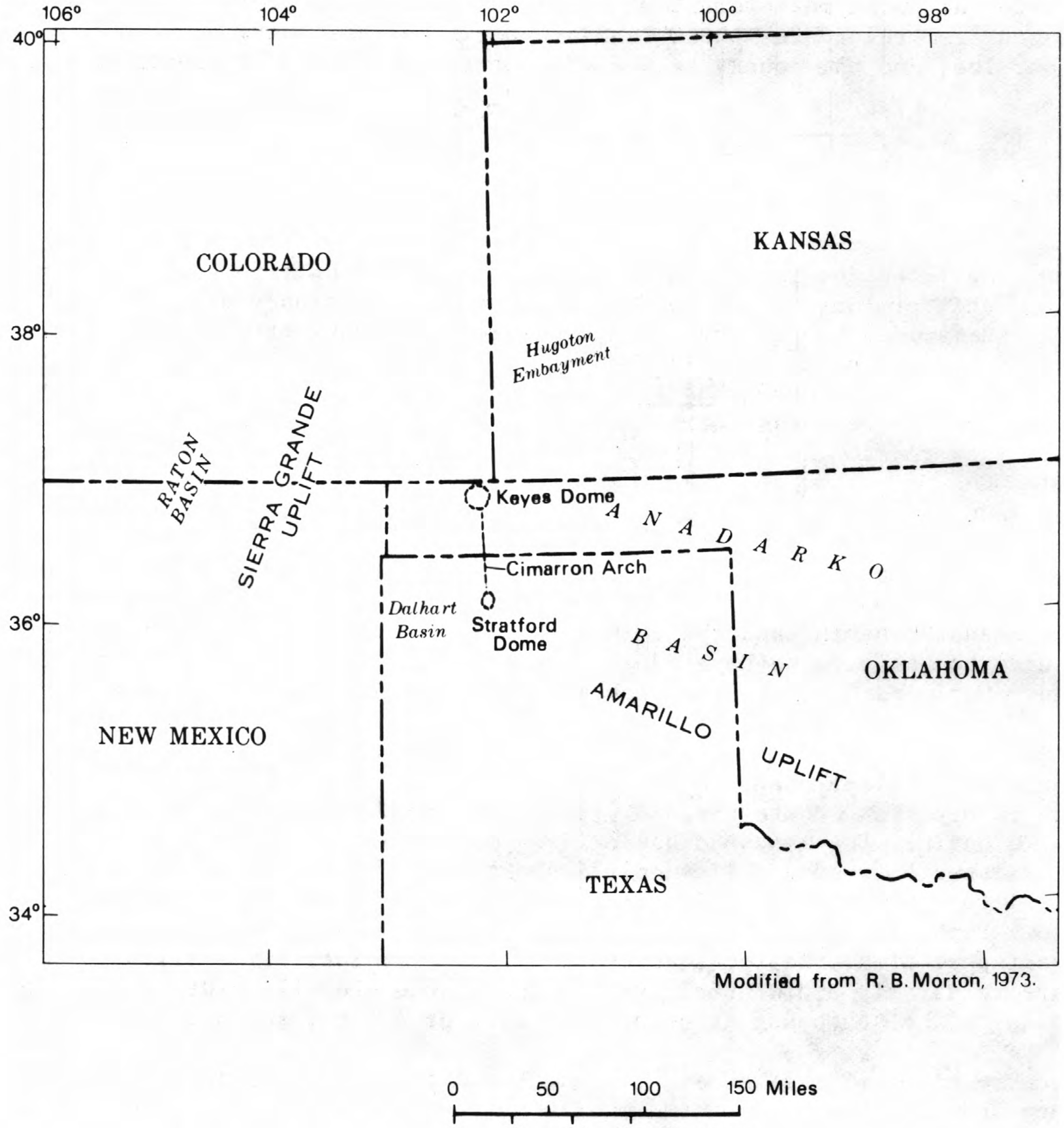

Figure 3.--Relative positions of some of the principal tectonic features.

Acknowledgments

The writers of this report express appreciation to the residents and well drillers of the Oklahoma Panhandle who gave information regarding their wells and test holes, permitted test drilling on their land and the use of their land and irrigation wells for aquifer tests, and to the many land owners for allowing measurement of water levels in their wells. Information furnished from records of the Oklahoma Water Resources Board, Soil Conservation Service, and the county agents was extremely helpful in preparing this report.

GEOLOGY

Regional Geology

The oldest beds considered in this report are the undifferentiated red beds of Late Permian age and the youngest are of Quaternary age. Table 1 briefly summarizes the geologic and water-bearing properties of the formations exposed in the area. All the units shown on table 1 are not present everywhere in the Panhandle as some of them may not have been deposited and others have been removed by erosion or truncated prior to the deposition of the Tertiary rocks.

The general configuration of the bedrock is the result of tectonic forces. As shown in figure 3, the major positive structural features are the Amarillo and Sierra Grande uplifts, and the major negative structural features are the Anadarko and Raton basins. The Hugoton embayment is a northwestern extension of the Anadarko basin, and the Dalhart basin probably is a western lobe of the Anadarko basin. The Keyes dome, Cimarron arch, and Stratford dome are alined roughly parallel to the Sierra Grande uplifts and, as a group, may be part of a positive structural axis related but subordinate to the Sierra Grande. The Keyes-Stratford dome alinement forms an interrupted structural divide of low relief near the western extremity of the Anadarko basin. Most of the report area, therefore, is within the northwestern limits of the Anadarko basin. The Anadarko basin is asymmetrical; the principal axis has a southeastward trend and lies only a short distance northeast of, and parallel to, the Amarillo uplift. The axis extends from the Texas and Oklahoma Panhandles southeastward toward south-central Oklahoma. In most of the report area, the rocks described occur at relatively shallow depths and are relatively undisturbed; consequently, the prevailing dip at shallow depth is to the southeast at an average rate of 1° or less (pl. 1).

A correlation exists in many areas between the relief on the pre-Tertiary surface and the thickness of the overlying Tertiary rocks. In areas where the pre-Tertiary surface remained topographically high, the overlying Tertiary rocks generally are thin, conversely where the pre-Tertiary surface was entrenched by ancient streams, the overlying rocks generally are thick. Thinning of the Tertiary rocks has also occurred by the entrenchment of modern rivers and streams.

Table 1.--Generalized section of geologic formations and their water-bearing characteristics.

System	Series	Stratigraphic unit	Thickness (feet)	Physical character	Water supply
Quaternary	Holocene and Pleistocene	Dune sand	0-50±	Light-brown, fine to medium sand with lesser amounts of clay, silt, and coarse sand formed into small hills and mounds by wind.	Lies above the water table and does not yield water to wells. The dunes have a high infiltration rate and are important as areas of ground-water recharge.
		Alluvium and terrace deposits	0-100±	Light-brown or gray, silt, clay, sand, and gravel along the major streams and valleys and in some adjacent uplands. Material is moderately permeable.	Deposits usually provide adequate water for stock and domestic use and, where sufficiently saturated, yield water for irrigation.
Tertiary	Pliocene	Basalt	0-85±	Dark, dense, poorly conductive vesicular rock forming cap rock of Black Mesa.	Yields no water to wells.
		Ogallala Formation	0-650±	Brown to light-gray but may include red, pink, yellow, black and white interfingering lenses of gravel, sand, silt, clay, limestone, and mixtures of these. In some places consolidated by lime cement, but mostly unconsolidated.	The Ogallala Formation is the principal water-bearing deposit in the Panhandle and yields as much as 2,500 gal/min.
Cretaceous	Upper Cretaceous	Colorado Group: Greenhorne Limestone	0-200±	Gray, fossiliferous limestone and calcareous shale. Limestone is poorly conductive.	Not known to yield water to wells.
		Colorado Group: Graneros Shale		Gray shale. Shale is poorly conductive.	
	Lower Cretaceous	Dakota Sandstone	0-200±	Buff to light-brown, fine to medium grained, thin to massive bedded sandstone with interbedded shale. Unit is moderately to highly conductive.	Adequate for stock and domestic and where sufficiently saturated yields as much as 150 gal/min.

Cretaceous	Lower Cretaceous	Purgatoire Formation	Kiowa Shale Member	0- 65±	Gray to black, fossiliferous shale with sandstone in the upper part. Shale is poorly conductive.	Not known to yield water to wells.
			Cheyenne Sandstone Member	0-125±	White to buff, massive fine to medium-grained sandstone, containing some conglomerate in the lower part. Sandstone is moderately to highly conductive.	Locally yields as much as 500 gal/min.
Jurassic	Upper Jurassic	Morrison Formation		0-470±	Varicolored shale, fine to very coarse-grained sandstone, limestone, dolomite, and conglomerate. Formation is poorly conductive except for isolated lenses of sandstone.	Sandstone units provide water for stock and domestic wells.
		Exeter Sandstone[1]		0- 50±	Massive, white to buff, fine to medium-grained sandstone. Sandstone poorly to moderately conductive.	Sandstone may yield as much as 20 gal/min.
Triassic	Upper Triassic	Dockum Group	Upper sandstone	0-450±	Varicolored siltstone or claystone, conglomerate, fine-grained sandstone, and limestone. Original conductivity low but fractures and solution openings provide some conductivity.	Adequate for stock and domestic supplies.
			Lower sandstone	0-200±	Varicolored, fine to medium-grained sandstone with some clay and interbedded shale. Conductivity ranges from poor to moderate.	Provides water to stock and domestic wells and also to some irrigation wells where sufficient saturated sandstone exists.
Permian	Upper Permian	Undifferentiated red beds		1,000+	Shale, siltstone, sandstone, dolomite, and anhydrite; local limestones and salt.	Supplies small quantities to stock wells, but will not supply enough for for irrigation wells.

[1] Equivalent to Entrada Sandstone of some geologists.

Tertiary and Quaternary deposits conceal the older rocks throughout most of the Panhandle. The configuration and approximate limit of pre-Tertiary rocks are shown in plate 2.

Geologic Units and Their Water-Bearing Properties

Most rocks that crop out in the Oklahoma Panhandle are represented in the subsurface by a similar lithology, but variations in thickness and lithology occur (pl. 3). The formations are of sedimentary origin except for the basaltic rocks in western Cimarron County and a few scattered volcanic ash deposits.

Permian System

Permian red beds undifferentiated.--Rocks of Permian age underlie all of the Oklahoma Panhandle. These rocks thicken east-southeastward toward the center of the Anadarko basin, and exceed 1,000 ft (305 m) throughout the area. Rocks of Permian age, commonly referred to as red beds, crop out along Palo Duro Creek in southeastern Texas County and along the Beaver and Cimarron Rivers and their tributaries in Beaver County. The red beds consist primarily of dark-reddish-brown rocks comprised of sandstone, siltstone, shale, and sandy shale. Most of the sandstone is fine to very fine grained. Silt is a common constituent in both the shale and sandstone as is halite and gypsum. Discontinuous zones of gray dolomite and limestone beds 1 to 2 ft (0.3 to 0.6 m) thick are present within the red beds at several localities.

The red beds belong to the upper part of the Permian section of Oklahoma; however, there is disagreement on what formations are represented and extent of their exposure. Recent correlations by Irwin and Morton (1969) indicate that the Whitehorse Group, Cloud Chief Formation, and Quartermaster Formation are present.

Most of the wells that obtain water from the red beds are in Beaver and southeastern Texas Counties where overlying aquifers have either been removed by erosion or are too thin to provide sufficient water. The red beds generally yield less than 10 gal/min (0.63 l/s), only enough water for domestic and stock supplies and the water usually contains more than 600 mg/l of dissolved solids. Electric logs indicate concentrations are lowest at very shallow depths and increase greatly with depth.

Triassic System

Dockum Group.--Rocks of Triassic age crop out in the northwestern part of Cimarron County and in the central part of Texas County. The Triassic rocks belong to the Dockum Group (Cummins, 1890, p. 189) which unconformably overlies the Permian red beds in the western part of the area.

For convenience of this discussion, the Dockum Group is divided into lower and upper units. Although both units are not identifiable at all locations, both generally are present.

The lower unit of the Dockum consists mostly of pink to red, fine- to medium-grained sandstone which is slightly micaceous and shaly. Above the basal sandstone unit is a series of thin-bedded varicolored shales and siltstones interbedded with sandstone.

The upper unit of the Dockum is principally red and green shale and lesser amounts of thinly bedded, mostly fine-grained, pink to red shaly sandstone and siltstone. The upper unit of the Dockum may grade rapidly from red and green to purple, yellow, brown, gray, and white.

The Dockum is present in west-central Texas County and throughout Cimarron County with the exception of the extreme northeast and southeast corners (pl. 3). The Dockum directly underlies the Ogallala Formation in much of eastern Cimarron County and in western Texas County. The eastern limit of the Dockum is in the vicinity of Guymon where the group is truncated by the overlying Ogallala Formation. The Dockum is approximately 650 ft (198 m) thick, or less. The aggregate thickness of the sandstone in the lower unit ranges from approximately 50 to 200 ft (15 to 61 m) and averages about 100 ft (30 m); the upper unit, which is predominantly shale, is approximately 450 ft (137 m) thick, or less.

The Dockum, where present, provides 10 to 50 gal/min (0.63 to 3.2 l/s) water to wells for stock and domestic use. In a few isolated areas, wells yielding as much as 500 gal/min (32 l/s) have been developed. The formation is most productive in T. 4 N., R. 10 E., Texas County. In other areas, the aquifer is used to supplement more productive aquifers that may overlie the Dockum. The water varies widely in chemical quality, but generally is more mineralized than water from the overlving aquifers and less mineralized than water from Permian aquifers.

Jurassic System

Jurassic rocks overlying the Dockum Group are the Exeter Sandstone (equivalent to the Entrada Sandstone of some geologists) and the Morrison Formation. The Exeter Sandstone is unconformable with the underlying Triassic age rocks and is disconformable with the overlying Morrison Formation.

Exeter Sandstone.--The Exeter Sandstone is the basal formation of the Jurassic in Oklahoma and crops out only in the northwestern part of Cimarron County. The sandstone overlies the Dockum in the western part of Cimarron County.

The Exeter Sandstone typically is buff to brown in the lower part grading to white near the upper part of the unit. The sand grains normally are fine to medium, subrounded to rounded, and well sorted. Locally, rounded gravel and lenses of clay are present. Cross-bedding is common in the upper part where the sandstone generally is friable.

Well cuttings and geophysical logs show that the Exeter has a maximum thickness of about 50 ft (15 m). The sandstone is thickest in the western part of Cimarron County and thins eastward because of pre-Morrison erosion or lack of deposition.

The sandstone generally is too thin to provide more than stock and domestic water supplies; however, wells tapping this aquifer reportedly yield as much as 20 gal/min (1.3 l/s). The chemical quality of the water limits its usefulness. In areas where the Exeter is overlain by the Morrison the chemical quality of the water probably is inferior to that where it is directly overlain by the Ogallala Formation.

Morrison Formation.--The Morrison overlies the Exeter Sandstone disconformably and underlies the Cheyenne Sandstone Member of the Purgatorie Formation. The prominent exposures are in the mesas and buttes near Black Mesa. Eastward from Black Mesa the cap rock of sandstone is missing and gentle slopes formed by the Morrison are covered by weathered materials. Several small inliers of Morrison are exposed in central and west-central Texas County.

The Morrison Formation is composed primarily of variegated shale, clay, marl, sandstone, conglomerate, limestone, dolomite, and some quartzite. The major part of the formation is shale, clay, and silt, but variations in lithology are common both laterally and vertically. The dominant color is greenish gray; however, brown, red, purple, yellow, and white are common. The exposures often are weathered and partly covered with soil or talus material. The sandstone, which commonly forms prominent exposures, ranges from very fine to very coarse grained, with some conglomerate beds. The exposed sandstones generally are buff in color but may be yellow or brown.

The Morrison is present throughout most of the western one-half of Cimarron County (pl. 2). Eastward from this area the unit either has been removed by erosion or was not deposited. The Morrison has a maximum thickness of about 470 ft (143 m) in the western part of Cimarron County and thins to a feather edge in the central part of the county. A buried outlier of Morrison is in west-central Texas County (pl. 2).

Because much of the Morrison Formation is fine-grained material, well yields generally are less than 20 gal/min (1.3 l/s). Only domestic and stock wells have been completed in this formation. Locally, the sandstone appears to be a significant water-bearing unit, but the sandstones generally are lenticular and probably could not be depended upon to yield water for extended pumping at large rates of discharge. The chemical quality of the water in the Morrison generally limits its usefulness and in many localities may not be acceptable for many uses.

Cretaceous System

Purgatoire Formation.--The Purgatoire Formation includes the Lower Cretaceous rocks between the Morrison Formation and the Dakota Sandstone. The Purgatoire crops out only in northwestern Cimarron County and along Currumpa and Cienequilla Creeks in southwestern Cimarron County. The formation is present in the subsurface in the western one-third of Cimarron County except in the major river valleys where it has been removed by erosion. Eastward the unit has been truncated by erosion except for a few small outliers that are present at the surface or in the subsurface. The Purgatoire is underlain unconformably and locally disconformably by the Morrison Formation and is overlain by the Dakota Sandstone. Locally, the Dakota Sandstone has been eroded and the Purgatoire is overlain by the Ogallala Formation.

