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CIRCULAR 61

Ground Water

Rush Springs Sandstone

HARRY H. TANAKA

and

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CARL C. BRANSON, *Director*

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Ground-Water Resources of the Rush Springs Sandstone in the Caddo County Area, Oklahoma

by

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U. S. Geological Survey

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GROUND-WATER RESOURCES OF THE RUSH SPRINGS SANDSTONE IN THE CADDO COUNTY AREA, OKLAHOMA

HARRY H. TANAKA AND LEON V. DAVIS

ABSTRACT

In this report is described an area of about 1,840 square miles in west-central Oklahoma. The area is characterized by rolling plains interrupted in places by sand dunes or deeply eroded stream valleys.

Rocks cropping out are of Permian age and include the El Reno and Whitehorse Groups and the overlying Cloud Chief Formation.

Rocks of the El Reno Group of Permian age crop out in the eastern and southern parts of the area. The El Reno Group ranges in thickness from 420 to 660 feet and includes, in ascending order, the Duncan Sandstone, Flowerpot Shale, Blaine Formation, and Dog Creek Shale. The Duncan Sandstone yields hard water under artesian pressure to a few wells but the other three formations yield little or no water to wells.

Rocks of the Whitehorse Group of Permian age crop out throughout the area except near the western edge, where they are overlain by the Cloud Chief Formation. They include, in ascending order, the Marlow Formation and the Rush Springs Sandstone. The Marlow Formation is composed of evenly bedded sandy or silty shale, ranging in thickness from 90 to 128 feet. It yields only a small amount of ground water to wells in the eastern half of the area but may yield a considerable amount of water to irrigation wells in the western half of the area, north of the Washita River.

The Rush Springs Sandstone is very fine-grained, cross-bedded sandstone, containing irregular silty lenses. It is the principal aquifer in the area and yields moderate to large supplies of water to wells in most of its outcrop area. The water is suitable for domestic, municipal, irrigation, and most industrial uses. Most towns in the area obtain their public water supplies from this formation, which also is the source of most of the domestic, irrigation, and industrial water supplies.

The Cloud Chief Formation of Permian age crops out in the western part of the area and as scattered outliers elsewhere. It does not furnish water to wells in the area.

Terrace and alluvial deposits of Quaternary age occur along major

streams and are composed of sand, silt, clay, and gravel. The terrace deposits yield small amounts of water to domestic and stock wells. The alluvium yields hard water for domestic, stock, irrigation, and industrial uses along the Washita River.

Laboratory analyses of 32 samples from the Rush Springs Sandstone and upper part of the Marlow Formation indicate that the porosity averages 32 percent, specific yield 25 percent, and permeability about 30 gallons per day per square foot.

The coefficient of transmissibility determined from four aquifer tests in the Rush Springs Sandstone in Caddo and Grady Counties was about 10,000 gallons per day per foot, and the coefficient of storage was about 0.02.

Ground-water recharge comes mostly from precipitation on the area and averages about 2.8 inches annually, or about 10 percent of the average precipitation. North of the Washita River ground water moves generally toward the south and east, although locally it moves toward the larger streams, such as Cobb and Sugar Creeks.

Ground water is discharged naturally through evaporation and transpiration. Discharge of ground water by seepage into Cobb Creek is computed to average 15,000 acre-feet annually; discharge of ground water by pumping is about 28,000 acre-feet annually for irrigation, public-supply, industrial, domestic, and stock needs.

The quality of water of the Rush Springs Sandstone is characterized by a hardness that ranges from 48 to 1,850 ppm and a dissolved-solids content that ranges from 48 to 3,160 ppm. Most of the ground water in the Caddo County area is calcium bicarbonate in type and is suitable for irrigation and, after treatment, other uses.

Increased use of ground water for irrigation is indicated by the increase in the number of wells, from 12 in 1951 to 537 in 1960. A large supply of ground water is in storage; however, in the heavily irrigated area north of the Washita River, local overdevelopment has caused the water table to decline about 6 feet. If drought conditions became prevalent, this decline would be accelerated.

INTRODUCTION

Purpose of the Investigation

The need for data about ground water in the Rush Springs Sandstone and associated strata in Caddo County and parts of adjacent Comanche, Kiowa, Washita, Canadian, and Custer Counties, Oklahoma, became apparent about 1950, and an investigation of ground water was begun in 1955 by the U. S. Geological Survey in cooperation with the Oklahoma Geological Survey. Before 1949 only farm and public-supply wells

tapped water in these rocks. In 1949 the first irrigation well was drilled, and in 1950 about a dozen more were completed. By 1956 the number had increased to approximately 380 wells. In 1960 the total number of wells had reached more than 500 and about 30,000 acres was under irrigation. The purpose of this investigation was to obtain data about the hydrologic properties of the aquifers in and the capacity and extent of the Rush Springs Sandstone and adjacent strata. This information is necessary to plan use of ground water to meet the future demands for water in this area.

Location and Extent of the Area

The Rush Springs Sandstone in Oklahoma crops out or underlies younger sediments in the trough of the Anadarko syncline. It also crops out in a small area in Harmon County in the southwestern part of the State. The Anadarko syncline is a major structural trough shaped in a wide-mouth V, the apex of which is in Stephens County. The northern boundary extends from Stephens County through Harper County, in the northwestern part of the State, into Kansas. The southern boundary extends westward along the northern side of the Wichita Mountains into Texas.

The area considered in this report includes about 1,840 square miles in west-central Oklahoma and is centered in Caddo County. Its location is shown in figure 1 and will be referred to herein as the Caddo County area.

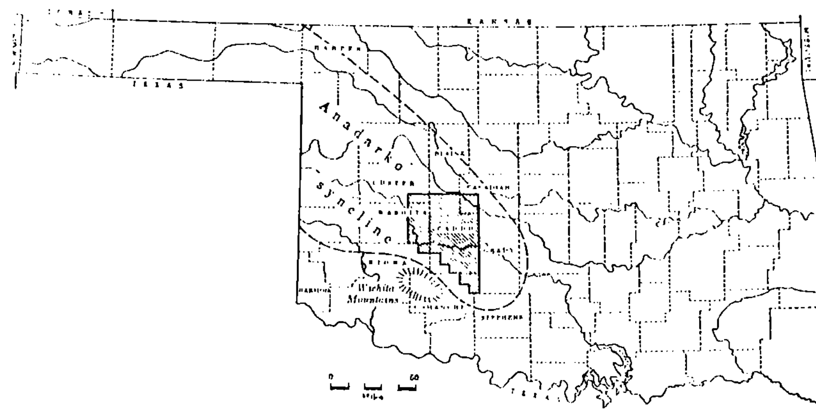

Figure 1. Index map of Oklahoma showing location of the Caddo County area (shaded).

Previous Investigations

The earliest reference to the water-bearing properties of the rocks now included in the Whitehorse Group (Rush Springs Sandstone and Marlow Formation) is by Gould (1905) who briefly mentioned these rocks in his report on the geology and water resources of Oklahoma. A report by Davis (1950) contains preliminary data on ground water in the Pond Creek (herein called Cobb Creek, see footnote, p. 35) drainage basin in Caddo County. Davis (1955) also discussed the water-bearing properties of the Rush Springs Sandstone and Marlow Formation in Grady and northern Stephens Counties, which lie immediately east of the area studied for this report. A map and accompanying text by Schoff (1955) give information on the areal extent of the permeable part of the Rush Springs Sandstone of the Whitehorse Group. Clark (1956) discussed a method of forecasting dry-weather flow in Pond Creek (Cobb Creek) by multiple correlations of the dry-weather flow in the creek and the water level in a well. Mogg, Schoff, and Reed (1960) discussed the geology and ground water of Canadian County and included four townships in the northeastern part of the area.

Methods of Investigation

This report is based on data obtained in the field in 1956, 1957, and part of 1958, during which time the geology was mapped and irrigation and domestic wells were inventoried. Approximately 860 wells were inventoried in the Caddo County area. The data regarding these wells (location, depth, depth to water, yield, etc.) are on open file in the offices of the Ground Water Branch, U. S. Geological Survey, Oklahoma City, and of the Oklahoma Geological Survey, Norman.