The Purgatoire Formation has been divided into a lower Cheyenne Sandstone Member and an upper Kiowa Shale Member. The formation has an estimated maximum thickness of 190 ft (58 m). The Cheyenne Sandstone Member attains a maximum thickness of about 125 ft (38 m) and the Kiowa Shale Member attains a maximum thickness of about 65 ft (20 m).

The Cheyenne Sandstone Member of the Purgatoire Formation is typically fine- to medium-grained, white to buff sandstone. The sandstone is cross bedded to irregularly bedded, massive appearing, and generally poorly cemented. The lower part locally is conglomeritic and this facies contains material ranging from very fine sand to 6-in (150 mm) cobbles. The general nature of the Cheyenne makes it relatively easy to identify both in surface exposures and subsurface well cuttings.

The Kiowa Shale Member consists of dark-gray to black shale that weathers to buff. The member is mostly clay and shale in the lower part that locally grades upward into sandy shale and thin-bedded sandstone. The upper part locally contains beds of thin dense limestone, generally gray in subsurface and tan to brown on weathered surfaces. In some areas, the shale has weathered to a very soft shale or clay, and where it crops out in relatively flat areas, forms an extensive soil cover.

Only the Cheyenne Sandstone Member of the Purgatoire Formation is known to yield water to wells in the Panhandle. Well yields as much as 500 gal/min (32 l/s) have been reported from this sandstone; the water may exist under water-table or artesian conditions. Irrigation wells completed in this aquifer usually are screened jointly in a younger water-bearing formation, where possible, to obtain greater well yields. Many of the wells completed in the Cheyenne Member pump sand because the rock is poorly cemented, the openings of well screens are too large to retain much of the sand, and gravel packs are too coarse for the fine sand usually present in the aquifer.

The Kiowa Member is not known to yield water to wells in the area. The shale generally acts as an aquitard restricting the movemnt of water.

Water from the Cheyenne Member generally is suitable for most uses, but may be more than 120 mg/l total hardness.

Dakota Sandstone.--The Dakota Sandstone includes the Lower Cretaceous rocks lying disconformably on the Purgatoire Formation and below the Graneros Shale, or where the Graneros has been removed by erosion, below Tertiary and Quaternary rocks. The sandstone crops out in northwestern Cimarron County and in a few places along the major streams in southwestern Cimarron County.

The Dakota Sandstone is mostly fine to medium sand, and is gray, buff, or brown. The sandstone is thin to massive bedded and locally contains a gray shale in the middle of the unit that separates the Dakota into three distinct units--a lower sandstone, a middle shale, and an upper sandstone. Locally the upper sandstone and the shale have been removed.

The sandstone is very conspicuous because it forms the caprock of many of the buttes and the rimrock of many of the canyons and because it weathers to picturesque columns and other unique shapes. The buff to brown sandstone locally is coated with iron oxide (desert varnish) on exposed surfaces. The oxide coating ranges in color from orange to brown to black and forms a hard veneer over the surface of the rock.

The Dakota is present throughout much of the western one-third of Cimarron County. Eastward from this area it has been removed by erosion except for a few isolated outliers and in western Cimarron County has been removed locally by downcutting streams (pl. 3). The Dakota reaches a maximum thickness of about 200 ft (61 m) and thins to a feather edge at its erosional boundaries.

The Dakota yields as much as 150 gal/min (9.4 l/s) of water to wells throughout most of its extent. Many irrigation wells are completed in this aquifer jointly with either deeper or shallower aquifers to increase well yields. Locally the Dakota may have a thin saturated thickness and provide less than 20 gal/min (1.3 l/s) for domestic and stock uses.

The water may be under artesian pressure where overlain by relatively impervious Graneros Shale or by clay in the Ogallala Formation. Where overlain by a sandy facies of the Ogallala, water-table conditions prevail.

Water from the Dakota generally is suitable for most uses, but may be more than 120 mg/l total hardness similar to that of the Ogallala.

<u>Colorado Group</u>.--The Colorado Group of Lower and Upper Cretaceous age overlies the Dakota and underlies the Ogallala Formation. The group consists of two formations; the lower unit is the Graneros Shale and the upper unit is the Greenhorn Limestone. The two rock units that comprise the Colorado Group are difficult to separate in Cimarron County, and the use of the group name is convenient for discussion in this report.

Rocks of the Colorado Group, which consist of alternating beds of gray to brown shale, marl, limestone, and bentonite, weather rapidly to flat grass-covered slopes.

The Colorado Group occupies an area in west-central Cimarron County between the Beaver and the Cimarron Rivers and extending eastward about 14 mi (23 km) from the New Mexico-Oklahoma State line. In addition, a few small outliers occur in the northwestern part of Cimarron County.

The Colorado Group has a maximum thickness of about 200 ft (61 m) but in most areas has been thinned by erosion.

No wells are known to obtain water from the Colorado Group. Water supplies of 1 or 2 gal/min (0.06 or 0.1 l/s) might be developed in the upper weathered sections of the rock, but wells that are drilled through the Colorado Group and into the underlying Dakota Sandstone generally yield larger supplies.

Tertiary and Quaternary Systems

The Tertiary and Quaternary Systems as used in this report are combined for discussion because most of the units are similar in both lithologic and hydrologic characteristics except in the small areas where volcanic rocks are present. The lower unit is the Ogallala Formation; this is overlain by Pliocene basalt, and undifferentiated Pleistocene and younger material.

The Ogallala Formation was deposited by eastward-flowing streams upon the erosional surface of rock of Cretaceous age and older. Material forming the Ogallala was derived from the Rocky Mountains and from the exposed sedimentary rocks at the foot of the mountains. Large rivers and streams transported vast quantities of rock from the west and deposited the material over all the Panhandle. These streams alternately deposited sediments and then reworked much of their previously deposited material. Apparently large lake and back-swamp areas were filled with clay and silt and old river channels were filled with gravel and coarse sand. In places the ancestral streams have eroded and reworked older underlying rock making the base of the Ogallala Formation difficult to distinguish from pre-Ogallala Formations. Late in the depositional cycle of the Ogallala, basalt flows originating in northeastern New Mexico and southeastern Colorado spread into parts of Cimarron County and small amounts of volcanic ash were deposited in scattered areas throughout the Panhandle. As the last major depositional cycle of the rivers forming the Ogallala subsided, the present stream system began to evolve by cutting of new channels. Later, deposition by the streams formed terrace deposits and alluvium-filled valleys. Winds blowing across the unconsolidated surface materials have caused a gradual shifting of the sand and created large areas of dune cover.

Ogallala Formation.--The following discussion includes both the Ogallala Formation of Tertiary age and the overlying unconsolidated material of Pleistocene age because the units are difficult to separate and for all practical purposes are a hydrologic unit. In the hydrology section of this report the rocks of Tertiary age and younger will be referred to as the Ogallala aquifer, a term which is in common use by the residents of the High Plains.

In the subsurface the Ogallala Formation consists of a heterogeneous mixture of sand, gravel, silt, clay, caliche and local beds cemented with calcium carbonate. The various rock types generally occur as lenses and poorly sorted beds of loosely cemented material. Locally the beds may be modererately cemented with calcium carbonate and beds of caliche commonly occur near the surface. Test drilling has shown that in a few areas the Ogallala consists of several hundred feet of coarse sand and fine gravel and in other areas it consists of as much as 300 ft (91 m) of gray clay with a few thin interfingering lenses of very fine sand. Gradation of material from one size to another both vertically and horizontally is common, but sand generally predominates. The formation generally is brown or light gray in color, but may also include red, pink, yellow, black, and white.

The Ogallala Formation was deposited over the entire Oklahoma Panhandle but has been removed locally by stream erosion and has been truncated completely by erosion a short distance east of Beaver County. A complete section of Ogallala is not present in Oklahoma because the upper part has been eroded.

The maximum thickness of the Ogallala is about 650 ft (198 m), but it thins along major drainageways and over bedrock highs. The approximate thickness of the Ogallala aquifer is shown in plate 4.

Sand and gravel of the Ogallala Formation are the principal sources of ground water in the Oklahoma Panhandle. Well yields range from a few gallons per minute to more than 2,000 gal/min (126 l/s). Wells yielding less than 350 gal/min (22 l/s), at present, usually are not completed for irrigation wells.

Although it usually contains more than 180 mg/l total hardness, water from the Ogallala generally is chemically suitable for most purposes. However, in Tps. 1, 2, and 3 N., Rs. 18 and 19 E., some wells tapping the lower zones of the Ogallala pump water containing dissolved solids in excess of 5,000 mg/l.

Basalt.--The basalt of Pliocene age is the only igneous rock exposed in the Panhandle except for a few isolated areas of volcanic ash. The rock is a dense olivine basalt with ophitic texture, and is black, greenish gray, or brown in color. It commonly is finely crystalline in the lower part but near the top becomes vesicular with many of the vesicles filled with calcite.

The thickness of the basalt ranges from about 85 ft (26 m) at the New Mexico State line to about 50 ft (15 m) at its eastern extent. The basalt is present only as a cap rock of Black Mesa in extreme northwestern Cimarron County and has a total area of less than 5 mi^2 (13 km^2).

This unit is not known to yield water to wells and has little hydrologic significance.

Alluvium and terrace deposits.--The alluvial and terrace deposits overlying the Ogallala Formation consist of poorly sorted, gray to brown sand, gravel, clay, and silt. Alluvium occurs along all streams, but terrace deposits occur in small isolated patches or as larger remnants adjacent to the present rivers. The alluvium and low terrace deposits are shown combined on the geologic map, but the high terrace material is included with the Ogallala. The thickness of the alluvial deposits seldom exceeds 100 ft (30 m) in this area and the width of these sediments along the major rivers range from less than 1 mi (1.6 km) to as much as 2.5 mi (4 km).

In most places along the Beaver and Cimarron Rivers the alluvium yields more than 20 gal/min (1.3 l/s) for stock and domestic needs and may provide enough water for irrigation. This unit commonly is screened jointly with underlying aquifers to obtain larger quantities of water. The alluvial deposits are not saturated in southeastern Cimarron County where the water percolates downward to the water table in the Ogallala Formation. Water generally is chemically suitable for most uses.

Dune sand.--Dune sand probably is of late Pleistocene and Holocene age and is composed primarily of fine to medium, well-rounded to subrounded quartz grains. The deposits are characteristically cross bedded and are white, brown, or reddish brown in color. The dune deposits are estimated to be 0 to 50 ft (0 to 15 m) thick. The dune deposits are above the water table and do not constitute an aquifer but they are hydrologically important because of their capacity to absorb precipitation and transmit the water to underlying units.

HYDROLOGY

The Ground-Water System

Under natural conditions in the Oklahoma Panhandle the water table or potentiometric surface generally is near equilibrium and the quantity of water stored in ground-water reservoirs is relatively constant, varying slightly in response to changes in annual precipitation, streamflow, and evapotranspiration. However, pumping of large quantities of water for irrigation and other uses have disturbed the natural equilibrium causing water levels to decline in some areas. The understanding of the operation of a ground-water reservoir requires a knowledge of a number of factors, summarized as follows:

Change in storage = recharge-discharge

Although each of these factors may consist of several components, the relation between them is simple and direct. When recharge exceeds discharge, the quantity of water in storage increases and the water level rises. Conversely, when discharge exceeds the recharge, the quantity of water in storage decreases and the water level declines. In all the heavily pumped areas in the Panhandle ground water is being mined, therefore, water levels presently are declining.

Recharge may occur by inflitration from precipitation and return flow from irrigation, infiltration from overlying aquifers, or by water loss from streams, lakes, and rivers.

Hydrologic Properties of Water-Bearing Materials

The quantity of ground water that an aquifer will yield to wells depends upon the hydrologic properties of the aquifer. The capacity of an aquifer to transmit water is measured by the transmissivity (T). The transmissivity is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. The transmissivity is expressed in feet squared per day. Hydraulic conductivity (K) may be defined thus: A medium has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of ground water at the prevailing viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow. Hydraulic conductivity is expressed in feet per day in this report. The term "hydraulic conductivity" replaces the term "field coefficient of permeability," and the terms "conductive and "permeable" may be considered synonymous in describing the capacity of a material to transmit water. The storage coefficient (S) is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per change in unit head. Under water-table conditions the storage coefficient is practically equal to the specific yield, which is defined as the ratio of the volume of water a saturated material will yield to gravity in proportion to its own volume.

The hydrologic properties described above commonly are determined from aquifer tests and these tests may be used in conjunction with the water-level contour maps to estimate the quantity of ground water moving laterally through the water-bearing formations. Hydrologic coefficients can be used to estimate storage, change in storage, and amount of local recharge, the change in storage being the quantity being removed or returned to the ground-water reservoir.

The specific capacity of a well is the rate of discharge of water from the well divided by the drawdown of water level within the well. Specific capacity was determined in a number of wells to estimate the maximum discharge that might be expected in areas of the aquifer where transmissivity has not been determined.

Aquifer Tests and Analyses

Aquifer tests, summarized in table 2, were conducted to determine the hydraulic properties of the Ogallala aquifer. Transmissivity, storage coefficient, and hydraulic conductivity were calculated from seven aquifer tests, and transmissivity and hydraulic conductivity were calculated from three recovery tests. In addition to the 10 tests used to determine transmissivity values, 25 wells were pumped to determine their specific capacity.

As shown on table 2, storage coefficients ranged from 0.002 to 0.11. Tests that were run for relatively short periods generally had low values indicating that semiartesian conditions may exist whereas tests that were run for long periods had considerably higher values indicating water-table conditions. Storage coefficients in untested areas may have values both less and greater than those in the test sites. In some areas, during initial well development and pumping, the aquifer may react as a semiartesian system and after development may becomes primarily a water-table system. An average storage coefficient for the Ogallala aquifer of 0.10 may be conservative, but seems to be a valid estimate based on the present data.

Table 2.--Summary of aquifer tests of the Ogallala aquifer.

Test location[1]	Transmissivity (ft^2/d)	Storage coefficient	Hydraulic conductivity (ft/d)	Length of test (days)	Radius of observation (feet)	Observation well: Depth (feet)	Observation well: Static water level before test (feet)	Observation well: Thickness of aquifer (feet)	Observation well: Saturated thickness of aquifer (feet)	Pumping well: Depth (feet)	Pumping well: Static water level before test (feet)	Pumping well: Drawdown at end of test (feet)	Pumping well: Average discharge (gal/min)	Pumping well: Specific capacity at end of test [(gal/min)/ft]
1N-21E- 5DDD1	500	0.002	2.1	3	385	419	194	430	236	682	196	27	385	14
2N-23E-21CBD1	[2]790	.....	3.6	3	.5	282	65	282	217	282	65	99	276	3
5N-21E- 9BBC1	2,400	.002	8.4	7	1,120	438	165	452	287	448	171	90	817	9
2N- 7E-26ACC1	6,700	.11	37	32	r_1=657	375	224	405	181	400	214	33	810	24
					r_2=1,500					380	235	39	780	20
					r_3=4,170					334	202	51	775	15
2N-14E-23CBB2	6,000	.09	39	22	388	287	142	298	156	311	145	44	1,150	26
2N-15E- 6CCC1	[2]8,700	.....	33	61	1	423	160	422	262	423	160	32	1,280	40
2N-15E-15BAA1	1,090	.10	4.7	93	414	410	212	442	230	432	211	171	706	4
3N-15E-21BBC1	[2]10,200	.....	38	1.2	1	350	82	350	268	350	82	43	840	20
4N-14E-11CDB1	11,800	.02	55	9	1,950	402	189	402	213	468	178	22	1,000	46
5N-17E-27BBC1	[3] 6,200	[3].03	36	4	390	215	127	620	493	315	126	59	570	10

[1]Test locations are identified by well-location number of observation well.
[2]Transmissivity determined from recovery tests.
[3]Partially penetrating well

The theory of nonequilibrium flow with delayed yield by Boulton (1963) was judged to best fit the conditions that exist in the Ogallala aquifer in the Oklahoma Panhandle. Therefore Boulton's method was used in determining the aquifer properties for most of the tests. The theory of nonequilibrium flow by Theis (1935) was used for a few tests.

The assumption that the hydrologic coefficients are constant throughout the aquifer and that they remain so with time is common to formulas describing the potential distribution in ground-water reservoirs. If this assumption were true, the coefficients could be determined from one aquifer test; however in practice, coefficients differ from place to place reflecting differences in geologic conditions such as thickness and the heterogeneous, anisotropic nature of the aquifer.

Six of the tests are described in detail in the section Aquifer Tests Data and Analyses to give more of the pertinent data and to show the types of analyses made. The number of the observation well is used to identify each test.