Ground-water data published in previous reports on the area by Davis (1950) and Clark (1956) also were used in this report. Altitudes of wells were leveled by Bureau of Reclamation engineers and interpolated from 7½- and 15-minute topographic maps having 10- and 20-foot contour intervals. Altitudes of a few wells south of the Washita River were determined by aneroid barometer.

Some of the geology shown on the map (pl. I) was taken from oil-company maps, but most of the area was mapped on

aerial photographs and lines of geologic contacts transferred to a 1:63,360-scale base map. The base map is modified from an enlargement of the Clinton and Lawton sheets of th Army Map Service series (scale 1:250,000).

Well-numbering System

The well-numbering system used in this report is based upon the location of wells with respect to the Federal land-survey system used in Oklahoma. The component parts of a well number are the township, range, and section numbers, two lowercase letters which indicate the quarter section and the quarter-quarter section in which the well is located and a serial number (fig. 2). The final number indicates a specific well within the quarter-quarter section, numbered in the order in which the well record was made. Thus well 10N-12W-23bc1 is the first well scheduled in the SW¼ NW¼ sec. 23, T. 10 N., R. 12 W. (fig. 2).

Acknowledgments

Many farmers, well drillers, and municipal officials assisted in the collection of information concerning water wells. C. E.

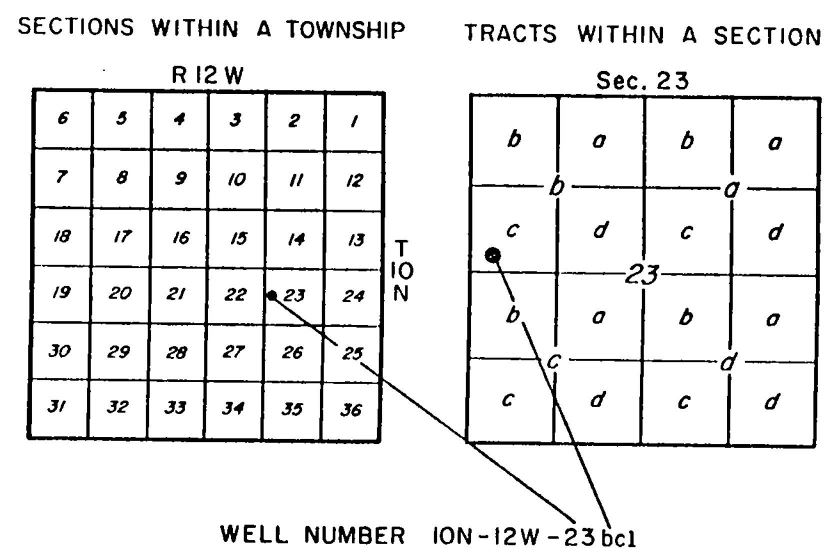

Figure 2. Well-numbering system.

Smith and Elton Jackson gave permission to run pumping tests on their wells near Sickles and Eakly; Billy Bryan, manager of the Caddo County Electric Cooperative, supplied data on irrigation wells; engineers from the U. S. Bureau of Reclamation established altitudes of the irrigation and domestic wells; and E. V. Jones, V. F. Drake, M. D. Moeller, and D. E. Spiser aided in the measurement of water levels.

GEOGRAPHY

Topography and Drainage

The area of this report is a part of the Western Sandstone Hills and the Western Redbed Plains (Curtis and Ham, 1957). The surface is moderately rolling and is cut by deep drainage channels. Soils are generally sandy, having been derived chiefly from the weathering of the friable Rush Springs Sandstone, which crops out over much of the area. In the western part are many cuestas with eastward-facing escarpments that generally have less than 75 feet of relief. These cuestas are capped with dolomite or gypsum that occur elsewhere in the area as outliers, in places capping steep-sided buttes an acre or less in areal extent. The altitude ranges from less than 1,130 feet where the Washita River leaves Caddo County, east of Anadarko, to about 1,820 feet in the northwestern part, near Weatherford.