Specific Capacity Tests

Specific capacity tests were used as a method to obtain estimates of transmissivity and of maximum yield from the aquifers at various locations. The method used to derive the maximum well yield is discussed in the section Quantities Available. Specific capacity is a measure of well performance; its value will vary with the hydraulic properties of the aquifer and with well-construction factors such as the diameter of the well, its depth of penetration into the aquifer, the type and amount of perforations in the casing, the amount of well development, and length of time since pumping started. The specific capacity tests conducted by the Geological Survey are shown in table 3 and include the specific capacity data of the pumping wells used in more extensive aquifer tests. The specific capacity values ranged from 2.0 to 47.5 (gal/min)/ft [0.41 to 9.8 (l/s)/m] of drawdown. An average specific capacity for these wells in the Ogallala aquifer is 17 (gal/min)/ft [3.5 (l/s)/m] of drawdown. The maximum well discharge measured was 1,710 gal/min (108 l/s).

Figure 4 shows the measured relationship between the drawdown in the pumping well, 2N-14E-23CBB1, and the time since the pumping was started. The graph also shows the computed relationship between the specific capacity and the time since the pumping was started. The specific capacity was 38 (gal/min)/ft [7.9 (l/s)/m] of drawdown at the end of one-half day of continuous pumping and declined to 26 (gal/min)/ft [5.4 (l/s)/m] of drawdown at the end of 22 days.

In addition to the 35 specific capacity tests conducted by the Geological Survey, the results of 767 additional tests were obtained from the Oklahoma Water Resources Board, U.S. Soil Conservation Service, land owners, and local well drillers.

Table 3.--Summary of specific capacity tests.

Well location	Specific capacity (gal/min)/ft of drawdown	Discharge (gal/min)	Drawdown (feet)	Length of pumping (days)	Aquifer thickness (feet)	Diameter of well (inches)	Diameter drilled (inches)	Aquifer	Remarks
BEAVER COUNTY									
1N-21E- 4CCC1	2.1	510	240	5	397	16	30	Ogallala	Perforated, gravel packed.
1N-27E-19BBB1	14.8	487	33	5	128	8	14	do.	Torch perforated, gravel packed.
2N-23E-21CBD1	2.8	276	99	.8	217	7	..	do.	Gravel packed.
2N-24E-23BCB1	32.3	194	6	2	130	7	12	do.	Perforated, gravel packed.
2N-26E-10ADA1	12.8	638	50	1	156	..	..	do.	
5N-21E- 9BDB1	9.1	817	90	3	274	16	..	do.	Perforated, no gravel pack.
CIMARRON COUNTY									
1N- 1E-20CCC1	2.9	546	186	1	267	..	..	Ogallala, Cretaceous, Morrison and Dockum	Gravel packed.
1N- 2E-18AAA1	5.7	1,000	175	12	322	18	18	Ogallala, Morrison, and Dockum	Perforated.
1N- 3E- 8ADB1	9.3	990	106	45	620	16	18	Ogallala, Cretaceous, Morrison, and Dockum	Machine perforated.
2N- 5E- 5BCA1	16.1	242	15	3	64	..	..	Ogallala	
2N- 5E- 6ADA1	2.0	138	69	3	256	..	22	Ogallala, Morrison	Perforated.
2N- 7E-23DDD1	39.0	780	20	2	145	16	24	Ogallala	Gravel packed.
2N- 7E-25DBB1	25.0	775	31	2	108	16	24	do.	Gravel packed.
2N- 7E-26ACA1	33.8	810	24	1	160	..	..	do.	
3N- 5E-23BBB1	37.9	720	19	1	83	16	24	do.	Perforated.
3N- 9E-13ABB1	2.2	238	110	10	142	16	..	Dockum	
4N- 4E-26BCB1	8.6	480	56	147	...	16	20	Morrison	
4N- 6E-35CBC1	7.0	288	41	2	53	16	..	Ogallala	Perforated.
TEXAS COUNTY									
1N-17E-19CCC1	3.5	245	70	10	191	16	30	do.	Perforated, gravel packed.
1N-17E-30ABC1	2.4	155	65	1	180	..	..	do.	
1N-17E-30ACC1	4.2	360	86	1	195	..	..	do.	
2N-10E-20BAD1	9.6	625	65	2	91	16	26	do.	Torch perforated, gravel packed.

2N-14E-23CBB1	26.1	1,150	44	22	166	16	..	Ogallala	Perforated and 10 feet screen.
2N-15E- 6CCC1	40.0	1,280	32	53	262	16	30	do.	Perforated, gravel packed.
2N-15E-10DCC1	4.7	710	152	7	215	16	..	do.	Perforated, gravel packed.
2N-17E-22DAB1	4.4	526	119	1	221	16	30	do.	Torch perforated, gravel packed.
3N-14E-35CCB1	7.6	550	72	72	202	16	..	do.	Perforated, gravel packed.
3N-15E-11CBA1	24.4	1,710	70	1	329	..	..	do.	
3N-15E-21BBC1	19.5	840	43	.2	268	..	..	do.	
4N-10E-34CBC1	6.3	425	67	42	109	16	20	Dockum	
4N-14E-14ABB1	45.5	1,000	22	9	286	16	..	Ogallala	
4N-19E- 5DAB1	6.5	1,015	155	2	398	..	..	do.	
5N-10E-15BDD1	21.6	777	36	2	144	..	..	do.	No gravel pack.
5N-13E-28CDD1	6.3	700	112	3	117	16	28	do.	Machine perforated, gravel packed.
5N-17E-27BBC1	9.7	570	59	4	168	16	30	do.	Gravel packed.

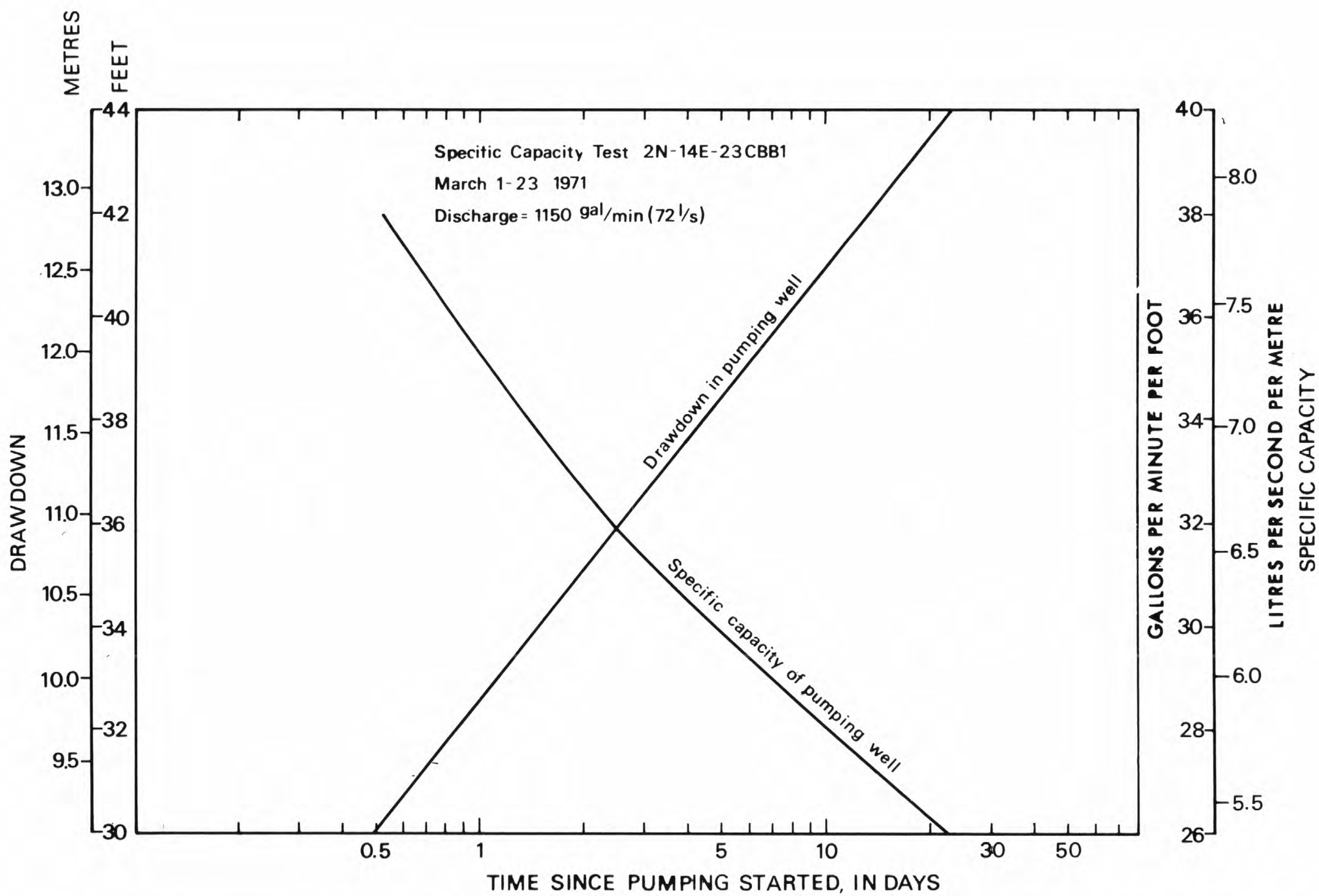

Figure 4.--Drawdown of water level and specific capacity of the pumping well 2N-14E-23CBB1 plotted against time since pumping started.

Water Levels

Water-level altitude changes show changes in saturated thickness, loss of ground water from storage, and determination of water-level trends. The stresses may be natural or man-made and may cause water levels to rise or decline. The major forces affecting the water level include unusually wet or dry periods, pumping and change in pumping rates.

History of Water Levels

Periodic water-level measurements were begun in Texas County in 1937 and in Beaver and Cimarron Counties in 1938. Prior to 1966 about 100 wells were measured in the Panhandle. More extensive measuring began in Texas County during 1966 and in Beaver and Cimarron Counties in 1967. Since 1967 approximately 500 wells have been measured annually throughout the Panhandle to determine water-level change and to aid in contouring of water levels.

Very few wells in which water-level measurements were made in the late 1930's and early 1940's are presently being measured because many have been destroyed and because the water level has declined below the bottoms of some of the shallow wells owing to increased pumpage for irrigation.

The depth to water in the three Panhandle counties is shown in plate 5. This plate shows the approximate depth that a well must be drilled to reach the top of the water-bearing zone in the Ogallala aquifer. Holes somewhat deeper than those shown in plate 5 may have to be drilled in the pre-Ogallala aquifers because the lines represent the potentiometric surface which does not necessarily coincide with the top of the water-bearing zone.

The ground-water gradient generally is eastward except where it is modified by the streams that have cut below the water table as shown in plate 6. The average gradient in the Ogallala aquifer is 14 ft/mi (2.6 m/km). Because of the eastward gradient, no large quantities of water enter or leave the area from either Kansas or Texas and only very small quantities of water are entering from the New Mexico-Oklahoma border because the Ogallala is above the water table except in the extreme southwestern corner of Cimarron County.

Hydrographs in figures 5 and 6 show the trend of water levels in wells in the Panhandle. Two distinct trends can be identified in this group of hydrographs. Water levels in some wells, such as 5N-25E-4BAC1, were relatively stable with only small fluctuations in the early 1960's because discharge from the aquifers by pumping was relatively small aa this time. Water levels in this well and others remote from heavy pumpage have continued this trend. Water levels in other wells, such as in well 2N-15E-9BCB1, show a rapid decline typical of wells in or near an area that is heavily pumped for irrigation. Steady water-level declines in the Ogallala aquifer represent a dewatering or mining of ground water from the aquifer. Two wells, 1N-3E-29CCB1 and 1N-2E-7DAA1, completed in the Dakota Sandstone and Cheyenne Sandstone Member and in the Ogallala Formation and the Cheyenne, respectively, show 10 to 30 ft (3 to 9 m) of annual fluctuation but net declines during the period from

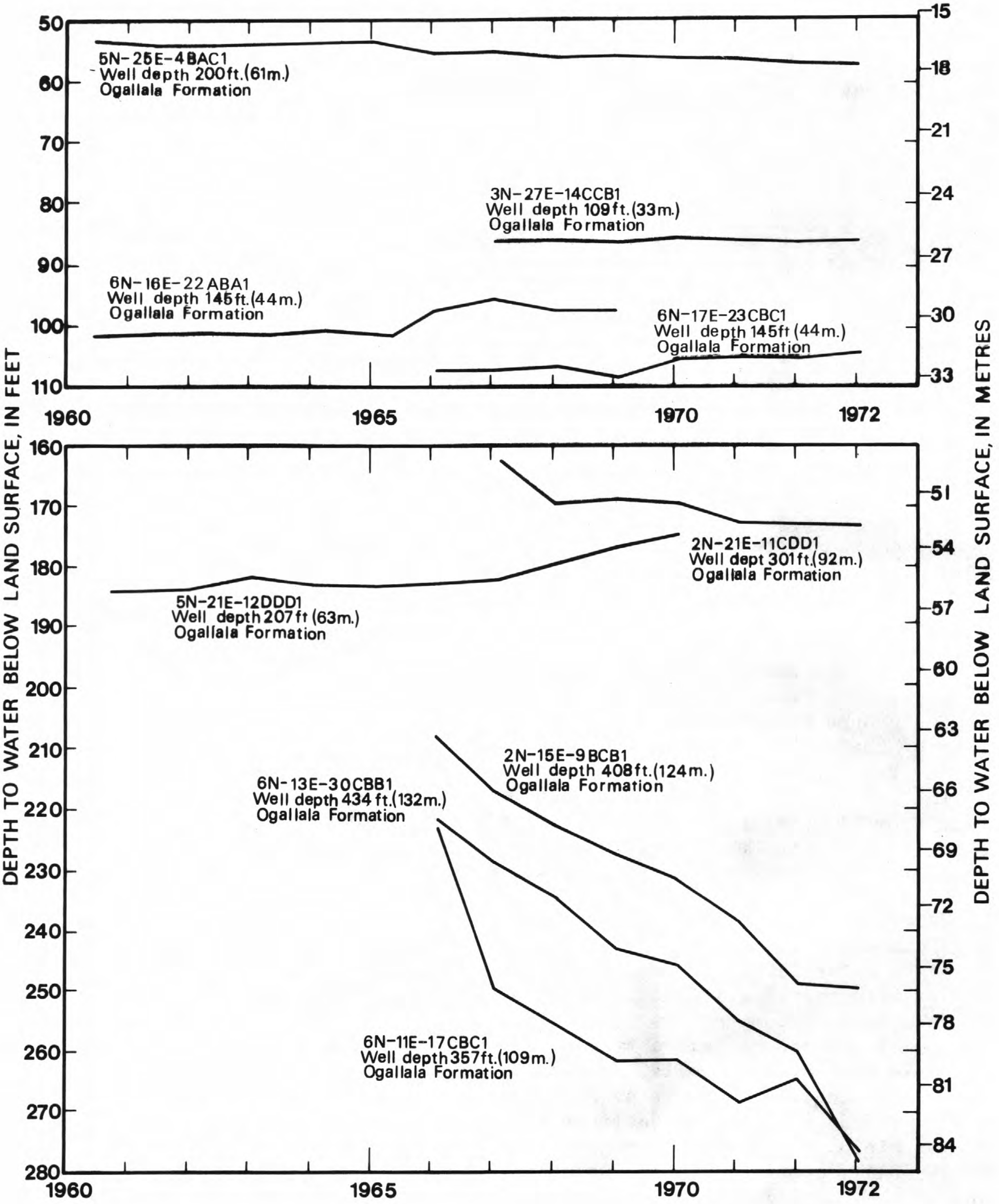

Figure 5.--Water levels in wells, Beaver and Texas Counties.

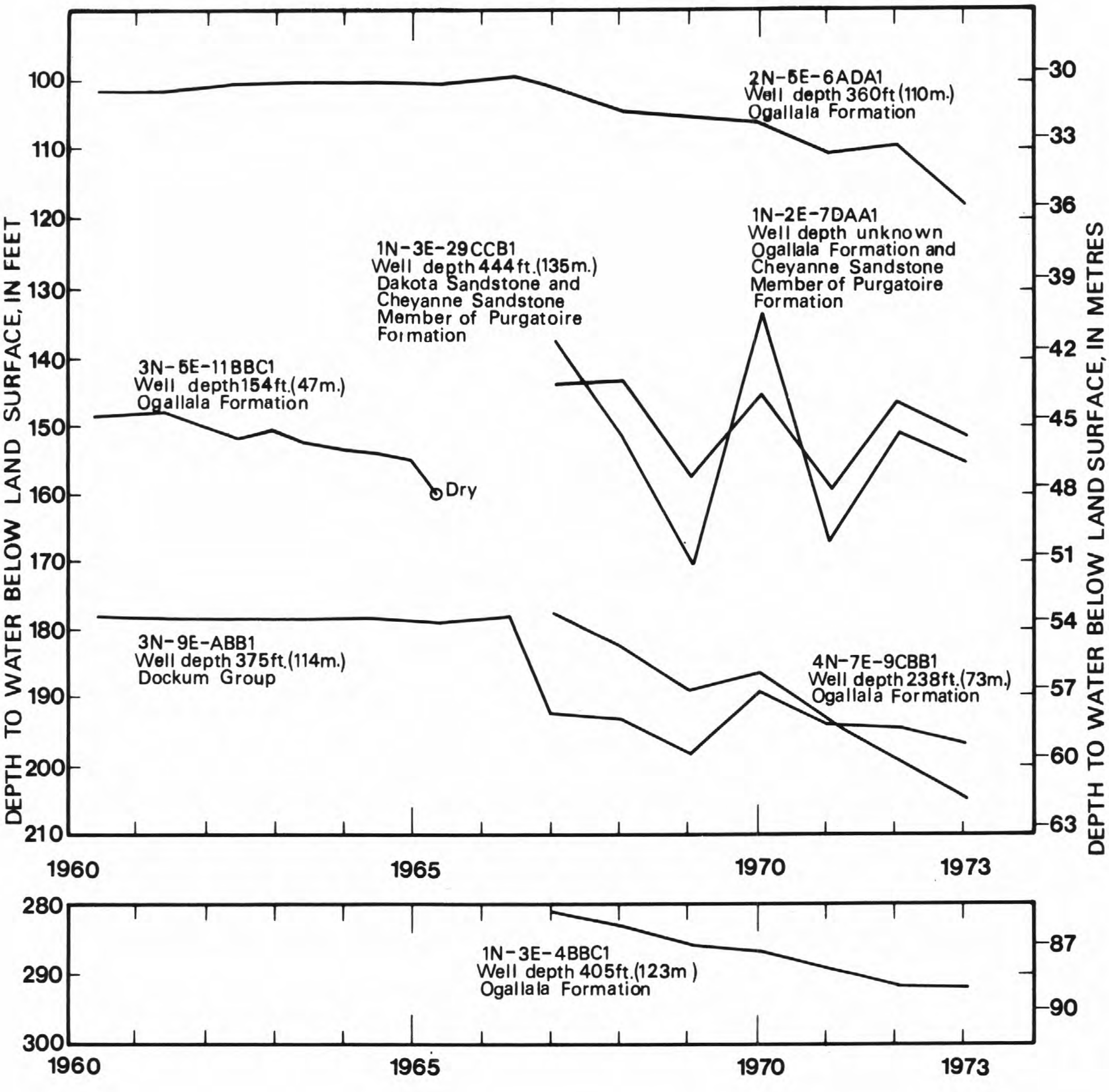

Figure 6.--Water levels in wells, Cimarron County.

1966 through 1972 have been less than 15 ft (5 m). Because the water in the Cheyenne usually is under artesian conditions, it reacts differently to stresses imposed on it than does water in water-table or semiartesian aquifers such as the Ogallala Formation. Major water-level fluctuations in the Ogallala aquifer are primarily a response to the relation between pumpage and recharge from year to year.

Ground-Water Withdrawals

Pumpage for irrigation began in the 1930's, and by the end of the decade there were fewer than 30 wells. The drilling of irrigation wells continued at a slow but steady rate until 1964 when the rate increased very rapidly in Cimarron and Texas Counties as shown in figure 7.

Distribution of known irrigation wells and selected small-capacity wells are shown in plate 7. Wells pumped for irrigation generally yield a minimum of 250 gal/min (16 l/s) and a maximum of 2,400 gal/min (150 l/s). Wells yielding less than 250 gal/min (16 l/s) are seldom completed for irrigation use. The Oklahoma Water Resources Board, at the present time allows ground-water withdrawal at a rate of 2 acre-ft per year per acre [6.90 x 10^5 (m^3/yr)/km^2] for irrigation, however, wells are not metered and little data are available concerning actual withdrawals.

In 1960 about 400 irrigation wells in the Panhandle were used to irrigate 80,000 acres (324 km^2); in 1965 the number had increased to about 975 wells used to irrigate 220,000 acres (890 km^2). During 1971 about 1,846 wells were used to irrigate 344,040 acres (1,392 km^2)--236 irrigation wells were reported in Beaver County, 715 in Cimarron County, and 895 in Texas County. Because the wells generally are in groups, the effect of heavy pumpage is readily apparent by the lowering of water levels. Ground-water withdrawal rates in several large areas exceed the recharge rate as shown by water-level declines. Water levels, during the period 1966 to 1972, have declined at the rate of 1 to 5 ft (0.3 to 1.5 m) per year in the Boise City area, 1 to 7 ft (0.3 to 2.1 m) per year in the Guymon area and in an area in north-western Texas County. Because of the fewer number of wells in Beaver County, water levels throughout most of this area have not shown a general decline as have those in Texas and Cimarron Counties. The rate of decline varies from year to year in response to above- or below-normal precipitation of preceding years and the quantity of water withdrawn annually from the aquifer.

Estimates of pumpage were calculated from crop acreage and the amount of water applied annually to the various crops. This information is collected on an alternate-year basis by the Oklahoma Extension Irrigation Specialist. Figure 8 shows the estimated pumpage in thousands of acre-feet for the odd-numbered years 1965 through 1971. The estimated pumpage for the 7-year period 1965-71 for Beaver County was 310,000 acre-ft (5.06 x 10^8 m^3). Cimarron County was 1,100,000 acre-ft (1.36 x 10^9 m^3), and Texas County was 2,700,000 acre-ft (3.33 x 10^9 m^3). The estimated pumpage in the three-county area during 1971 was 736,000 acre-ft (9.07 x 10^8 m^3).

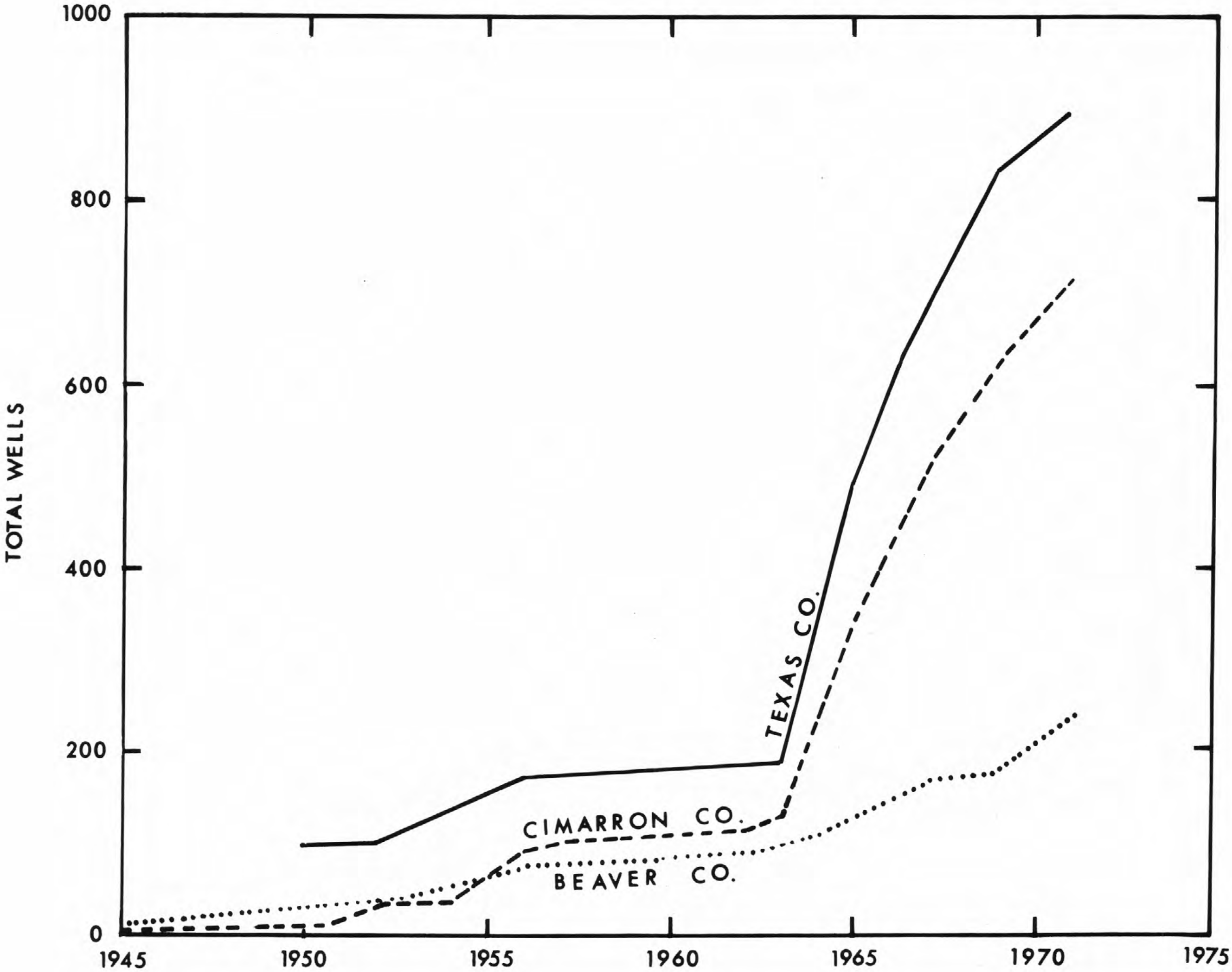

Figure 7.--Number of irrigation wells in Panhandle Counties, 1945-71.

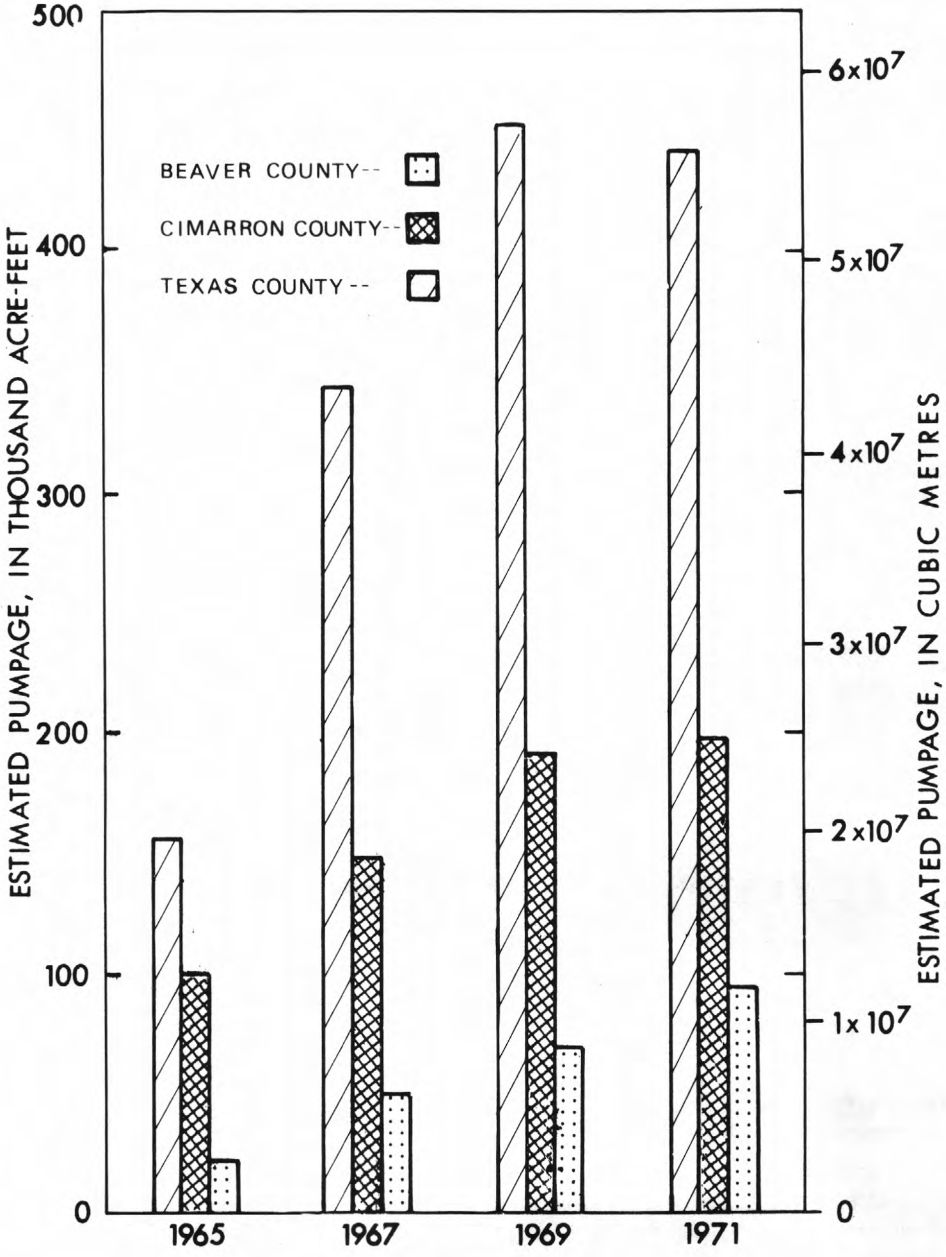

Figure 8.--Estimated pumpage for odd-numbered years, 1965-71.

Ground-Water Recharge

Rainfall is the primary source of recharge to aquifers in the Oklahoma Panhandle. The climate of the area is characterized by moderately low precipitation, low relative humidity, brisk wind movement, abundant sunshine, high solar radiation, and a high rate of evaporation. Weather records show that the average precipitation ranges from about 16 in (410 mm) in the extreme western part of the area to about 21 in (530 mm) in the eastern part.

The net rise in water level in observation well 6N-16E-22ABA1 was used to estimate the amount of recharge to the Ogallala aquifer from precipitation for the years 1938-69. This well was selected because the area is not greatly affected by pumpage since there are only a few wells in the area with the nearest irrigation well 2 mi (3 km) away and because the area is partly dune covered and represents a rather ideal catchment and recharge area. Recharge at this site probably represents a near maximum rate. Since the relatively low-water level in 1938, which resulted from prior drought conditions, the water level in the observation well rose 26.2 ft (8 m). Based on an assumed storage coefficient of 0.1, recharge to the aquifer was at least 2.6 ft (0.8 m) of water over the 31-year period or 1 in (25 mm) per year, assuming underflow through the area is relatively constant. Water levels in other wells in the Panhandle indicate significantly smaller rates of recharge. An average rate of 0.25 to 0.5 in (6 to 13 mm) per year probably is more representative of the entire Panhandle area. This estimate is in agreement with that made by C. V. Theis (1937) for the Southern High Plains in New Mexico and Texas. Estimated recharge in the Southern High Plains, which has comparable rainfall to that in the Oklahoma Panhandle, was determined to be somewhat less than 0.5 in (13 mm).

The surface area of the Ogallala aquifer is about 5,200 mi^2 (13,468 km^2) and if the average recharge from precipitation is 0.25 to 0.5 in (6 to 13 mm) per year, the quantity of water added annually to the aquifer ranges from 69,000 to 138,700 acre-ft (8.51×10^7 to 1.71×10^8 m^3). The quantity of ground water being added to the aquifer annually is considerably less than the annual withdrawals, and ground water is being taken from storage or mined.

In addition to recharge from precipitation, some recharge probably is provided by return flow from irrigation water. Although return flow was not estimated, the hydrologic conditions are similar to those in southwestern Kansas where return-flow estimates range from 15 to 25 percent of the total water applied on a well-drained soil (Meyer, Gutentag, and Lobmeyer, 1970, p. 71-73). If the average return flow from irrigation is estimated at 20 percent of the applied water, return flow would add an additional 147,000 acre-ft (1.81×10^8 m^3) of water to the aquifer. This amount added to maximum recharge from precipitation would result in recharge to the aquifer of 285,700 acre-ft (3.52×10^8 m^3) annually.

Availability of Ground Water

Reservoir Storage and Storage Change

The volume of water stored in the Ogallala aquifer was computed from the saturated thickness, which is the distance from the water level to the base of the aquifer, and the storage coefficient. As shown on page 24, storage coefficients range from 0.002 to 0.11. Storage coefficients in untested areas have values both less and greater than those in the test sites. It is known that the storage coefficients range widely in different areas and may have considerable range vertically in the saturated section of the aquifer. The following data in this section are based on an average storage coefficient of 0.10. Storage coefficients in the Ogallala in Texas range from 0.15 to about 0.28 (Cronin, 1964) and (Jones and Schneider, 1969). The Ogallala in Oklahoma may contain more clay and fine-grained sand than it does in the Southern High Plains of Texas resulting in lower storage coefficients.

The saturated thickness of the Ogallala aquifer in Beaver County ranges from zero to greater than 500 ft (152 m) (pl. 8) and in 16 percent of the county is unsaturated. The saturated thickness in Cimarron County ranges from zero to greater than 150 ft (46 m) and in 41 percent of the county is unsaturated. The saturated thickness in Texas County ranges from zero to greater than 550 ft (168 m) and in 7 percent of the county is unsaturated.

Excluding those areas where the Ogallala is unsaturated, the mean saturated thickness is 165 ft (50 m) in Beaver County, 70 ft (21 m) in Cimarron County, and 240 ft (73 m) in Texas County. The volume of water in the Ogallala aquifer, assuming a storage coefficient of 0.10, is 16, 5, and 29 million acre-ft (1.970×10^{10} m^3, 6.16×10^9 m^3, and 3.580×10^{10} m^3), respectively, or a total of about 50 million acre-ft (6.165×10^{10} m^3) for the Oklahoma Panhandle.

The volume of water in storage in the Cretaceous, Jurassic, and Triassic aquifers was not computed because data on the saturated thickness and storage coefficients are not adequate.

Water-level change maps constructed from annual water-level measurements are used to compute the volume of storage change in the aquifer. Water-level declines primarily show the effects of pumping and water-level rises show the effects of recharge or reduction in pumpage. Water-level change maps were used to compute the change in storage for the periods 1938-72 and 1967-72 (pl. 9). A zero line is not shown because of the lack of control in the undeveloped areas. The areas between the first plus contour and the first minus contour are assumed to have a mean change of zero. In the areas where control for contouring is lacking some numerical data are shown. Gains in storage or recharge may occur more or less continuously in some parts of the aquifer because of good infiltration characteristics while losses may occur simultaneously in other parts of the aquifer because of pumpage or natural discharge. Table 4 summarizes the net change in storage for the periods indicated.

Table 4.--Summary of storage characteristics of the Ogallala aquifer.

(Based on an assumed storage coefficient of 0.10.)

County	Total water in storage 1972 (acre-feet)	Percent of total water in Panhandle present in each county	Net change 1938-72 (acre-feet)	Percent change 1938-72	Net change 1967-72 (acre-feet)	Percent change 1967-72
Beaver	16,000,000	32	238,000	1.5	-10,000	-0.1
Cimarron	5,000,000	10	-176,000	-3.5	-166,000	-3.3
Texas	29,000,000	58	-445,000	-1.5	[1] -902,000	[1] -3.1
TOTALS	50,000,000	100	-383,000	-.1	-1,078,000	-2.2

[1] Texas County period of record 1966-72.

Owing to the low water levels caused by the drought of the late 1930's, the period from 1938 to the early 1960's was primarily a gaining period, whereas the period from the early 1960's to 1972 was primarily a losing period because of the large increase in irrigation in the 1960's.

The storage change in the Ogallala aquifer computed from the 1967-72 (pl. 9) water-level change map for Beaver County shows no areas of serious overdevelopment. The decline in water level in T. 1 N., Rs. 22 and 23 E., and Tps. 4 and 5 N., R. 20 E., are the result of irrigation pumpage, although the cones of depression are of significant areal extent, they show a relative small decline when compared to the saturated thickness. The rise in the water level in Tps. 4 and 5 N., Rs. 20, 21, and 22 E., in a sand-dune area, shows it is a significant recharge area.

The volume of storage change in the Ogallala aquifer, computed from the 1938-72 water-level change map for Beaver County shows a net increase in storage. The increase in the volume of water in the Ogallala aquifer shows that the 1938-72 period has been primarily a recharge period. The greatest increase in storage occurred in the northwest part of Beaver County.

The 1967-72 water-level change map (pl. 9) for Cimarron County shows a net decrease in storage in the Ogallala aquifer. The two main areas of storage decline are in the areas of central Cimarron County, and in T. 2 N., Rs. 7 and 8 E. The saturated thckness has been reduced as much as 24 percent since 1967 in T. 3 N., R. 5 E., and as much as 39 percent in T. 4 N., Rs. 6 and 7 E. Large declines have developed in these two areas because of irrigation pumpage. Two small areas with a decline greater than 5 ft (1.5 m) occurred in the Cretaceous aquifers during 1967-72 in the southwestern part of the county.

The 1938-72 water-level change map for Cimarron County shows that the Ogallala aquifer has had a net decline in storage. The water-level declines in the southeastern part of the county for the 1938-72 period are similar to the 1967-72 period indicating most declines have occurred since 1967.

The 1967-72 water-level change map for Texas County show large water-level declines in several areas of the county. The volume of storage change in the Ogallala aquifer is a net decrease. The larger declines have occurred in the south-central part of the county where the saturated thickness inside the 40-foot (12.2 m) line has been reduced by 16 percent since 1966. A reduction of the saturated thickness, as much as 30 percent since 1966, has occurred in T. 6 N., Rs. 11, 12, and 13 E.

The 1938-72 water-level change map for Texas County shows larger declines in T. 2 N., Rs. 15 and 16 E., and T. 2 N., R. 13 E., than those on the 1967-72 map, and large increases in storage in the northeast part of the county. The northeast part of Texas County is covered largely by sand dunes that facilitate recharge. The rise in water levels indicates that 1938-72 was a recharge period. The volume of storage change in the Ogallala aquifer for the 1938-72 period shows a net decline.

The storage change in the Cretaceous, Jurassic, and Triassic aquifers was not computed since the storage coefficient is not defined. The water-level change in the Cretaceous, Jurassic, and Triassic aquifers, which are used for irrigation in the southwestern and east-central part of Cimarron County, show a decline of as much as 20 ft (6 m). Most of this decline has occurred since 1967. The water-level change in these aquifers generally is represented by change in the potentiometric surface and may not represent true changes in storage because these aquifers are confined in most areas.

Quantities Available

The yield of water available from a well is dependent on the hydraulic conductivity, saturated thickness, and specific yield of the aquifer, and the radius and efficiency of the well. In an unconfined aquifer the saturated thickness and transmissivity decrease with a decline of water level, reducing the potential yield of the wells. In a confined aquifer a lowering of head does not decrease the saturated thickness but the head change results in a reduction of the potential yield of the well.

A direct relationship between transmissivity of the aquifers and specific capacity of the wells was used to extend the transmissivities determined from pumping tests to wells with only specific-capacity data available. The equation used is:

$$T = C \times (\text{specific capacity})$$

$$T = C\left({}^{Q}/_{s}\right)$$

where: T = Transmissivity, in feet squared/day

Q = discharge, in gallons per minute

s = drawdown, in feet

C = constant

C was determined by plotting the T values obtained from aquifer test versus the specific capacity of the pumping wells used in the tests. From the slope of the line a value of 1,800 was determined for C. From the relationship between T and Q/s, values of T were estimated for every well where Q/s was known. The resultant value of T is applicable for the time when the discharge was measured, generally shortly after the well was drilled. Because large declines in water level have occurred in some areas since the wells were tested, the T value for 1972 is smaller than the originally estimated T value. Using the relationship that

$$K = \frac{T_o}{b_o} = \frac{T(1972)}{b_{(1972)}}$$

where: K = hydraulic conductivity

T_o = original transmissivity

$T_{(1972)}$ = 1972 transmissivity

b_o = original saturated thickness

$b_{(1972)}$ = 1972 saturated thickness

and assuming that the linear relationship of Q/s to T is unchanged, and that specific yield and hydraulic conductivity are constant, the following formula was used to estimate the maximum well yield for a well developed in 1972 and pumped at a rate that would develop a drawdown in the well equal to two-thirds the saturated thickness:

$$Q_{(max)} = \frac{(0.67)\left(b_{(1972)}\right)^2 \left(Q_o\right)}{(S_o)(b_o)}$$

where: $Q_{(max)}$ = 1972 well yield, in gallons per minute, when drawdown is 2/3 the saturated thickness

$b_{(1972)}$ = 1972 saturated thickness, in feet

b_o = original saturated thickness when tested, in feet

Q_o = discharge when tested, in gallons per minute

S_o = drawdown in well when originally tested, in feet

It is assumed that the well fully penetrates the aquifer, is adequately screened through the water-bearing zones, and is developed in an efficient manner.

Plate 10 shows the 1972 estimated potential discharge from wells tapping the major aquifers in the Panhandle. Potential well yield of the Ogallala aquifer ranges from zero to as much as 2,500 gal/min (158 l/s). The estimated potential well yield for the Cretaceous aquifers range from zero to more than 300 gal/min (19 l/s). The estimated potential well yield for completed wells in the Cretaceous, Jurassic, and Triassic aquifers in the southwest part of Cimarron County ranges from 300 gal/min (19 l/s) to as much as 1,000 gal/min (63 l/s). The estimated potential well yield is in excess of 300 gal/min (19 l/s) for the Triassic aquifers in the east-central part of Cimarron County. In certain areas where one aquifer overlies another, it is possible with proper well construction to obtain well yields equal to the sum of the well yields of both aquifers. The alluvium of the Beaver and Cimarron Rivers yields small amounts of water in areas where the Ogallala yields no water.

In Beaver County the range in well yields from the Ogallala are zero to greater than 1,500 gal/min (95 l/s). Areas of zero well yields include a significant part of the county. Wells in these areas obtain water from the red beds.

The 1972-estimated potential well-yield map shows four different line patterns for different aquifers in Cimarron County. In the Cretaceous, Jurassic, and Triassic aquifers a zero well yield contour is not shown. Multiple aquifer completions by wells are possible in several areas within the county. For example, in the northeast corner of T. 1 N., R. 3 E., the estimated potential-well yield is greater than 1,100 gal/min (69 l/s).

The estimated well yield for the Ogallala aquifer in Texas County ranges from zero to a maximum of greater than 1,500 gal/min (95 l/s). The estimated potential well yield for the Triassic aquifers in the west-central part of the county is greater than 300 gal/min (19 l/s). A zero line is not defined for the Triassic aquifers.

Declining Well Yields

A reduction of the saturated thickness results in a reduction of the maximum well yield; therefore, in areas of declining water levels the maximum well yields also decline. In order to obtain the same quantity of water from wells in areas where the saturated thickness has been reduced, the wells must be pumped for longer periods of time or additional wells must be drilled.

In a homogeneous unconfined aquifer a reduction in saturated thickness reduces the transmissivity and the maximum possible drawdown, and consequently the maximum well yield. The head is the difference in altitude between the base of the aquifer and the water level for a confined aquifer. The head and saturated thickness are equal for an unconfined aquifer. For a confined aquifer a reduction in head reduces the maximum possible head difference that can be developed between the well and the aquifer and does not affect the transmissivity. The direct relationship between the percent reduction in head and the percent reduction in maximum well yield is shown in figure 9. The upper line illustrates the relationship for the homogeneous unconfined aquifer, exemplified locally by the Ogallala aquifer. The lower line illustrates the relationship for a confined aquifer, exemplified by most of the pre-Ogallala aquifers. For example, a 50-percent reduction in the head would result in a 50-percent reduction in maximum well yield of a well screened in a pre-Ogallala aquifer. A 50-percent reduction in head in the Ogallala aquifer will result in a 75-percent reduction in maximum yield. If the top of the Ogallala aquifer consists of finer materials than the lower part of the aquifer, the relationship between the percent reduction in head and the percent reduction in maximum well yield would lie between the two lines shown in figure 9.

Chemical Quality of Ground Water

All natural water contains mineral matter dissolved from rock and soil with which it has come in contact. The quantity and kind of dissolved mineral

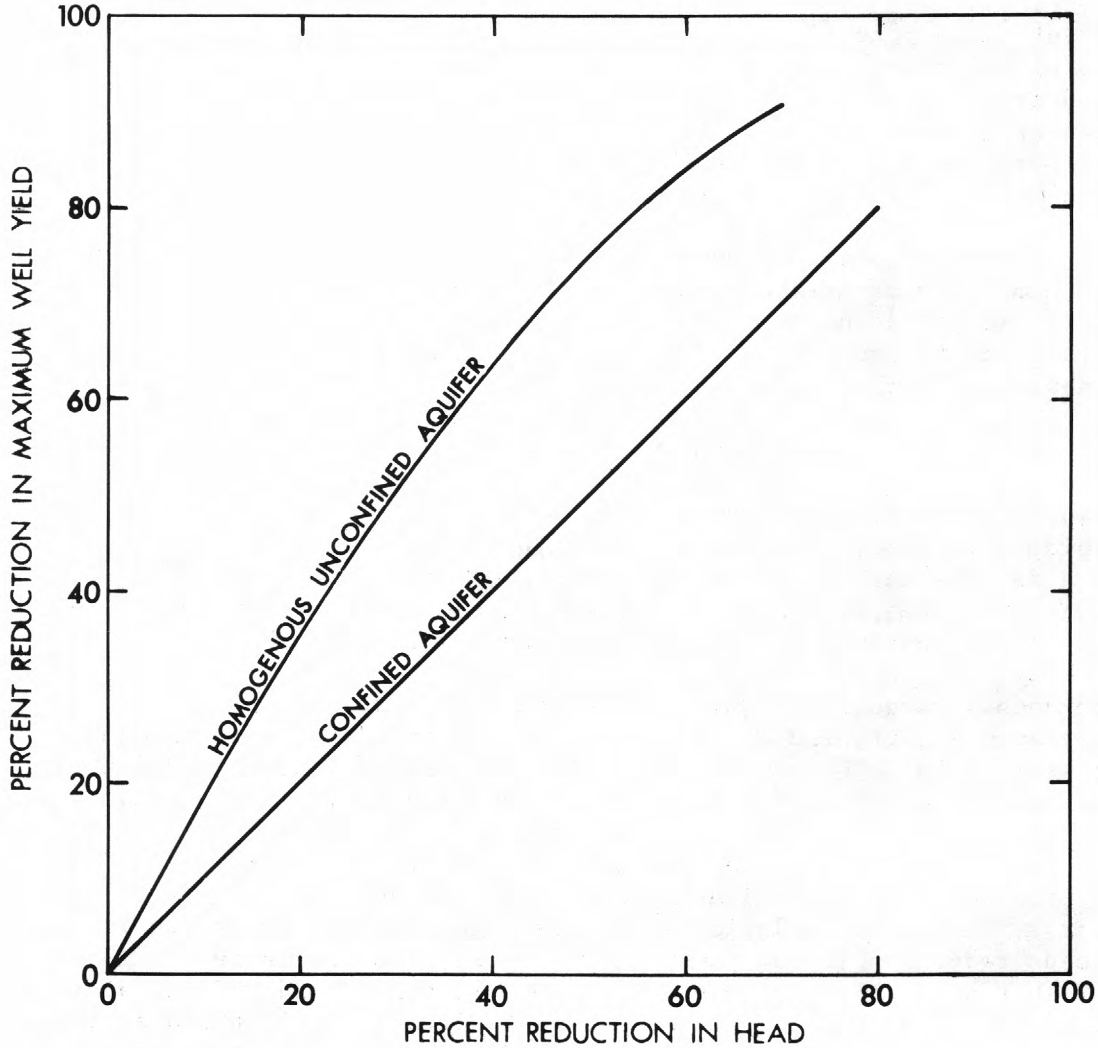

Figure 9.--Relation of percent reduction in maximum well yield and percent reduction in head.

matter in ground water depends on the type of rocks or soil through which the water has passed, the duration of contact, and the pressure and temperature. In addition to natural factors there are others associated with human activities such as infiltration of polluted water from streams, ponds, and wells.

The mineral constituents and physical properties of ground water from selected wells in the Panhandle are reported in table 5. Analyses of 94 water samples were chosen for inclusion in this table because they seem representative of the water in their respective aquifers and location. Most water samples were collected by either the Geological Survey or the Soil Conservation Service, and all were analyzed by the Geological Survey. A total of 543 water-sample analyses were available for inspection; of these, 112 were in Beaver County, 107 were in Cimarron County, and 224 were in Texas County.

Water-quality parameters in table 5 include those useful in evaluating the chemical suitability of water for some beneficial use. Water used for municipal and domestic supplies should be colorless, oderless, and palatable; and wherever possible should conform to the limits of the Oklahoma State Department of Health (1964). Although water of a quality that meets Oklahoma Department of Health standards is desirable and water of even better quality would be more desirable, not all communities in the Panhandle have a source of water that meets these standards.

The chemical composition of a water is an important factor in determining its usefulness for irrigation, because the quality of the water should not adversely affect the productivity of the land irrigated. The extent to which chemical quality limits the suitability of a water for irrigation depends on many factors, such as the nature, composition, and drainage of the soil and subsoil; the amounts of water used and the methods of applying it; the kind of crops grown; and the climate of the region. Because these factors are highly variable, every method of classifying waters for irrigation is somewhat arbitrary.

The most important characteristics in determining the quality of irrigation water according to the U.S. Salinity Laboratory Staff (1954, p. 69) are: (1) total concentration of soluble salts, (2) relative proportion of sodium to other cations, (3) concentration of boron or other elements that may be toxic, and (4) the excess of equivalents of calcium plus magnesium.

High concentrations of dissolved salts in irrigation water may cause a buildup of salts in the soil solution, and may make the soil saline. The increased salinity of the soil may reduce crop yields by decreasing the capacity of the plants to take up water and essential plant nutrients from the soil solution. The tendency of irrigation water to cause a buildup of salts in the soil is called the salinity hazard of the water. The specific conductance of the water is used as an index of the salinity hazard.

Table 5.--Analyses of water from selected wells in the Oklahoma Panhandle.

(Constituents in milligrams per litre; analyses by U.S. Geological Survey.

Location	Depth (feet)	Probable aquifer	Date of collection	Calicum (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CACO_3$		Sodium-adsorption ratio (SAR)	Specific conductance (micromhos at 25°C)
													Calcium magnesium	Noncarbonate		
BEAVER COUNTY																
T1N-R20E-32BBC1	430	QT	5- 6-65	..	....	69	224	46	50	4.5	0.11	347	156	0	2.4	602
T1N-R21E-3AAB1	430	QT	11-29-66	..	....	152	186	352	192	....	.48	1,040	460	.....	3.1	1,560
T1N-R22E-26DDB1	515	QT	7-23-64	..	....	224	232	207	285	....	.21	1,110	324	134	5.4	1,380
T1N-R23E-8DCD1	504	QT	10- 9-69	..	....	162	282	125	110	6.1	.19	618	170	0	3.1	1,020
T1N-R23E-26DDD1	409	QT	8-14-59	46	32	91	226	67	130	5.4	.25	585	245	60	2.5	909
T1N-R27E-6ACB1	117	QT	10- 8-69	..	....	128	256	68	178	1.0	.07	642	260	50	3.4	1,100
T2N-R22E-26CBB1	300	QT	3-26-67	..	....	12	68	13	55	.9	.00	140	116	60	.4	318
T2N-R23E-21CBD1	282	QT	4- 5-67	..	....	63	238	33	44	5.9	.18	357	164	0	2.0	574
T2N-R25E-33ACA1	748	QT	10- 9-69	..	....	32	272	87	13	2.1	.06	407	226	43	.8	629
T2N-R26E-R34BA1	425	QT	12-30-64	..	....	48	360	20	39	.4	.62	455	270	0	1.2	693
T2N-R26E-34BDB1	494	QT,P	4-20-64	..	....	600	234	150	950	1.3	.25	2,040	384	192	13	3,500
T2N-R28E-31DC1	280	QT	8- 4-66	..	....	318	246	174	445	....	.25	1,200	316	114	7.8	2,090
T3N-R24E-16AAB1	83	P	11-29-39	..	...	.....	100	1,700	23	1.2	...	.....	1,440	.....	....	.....
T4N-R20E-5CDC1	533	QT	3-17-66	..	....	318	246	172	445	....	.25	1,200	316	114	7.8	2,090
T4N-R23E-20CDD1	78	P	11-28-39	..	....	.....	32	2,000	1,355	1.7	....	.....	2,040	.....	....	.....
T4N-R24E-29B1	170	P	8-24-64	..	....	1,330	44	1,860	2,200	.9	....	6,920	2,190	2,150	12	8,940
T4N-R27E-2BDC1	230	QT	8-12-59	88	9.8	11	252	23	25	22	.18	323	260	54	.3	323
T5N-R20E-34BBB1	455	QT	4- 4-66	..	....	263	244	148	372	....	.08	1,040	312	.....	6.5	.....
T5N-R22E-29CBD1	402	QT	4-10-67	..	....	43	236	37	42	13	.12	360	218	24	1.2	596
T5N-R24E-30CCC1	100	QT	1961	54	12	41	254	13	34	3.5	....	326	184	.....	1.0	547
T5N-R25E-17DAD1	179	QT	4- 3-40	..	....	.....	247	38	35	10	....	.....	243	.....	....	.....
T5N-R26E-25ADB1	215	QT	4- 4-40	..	....	.....	200	13	18	1.4	....	.....	189	.....	....	.....
T5N-R28E-32DDD1	48	QT	11-19-51	91	11	10	291	15	8	32	....	342	272	34	....	539
T6N-R20E-35DCC1	560	QT	11-13-65	..	....	154	260	155	150	2.2	.24	671	252	39	4.2	1,090
CIMARRON COUNTY																
T1N-R 1E-15BBB1	412	C	9-27-64	..	....	27	248	38	9	....	.14	280	196	0	.8	464
T1N-R 1E-28DBB1	358	QT	9-10-64	..	....	8	196	19	6	....	.07	225	172	11	.2	386
T1N-R 2E-10BDD1	210	QT	11-20-58	48	18	25	234	39	10	.7	.67	273	192	0	.8	442
T1N-R 3E-8ADB1	703	J.T	4-25-67	...	...	33	256	56	18	4.8	.10	338	228	18	.9	543

T1N-R 3E-23AAD1	470	C	10-15-63	32	24	25	216	42	10	....	....	284	180	3	.8	457
T1N-R 4E-25DAB1	275	QT	4-15-64	...	...	34	236	58	19	....	.02	341	208	14	1.0	554
T1N-R 5E-20BCC1	286	QT	4-25-67	...	...	45	236	50	13	5.0	1.7	303	180	0	1.4	500
T1N-R 7E-18DCC1	104	QT	1- 8-63	...	...	32	272	42	23	3.0	.14	387	232	9	.9	566
T1N-R 9E-15BAB1	300	QT	11-10-38	39	25	27	207	49	18	9.0	....	307	200	.....	.8	.....
T2N-R 3E-1AAD1	120	QT	4-14-39	...	...	.....	259	60	22	7.2	....	.....	273	.....	....	.....
T2N-R 5E-2DAA1	243	QT	7-15-65	...	...	22	234	38	18	....	.13	321	210	18	.6	516
T2N-R 7E-10DDD2	280	QT	8- 8-67	...	...	23	212	37	17	7.4	.07	281	196	22	.6	458
T2N-R 8E-19BAB1	424	QT	8- 8-67	...	...	33	226	45	19	8.0	.11	326	202	17	1.0	508
T3N-R 3E-11BBA1	198	QT	1- 1-68	...	...	17	218	17	20	....	....	335	208	29	.5	498
T3N-R 4E-23CDC1	202	QT	8- 8-67	...	...	26	216	55	27	12	.08	343	232	55	.7	539
T3N-R 4E-33BCC1	415	QT,C	7-31-63	...	...	211	446	71	10	.6	.35	553	16	0	23	869
T3N-R 5E-10ACC1	270	QT	8- 8-67	...	...	26	218	39	26	14	.07	319	214	35	.7	517
T3N-R 6E-33CCB1	223	QT	3-29-67	...	...	27	200	36	24	14	.16	316	196	32	.7	496
T3N-R 7E-20CBA1	193	QT	4-24-67	...	...	27	286	33	12	9.6	.20	329	244	10	.6	528
T3N-R 9E-16AAA2	330	T	1- 2-62	6	4	264	296	300	35	3.1	.57	784	32	0	20	1,210
T4N-R 5E-36CBB1	288	QT	11-19-63	...	...	21	204	29	19	16	.16	300	192	25	.6	.....
T4N-R 7E-5BBC1	304	QT	4-23-64	...	...	12	194	34	22	11	.25	276	208	49	.4	449
T4N-R 8E-27CCC1	280	T	2 -63	...	...	86	294	68	9	8.5	.50	384	144	0	3.1	640
T5N-R 1E-4CA1	29	J	8-12-59	99	89	349	450	867	72	1.9	.41	1,750	615	246	6.1	2,320
T5N-R 5E-11ACC1	15	QT	10-23-62	...	...	442	520	842	75	.1	.56	1,790	448	22	9.1	2,480
T6N-R 1E-13CA1	70	J	3-21-61	27	29	173	219	163	18	.6	.30	641	185	0	5.5	1,030
T6N-R 1E-17BBA1	35	QT	2-12-59	77	75	38	203	200	22	8.2	.34	681	500	162	.7	1,010
T6N-R 9E-14AAA1	205	T	11- 4-63	...	...	109	402	144	18	1.5	.19	573	268	0	2.9	891
TEXAS COUNTY																
T1S-R15E-6BAB1	274	QT	5- 3-60	51	25			76	8	6.0	.34	335	230	52	.6	520
T1N-R16E-6BBC1	215	QT	11-20-51	44	30	30	239	65	11	9.9	....	328	234	38	....	539
T1N-R16E-31CAA1	413	QT	7- 8-66	...	...	26	226	69	8	8.5	....	339	222	37	.8	516
T1N-R17E-30ACC1	365	QT	4-11-64	...	...	32	230	128	17	....	.19	437	276	87	.8	660
T1N-R18E-24CBA1	207	P	5-21-61	364	121	1,150	58	2,230	1,050	....	1.8	5,060	1,360	1,310	14	6,540
T2N-R11E-31DAA1	310	QT	5- 5-67	...	...	25	212	33	16	7.2	.22	285	182	8	.7	459
T2N-R12E-25DBB1	332	QT	6-30-59	39	33	17	226	50	18	7.3	.14	316	232	47	.5	511
T2N-R13E-28BBA1	332	QT	6-18-59	32	31	20	224	40	16	4.6	.00	268	208	24	.6	484
T2N-R14E-12DBB1	339	QT	6- 7-65	...	...	13	194	72	16	11	.22	356	242	83	.4	510
T2N-R14E-23CBB1	282	QT	10-11-69	...	...	24	240	59	11	8.5	.10	331	228	32	.7	534
T2N-R15E-15BAA1	405	QT	10-11-69	...	...	26	252	97	7	6.2	.13	374	266	60	.7	604
T2N-15E-34ABC1	575	QT	11-25-67	...	...	72	324	220	26	2.2	.18	654	380	114	1.5	958
T2N-16E-10BBB1	372	QT	4- 6-67	...	...	47	256	105	13	5.9	.21	396	242	32	1.2	620
T2N-R17E-7CCC1	473	QT	4- 8-66	...	...	97	248	170	150	6.5	.24	745	390	.....	2.1	1,150
T2N-R18E-8BAD1	188	QT	2- 3-67	46	22	21	228	25	15	6.1	...	301	208	21	.6	491
T2N-R18E-24BCC1	269	QT	10- 6-69	...	...	1,090	268	338	1,590	0	.39	3,450	395	241	22	5,950
T3N-R15E-30AAC1	180	QT	4-21-59	61	42	34	252	155	16	10	.49	467	325	118	.8	722
T3N-R16E-35CDD1	418	QT	1- 7-63	...	...	42	256	112	18	5.0	.44	426	264	54	....	658

Table 5.--Analyses of water from selected wells in the Oklahoma Panhandle.--Continued

Location	Depth (feet)	Probable aquifer	Date of collection	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Boron (B)	Dissolved solids	Hardness as $CACO_3$		Sodium-adosrption ratio (SAR)	Specific conductance (micromhos at 25°C)
													Calcium magnesium	Noncarbonate		
TEXAS COUNTY--Continued																
T3N-R18E-4ACC1	560	QT	3-19-67	...	...	29	240	35	102	16	.10	509	340	137	.6	787
T4N-R10E-18CCB1	317	T	7-30-59	38	33	33	266	58	9	13	.24	375	230	12	.9	588
T4N-R10E-31BBB1	508	T	8-26-67	...	...	37	236	115	11	9.2	.12	387	256	62	.9	615
T4N-R15E-21ABD1	405	QT	9-17-59	62	32	58	264	152	22	5.7	.31	483	285	68	1.5	769
T4N-16E-19DBC1	465	QT	8-11-67	...	...	45	238	184	16	6.8	.12	516	324	129	1.0	764
T4N-R17E-22CBB1	559	QT	4- 2-66	...	...	34	204	168	15	5.6	.29	469	294	127	.9	681
T4N-R18E-29CBB1	646	QT	8-26-67	...	...	31	228	84	10	9.5	.11	336	236	49	.8	549
T4N-R19E-27ADC1	260	QT	10-13-69	...	...	24	292	58	20	1.6	.09	368	276	37	.6	610
T4N-R19E-27ADD1	618	QT,P	10-13-69	...	...	1,660	222	680	2,200	0	.66	4,860	380	159	40	8,110
T5N-R11E-16ACC1	311	QT	4- 6-66	...	...	29	236	28	6	6.3	.28	261	178	.....	1.0	448
T5N-R12E-5BCC1	365	QT	1- 6-66	...	...	59	266	103	16	....	.14	409	232	14	1.7	658
T5N-R13E-14DBB1	348	QT	3-14-68	...	...	30	...	50	8	....	...	299	196	11	.9	494
T5N-R14E-31ACC1	367	QT	5-18-67	...	...	13	204	23	8	8.5	.12	243	188	14	.4	399
T5N-R15E-34ABC1	575	QT	11-25-67	...	...	72	324	220	26	2.2	.18	654	380	114	1.5	958
T5N-R16E-32BBC1	630	QT	8-26-67	...	...	31	196	193	17	9.8	.06	510	328	168	.7	714
T5N-R17E-17CBA1	506	QT	8-16-67	...	...	32	192	116	12	12	.10	421	242	91	.8	577
T5N-R19E-19CCA1	608	QT	8-26-67	....	...	19	224	39	20	19	.06	326	230	46	.5	506
T6N-R10E-23ADA1	348	QT	9- 6-62	...	...	95	298	157	22	1.3	.20	513	232	0	2.7	785
T6N-R12E-19DBB1	325	QT	5- 4-67	...	...	54	316	180	15	6.5	.19	594	356	97	1.2	850
T6N-R13E-35BCD1	425	QT	7-25-63	...	...	79	246	232	22	2.2	.21	576	304	102	2.0	869
T6N-R14E-28BAA1	558	QT	3-11-65	...	...	47	308	195	18	6.8	.10	583	384	132	1.1	856
T6N-R15E-29BBB1	336	QT	4-24-67	...	...	49	...	.....	18	....	...	.....	318	.....	1.2	784
T6N-R17E-14DBB1	430	QT	2-26-59	50	17	26	148	92	16	14	.18	290	194	72	.8	491
T6N-R18E-25CBD1	286	QT	11-19-51	54	20	28	219	73	25	20	....	381	258	79	....	592

QT, Quaternary-Tertiary rocks, includes alluvium, Pleistocene rocks, and Ogallala Formation; C, Cretaceous rocks, includes Dakota Sandstone and Cheyenne Sandstone Member of Purgatoire Formation; J, Jurrasic rocks, includes Morrison Formation and Exeter Sandstone; T, Triassic rocks, includes the Dockum Formation; P, Permian rocks, includes rocks of Upper Permian age, undifferentiated.

High concentrations of sodium (Na) relative to the concentrations of calcium (Ca) and magnesium (Mg) in irrigation water can adversely affect soil structure. Cations in the soil solution become fixed in the surface of the soil particles; calcium and magnesium tend to flocculate the particles, whereas sodium tends to deflocculate them. This adverse effect on soil structure caused by high sodium concentrations in an irrigation water is called the sodium hazard of the water. An index used for predicting the sodium hazard is the sodium-adsorption ratio (SAR), which is defined by the equation:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}$$

where the concentrations of the ions are expressed in milliequivalents per litre.

Important factors other than salinity-sodium hazards are the types and drainage characteristics of soils, amount of water applied, and salt or mineral tolerance of crops. Water that may not be chemically suitable for use on normal or tight soils may be used on permeable, well-drained soils where good leaching practices are used.

The chemical quality of water affects its uses for certain purposes. Table 6 lists the constituents and properties commonly determined by the Geological Survey, and includes a resume of their source and significance.

The quality of the ground water in the Ogallala aquifer generally is suitable for most uses except in extreme eastern and southeastern Texas County, Tps. 1, 2, and 3 N., Rs. 18 and 19 E., where wells tapping water from the lower part of the Ogallala may contain excessive amounts of dissolved solids. The water contains large quantities of sodium chloride that generally is stratified in the lower 100 to 200 ft (30 to 61 m) of the aquifer. The most likely source of this water is infiltration from Permian rocks below and adjacent to the Ogallala aquifer. Development of large supplies of water from the overlying fresh-water zone in this area may induce upward migration of water from the lower zone because of the reduced head. The quantity of dissolved solids ranges from 140 to 3,450 mg/l, but generally is less than 500 mg/l except in the area noted above.

The quality of ground water in pre-Ogallala aquifers is summarized below from the relatively small number of analyses available. Ground water from the Dakota and Cheyenne aquifers in the western part of Cimarron County generally is suitable for most uses. The quantity of dissolved solids generally ranges from 200 to 500 mg/l. The Exeter Sandstone and Morrison Formation usually contain water with concentrations of dissolved solids in excess of 500 mg/l, and the water may not be suitable for most uses. Locally,

Table 6.--Source and significance of dissolved-mineral constituents and properties of water.

Constituent or property	Source or cause	Significance
Calcium (Ca) and magnesium (Mg)	Dissolved from pracctically all soils and rocks, but especially from limestone, dolomite, and gypsum. Calcium and magnesium are found in large quantities in some brines. Magnesium is present in large quantities in sea water.	Cause most of the hardness and scale-forming properties of water; soap consuming (see hardness). Waters low in calcium and magnesium desired in electroplating, tanning, dyeing, and in the textile manufacturing.
Sodium (Na) and potassium (K)	Dissolved from practically all rocks and soils, Found also in ancient brines, sea water, industrial brines, and sewage.	Large amounts, in combination with chloride, give a salty taste. Moderate quantities have little effect on the usefulness of water for most purposes. Sodium salts may cause foaming in steam boilers and a high sodium content may limit the use of water for irrigation.
Bicarbonate (HCO_3)	Action of carbon dioxide in water on carbonate rocks such as limestone and dolomite.	Bicarbonate and carbonate produce alkalinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot-water facilities to form scale and release corrosive carbon dioxide gas, in combination with calcium and magnesium, cause carbonate hardness.
Sulfate (SO_4)	Dissolved from rocks and soils containing gypsum, iron sulfides, and other sulfur compounds. Commonly present in mine waters and in some indus-	Sulfate in water containing calcium forms hard scale in boilers, in large amounts, sulfate in combination with other ions gives bitter taste to water. Some calcium sulfate is considered beneficial in the brewing process. U.S. Public Health Service (1962) drinking-water standards recommend that the sulfate content should not exceed 250 mg/l.
Chloride (Cl)	Dissolved from rocks and soils. Present in sewage and found in large amounts in ancient brines, sea water, and industrial brines.	In large amounts in combination with sodium, gives salty taste to drinking water. In large quantities, increases the corrosiveness of water. U.S. Public Health Service (1962) drinking-water standards recommend that the chloride content should not exceed 250 mg/l.

Nitrate (NO_3)	Decaying organic matter, sewage, fertilizers, and nitrates in soil.	Concentration much greater than the local average may suggest pollution. U.S. Public Health Service (1962) drinking-water standards, suggest a limit of 45 mg/l. Waters of high nitrate content have been reported to be the cause of methemoglobinemia (an often fatal disease in infants) and therefore should not be used in infant feeding. Nitrate has been shown to be helpful in reducing inter-crystalline cracking of boiler steel. It encourages growth of algae and other organisms which produce undesirable tastes and odors.
Boron (B)	Dissolved from igneous rock, especially granitic rocks and pegmatites.	Small amounts are essential to plant growth, but excessive concentrations are harmful and for some plants the toxic concentration is very low.
Dissolved solids	Chiefly mineral constituents dissolved from rocks and soils. Includes some water of crystallization.	U.S. Public Health Service (1962) drinking-water standards recommend that waters containing more than 500 mg/l dissolved solids not be used if other less mineralized supplies are available. Waters containing more than 1,000 mg/l dissolved solids are unsuitable for many purposes.
Hardness as $CaCO_3$	In most waters nearly all the hardness is due to calcium and magnesium. All the metalic cations other than the alkali metals also cause hardness.	Consumes soap before a lather will form. Deposits soap curd on bathtubs. Hard water forms scale in boilers, water heaters, and pipes. Hardness equivalent to the bicarbonate and carbonate is called carbonate hardness. Any hardness in excess of this is called noncarbonate hardness. Waters of hardness as much as 60 mg/l are considered soft; 61 to 120 mg/l, moderately hard; 121 to 180 mg/l, hard; more than 180 mg/l, very hard.
Specific conductance (micromhos at 25°C)	Mineral content of the water.	Indicates degree of mineralization. Specific conductance is a measure of the capacity of the water to conduct an electric current. Varies with concentration and degree of ionization of the constituents.

water from the Morrison Formation is used for irrigation in Cimarron County. Rocks of the Dockum Group provide some ground water for irrigation to southwestern Cimarron County and west-central Texas County, but the quality of the water is marginal for most uses and generally the quality of the water deteriorates with depth. The Permian red beds provide water that contains concentrations of dissolved solids that range from 600 mg/l to more than 9,000 mg/l. The water usually contains large quantities of sodium chloride and calcium sulfate which limit its uses although some domestic wells obtain water from this aquifer. Ground water pumped from the alluvium ranges widely in chemical properties but is suitable for most uses. The quality of the water generally is better where alluvium is adjacent to the Ogallala aquifer than where the alluvium is adjacent to the Dockum Group, Morrison Formation, or Permian red beds.

OUTLOOK FOR THE FUTURE

Water users in the Oklahoma Panhandle should be aware that ground water presently is being used at a more rapid rate than it is being recharged. Conservation practices in both irrigation and field management could extend the useful life of the aquifer. As the water table is lowered by pumping and the saturated thickness is reduced, the yields of the wells decline and pumping lifts increase. When well yields can no longer be increased by deepening the wells or by lowering the pumps, the yields will decline as the saturated thickness of the aquifer is reduced. The declines in water levels should be regarded in terms of the remaining saturated thickness. For example, a decline in water level of 50 ft (15 m) in an area resulting in a saturated thickness of 300 ft (19 m) represents a 14 percent loss, whereas as a decline of 25 ft (8 m) in an area resulting in a saturated thickness of only 100 ft (30 m) represents a 20-percent loss.

Declining water levels also increase pumping lifts which in turn cause an increase in energy usage. Original pumping equipment may become inadequate as yields decrease and pumping lifts increase so that pumps and power units are replaced with more suitable equipment. Additional costs to the irrigator may include the construction of new wells and pipe lines in order to obtain adequate quantities of irrigation water. Many stock and domestic wells that were drilled to a depth only slightly below the top of the aquifer may have to be deepened or replaced.

Based on the assumptions presented in this report:

1. Water in storage in 1972 = 50 million acre-ft (6.17×10^{10} m^3)
2. Ground-water pumpage in 1971 = 736,000 acre-ft (9.07×10^8 m^3)
3. Recharge from precipitation = 1/2 in/yr (0.8 cm/yr or 138,700 acre-ft (1.71×10^8 m^3)

4. Irrigation return flow in 1971 = 20 percent or 147,000 acre-ft (1.81×10^8 m^3)

If ground-water pumpage remains constant and natural discharge is intercepted, the estimated annual ground-water depletion rate would be 451,000 acre-ft (5.56×10^8 m^3). At this rate, 50 percent of the Ogallala aquifer would be dewatered in 55 years. If ground-water pumpage remains constant and natural discharge continues to be about equal to natural recharge, the estimated annual ground-water depletion rate would be 589,000 acre-ft (7.26×10^8 m^3). At this rate, 50 percent of the Ogallala aquifer would be dewatered in about 42 years. The actual rate of depletion probably would fall between these two values. If the usage of ground water continues to increase as it has during the past decade, the rate of depletion will accelerate. Dewatering of the aquifer would not be uniform however. Areas where the aquifer is heavily developed for irrigation would be depleted more than 50 percent in less than the time estimated above, whereas less developed areas remote from concentrated centers of pumping may show little or no depletion.

One available method that could aid in the prediction of approaching aquifer problems in both time and location is digital modeling. This could be useful in future planning and management of water use in the Panhandle. Data of the type obtained during this investigation should provide a suitable framework for making preliminary analyses by digital-modeling techniques.

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AQUIFER TEST DATA AND ANALYSES

2N-14E-23CBB2

An aquifer test was conducted for 22 days in March 1971 using a well owned by Nash Brothers. The test data were analyzed with Boulton's type curves. Adjustments were made on the drawdown in the observation well for changes in atmospheric pressure and changes in saturated thickness. Since the static water level was fairly constant before the tests, no adjustments were made for a prior trend in the static water level.

Figure 10 shows the plot of the drawdown versus the time for the water-level measurements in the observation well. Two different plots of data sets are shown that correspond to two different pumping periods. The first pumping period ended after 800 minutes of continuous pumping at 1,150 gal/min (73 l/s). A problem with the second pumping period was that the initial discharge rate was too low. Two additional problems that occurred during the test were: the pump was off for a 1-hour period and the discharge decreased from the 1,150 gal/min (73 l/s) for a few hours at one point. An accurate analysis of the aquifer test was obtained by using the two pumping periods together and ignoring the data plots around the three problem areas. The first pumping period defines the early drawdown versus time curve. The second pumping period defines the curve after the discharge was adjusted up to 1,150 gal/min (73 l/s). The solid curve line on the left side of figure 10 is the trace of early time-delayed yield-type curve with an r/D value of 1.0. The corresponding late time-type curve is traced on the right side of the figure. From the match of the late time-type curve to the data plotted, values of aquifer properties were calculated. Delayed-yield effect had ceased after 10 days of pumping.

2N-7E-26ACC1

In this aquifer test, an abandoned irrigation well, 2N-7E-26AAC1, in Cimarron County owned by Cayton Brothers, was used as an observation well to measure the drawdown caused by three pumping wells located at radial distances of 657, 1,500, and 4,170 ft (220, 457, and 1,271 m), respectively. The aquifer test was conducted in July and August of 1969 for a period of 32 days. A Theis composite-type curve was developed to correlate the effect of the three pumping wells and to analyze the aquifer test. Adjustments were made on the drawdown in the observation well for changes in saturated thickness. Adjustments were not made for atmospheric pressure changes or prior trend in the static water level.

The Theis nonequilibrium flow equation was used to develop a composite-type curve for the three pumping wells in this aquifer test. The composite curve for the three pumping wells (fig. 11) was constructed from the computer printout of various values of 1/u, and the summation of the well functions times the discharges. Figure 11 also shows the plot of the drawdown versus the time for the water-level measurements in the observation well. The

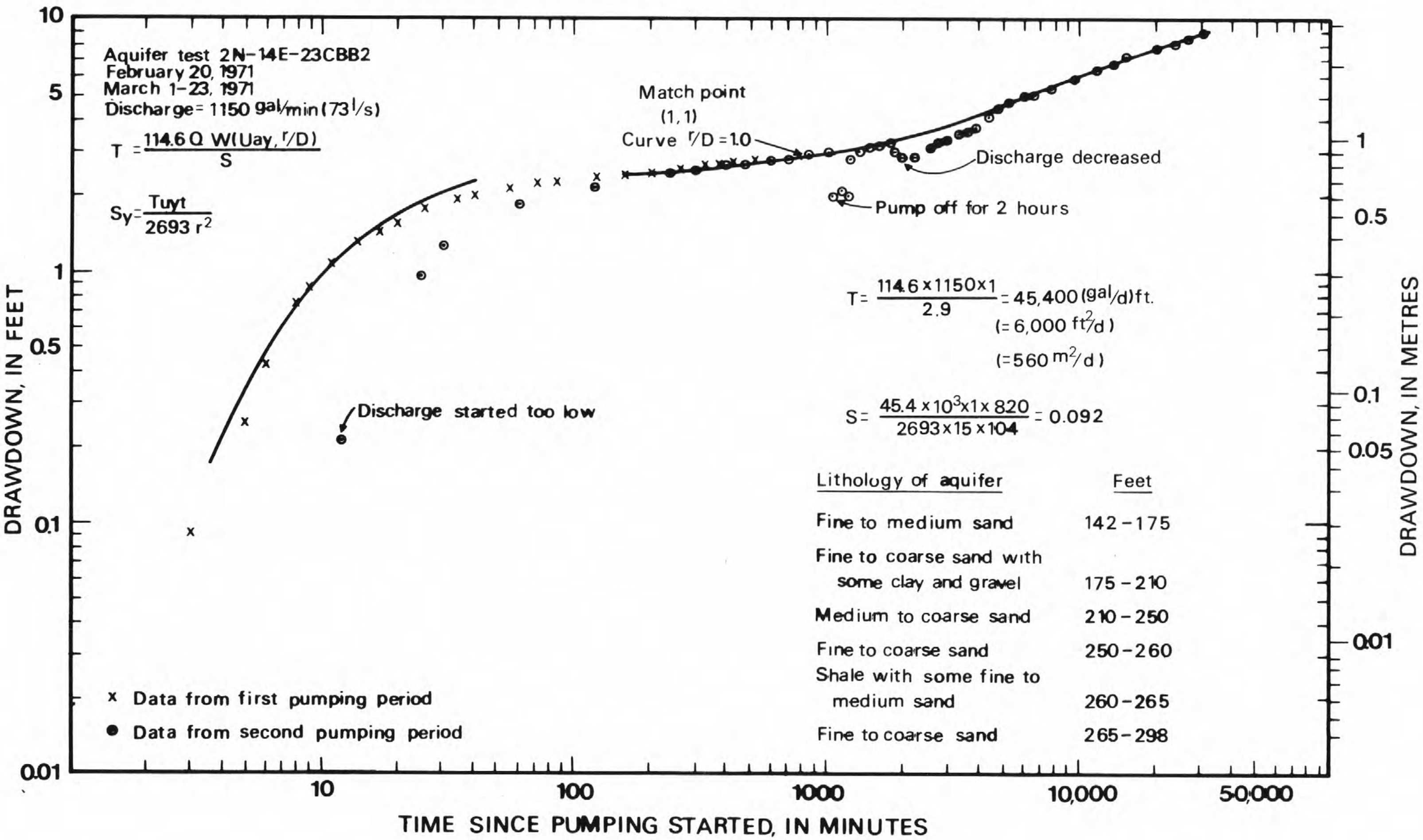

Figure 10.--Drawdown of water level in observation well 2N-14E-23CBB2 plotted against time since pumping started.

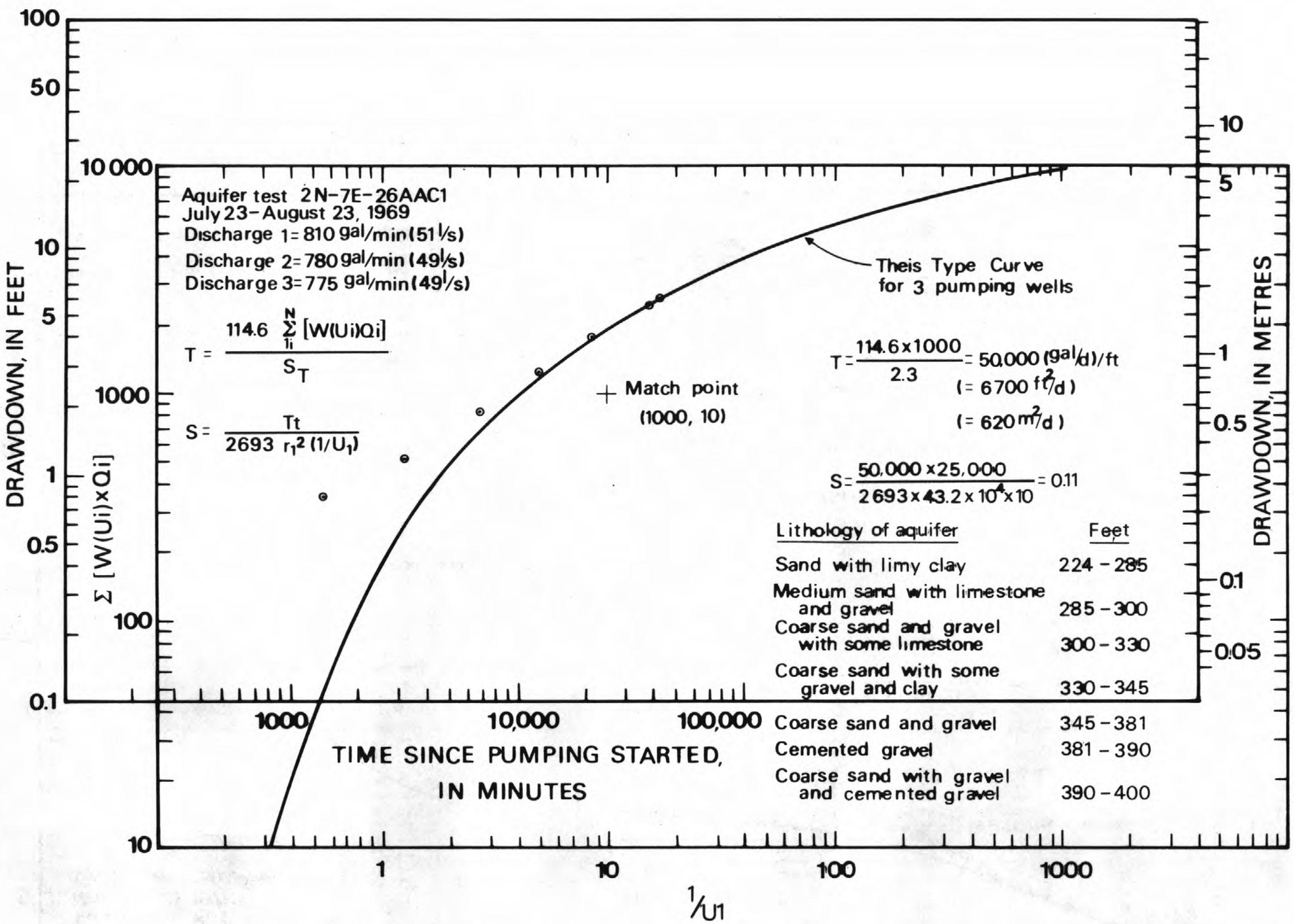

Figure 11.--Drawdown of water level in observation well 2N-7E-26AAC1 plotted against time since pumping started.

data points converge with the type curve after approximately 20,000 minutes of continuous pumping. The earlier data points plot above the type curve because delayed-yield effect has not ceased. An accurate analysis of the aquifer test was obtained by use of the composite curve and the data after the delayed-yield effects were ended. From the match point of the data plotted to the composite curve, aquifer properties were calculated. Delayed-yield effects had ceased after approximately 14 days of continuous pumping.

2N-15E-15BAA1

An aquifer test was conducted for 93 days in June to September of 1970 on a well owned by Charles Wiggins. The aquifer test was analyzed with Boulton's delayed-yield-type curve. The observation-well drawdown was adjusted for change in saturated thickness only. Prior trends in the static water level were not defined and changes in atmospheric pressure were not significant considering the large drawdowns that were observed.

Figure 12 shows the plot of the drawdown versus the time since pumping started for the observation well. This figure also shows two traces for the delayed-yield-composite curve of r/D equals 0.4. The left trace curve was fitted to the early time drawdown in the observation well, whereas the right trace curve was fitted to the late time drawdown. The majority of the water during the late time drawdown was coming from delayed yield from the dewatered zone. From the match of the late time composite curve to the data plotted, values of the aquifer properties were calculated. Delayed-yield effects ceased after approximately 26 days of pumping.

2N-23E-21CBD1

A recovery test was conducted in August 1971 on Keith Thomas's irrigation well, 2N-23E-21CBD1. The recovery of the static water level was measured for 50 hours after 18.3 hours of pumping. No corrections were made for prior trend, change in atmospheric pressure, or change in saturated thickness. Theis's nonequilibrium-flow formula for a recovery test was used to analyze this test. Figure 13 shows the residual drawdown in the pumping well plotted against the time since pumping started divided by time since pumping stopped.

3N-15E-21BBC1

A recovery test was conducted on a City of Guymon municipal well, 3N-15E-21BBC1, in July 1967. The well was pumped 4-1/2 hours and recovery of the water level was measured for 1 day. No corrections were made for prior trend, atmospheric pressure, or change in saturated thickness. Theis's nonequilibrium-flow formula for a recovery test was used to analyze this test. Figure 14 shows the residual drawdown in the pumping well plotted against the time since pumping started divided by time since pumping stopped.

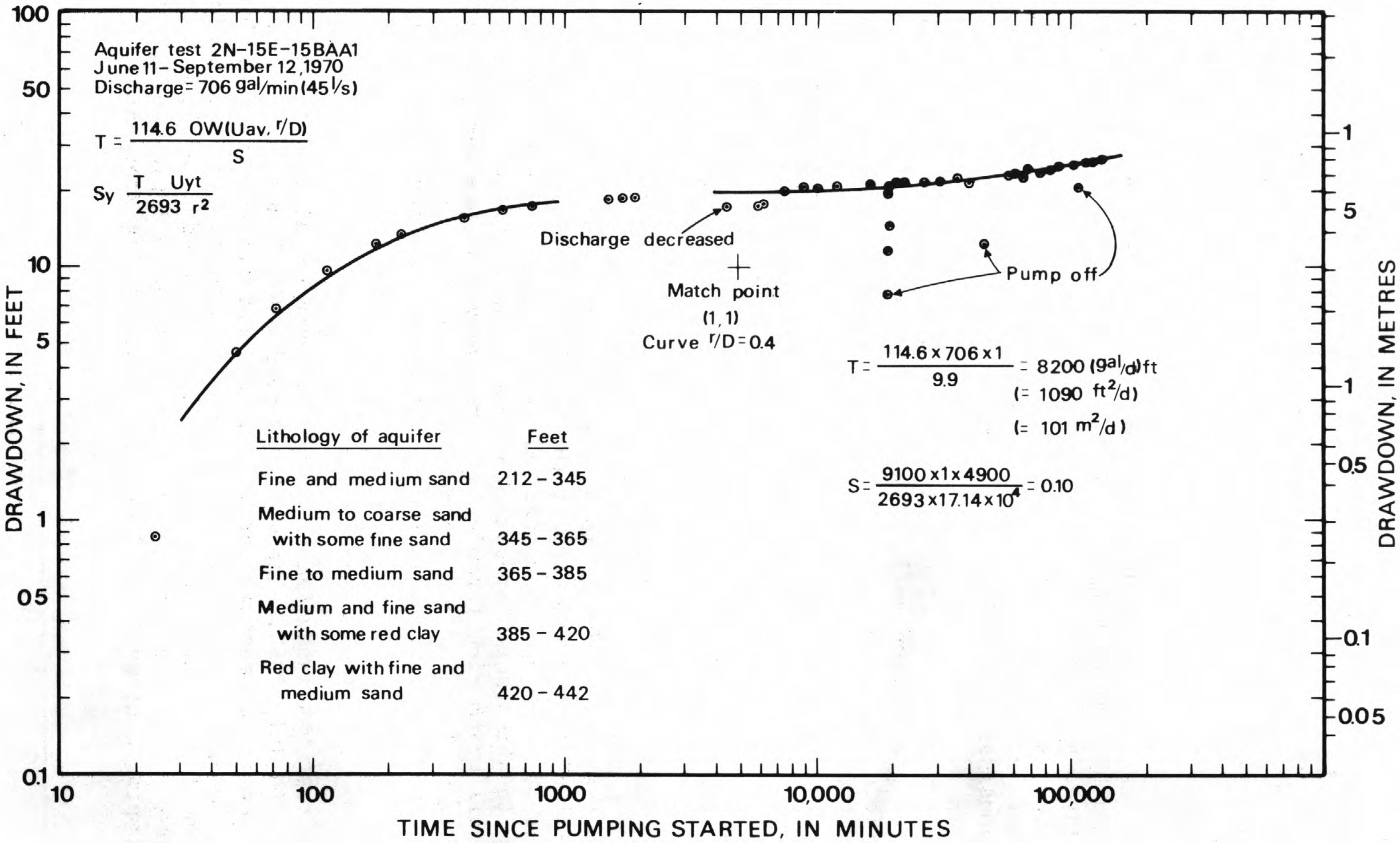

Figure 12.--Drawdown of water level in observation well 2N-15E-15BAA1 plotted against time since pumping started.

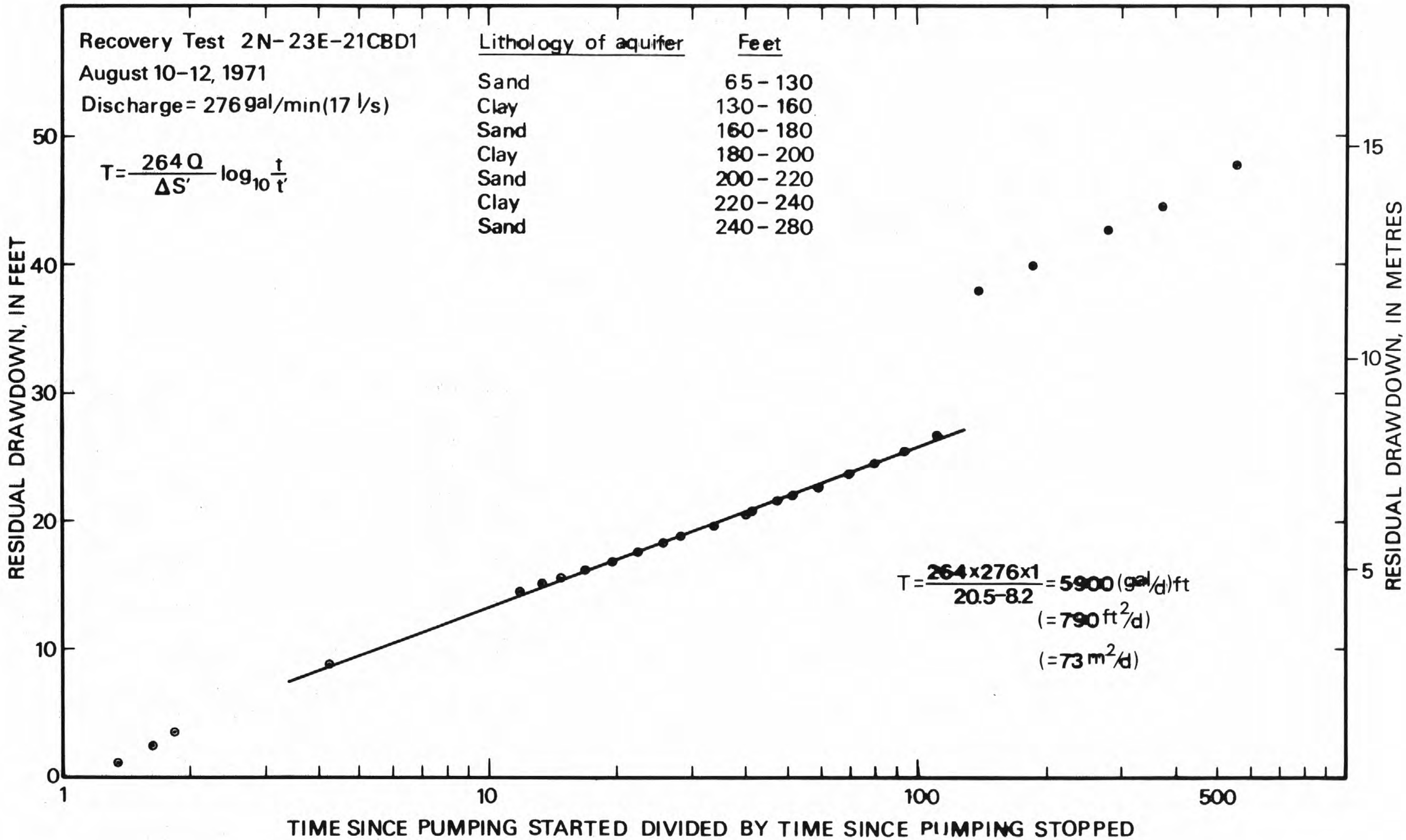

Figure 13.--Residual drawdown in well 2N-23E-21CBD1 plotted against time since pumping started divided by time since pumping stopped.

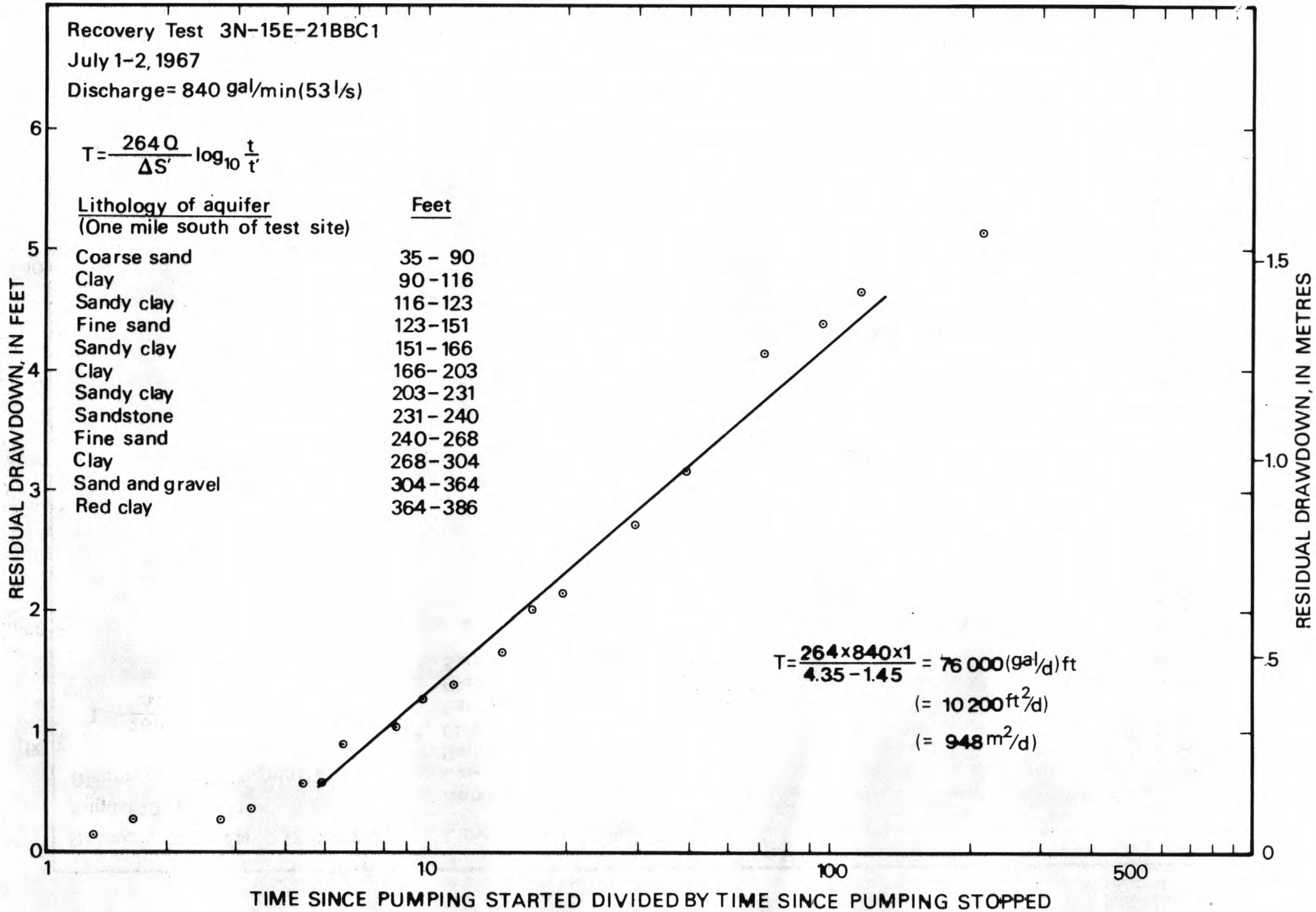

Figure 14.--Residual drawdown in well 3N-15E-21BBC1 plotted against time since pumping started divided by time since pumping stopped.

2N-15E-6CCC1

A recovery test was conducted on an irrigation well, 2N-15E-6CCC1, from September through November of 1967. The well is owned by Ewing Mathis. The recovery of the water level was measured for 61 days after 53 days of pumping. No corrections were made for prior trend, change in atmospheric pressure, or change in saturated thickness. Theis's nonequilibrium-flow formula for a recovery test was used to analyze the test. Figure 15 shows the results of the recovery test.

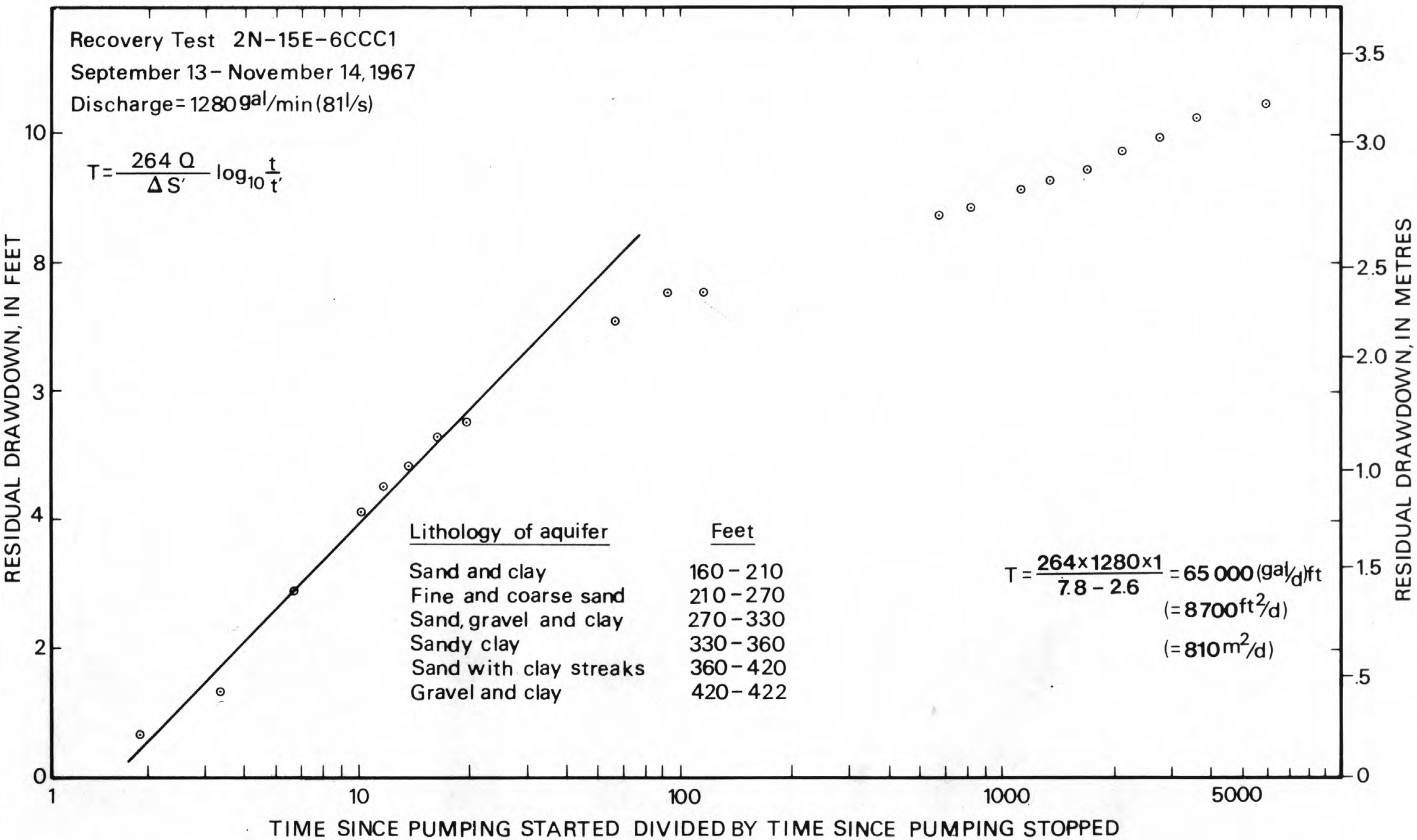

Figure 15.--Residual drawdown in well 2N-15E-6CCC1 plotted against time since pumping started divided by time since pumping stopped.

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