Most of the area lies within the drainage basin of the Washita River. Little Washita River and Cobb and Sugar Creeks are perennial streams, the base flows of which are maintained by seepage from the Rush Springs Sandstone. Principal perennial streams tributary to Cobb Creek are Spring and Willow Creeks. The area drained by Sugar Creek is dissected in a dendritic pattern by many small tributaries flowing in numerous steep-sided canyons formed by headward erosion in the Rush Springs Sandstone. A small area in the northern part is in the drainage basin of the Canadian River and is drained by Deer Creek.

The banks of the streams are bordered by a fringe of willow, sycamore, cottonwood, and oak trees, and by underbrush. The uplands and valley slopes generally are well drained; most of the area west of the topographic divide between Cobb and Sugar Creeks has been cleared for cultivation.

East of this divide much of the land is covered by scrub oak and grasses.

Economic Development

Agriculture is the principal occupation. In recent years diversification of crops has tended steadily to stabilize the economy of the region. The area now produces peanuts, cotton, grain sorghum, wheat, alfalfa, and melons. Peanuts are the major crop on about 20 thousand acres in the upland where ground water from the Whitehorse Group is used to supplement the water supply derived from rainfall. In 1960 more than 1,200 farmers in Caddo County harvested about 28,500 acres of peanuts. Large numbers of livestock are raised in conjunction with farming operations and on the terrain unsuitable for cultivation.

Mineral resources other than oil and gas are at present of little importance in this part of Oklahoma. The major oil field is Cement, named for the town in southeastern Caddo County. This field was discovered in 1917, and the cumulative production of oil through 1960 is estimated to be more than 100 million barrels. During 1960, the field produced more than 3.8 million barrels of oil, and reserves are estimated at more than 23 million barrels. A reliable total for the production of natural gas is not available; however, the estimated cumulative total is many trillion cubic feet. Smaller fields in the area of the report had a combined daily average production during 1959 of about 1,800 barrels (Louise Jordan, oral communication). Ham and Curtis (1958), in their investigation of the gypsum deposits in the Weatherford-Clinton area, calculated that approximately 1.3 billion short tons of workable gypsum and more than 500 million short tons of anhydrite are present in the Cloud Chief Formation in Washita, Custer, and Caddo Counties. The gypsum and anhydrite have been developed for local use as road ballast and agricultural gypsum.

Climate

The average annual precipitation in the Caddo County area, based on records for 1939-1960 from U. S. Weather Bureau stations at Carnegie, Fort Cobb, Lookeba, and Weatherford, is 28.10 inches. Average yearly totals have ranged from a maximum of 40.48 inches in 1941 to a minimum of 14.65

inches in 1954. More than 80 percent of the annual precipitation occurs during the growing season from March 1 to October 31, the greatest amount during May. Intense precipitation in small areas is common and results in local flash floods and quick runoff with little accretion to ground water.

The average annual air temperature at Weatherford is 61.3°F. January has the lowest average temperature (38.7°F) and July has the highest (83.3°F). Summers are long and generally hot, the maximum temperature exceeding 90°F day after day; the winters are generally mild with only short periods of cold weather. Snow generally occurs during January and February, but as a rule it is light and remains on the ground only a few days. Winds generally blow from the south, except during the winter when they blow alternately north and south.

Population

Anadarko, the largest town and the county seat of Caddo County, had a population of 6,299 in 1960. The urban population in this area is remaining steady or gaining slightly, whereas the rural population is decreasing. The losses in rural population may be attributed to the dry years during the thirties and to job opportunities in industry since that time. Other causes in recent years probably are related to more mechanization in farming and to the consolidation of small acreages into larger units. This part of Oklahoma has a population density of about 20 persons per square mile, and the 1,840-square-mile area of this report, including towns, had a total population of about 37,000 in 1960.

GEOLOGIC FORMATIONS AND THEIR WATER-BEARING PROPERTIES

The Whitehorse Group of Permian age, made up of the Rush Springs Sandstone and the Marlow Formation, crops out in a broad area of west-central Oklahoma. It lies at the surface over most of the area considered in this report (pl. I). About 15 percent of the area, mostly in Washita County, is covered by the overlying Cloud Chief Formation, and about 5 percent by Cloud Chief outliers. The Permian formations in the area consist of clastic sedimentary rocks and evaporites. These rocks are a part of the sequence of deposits belonging to the Permian System which crops out from southeastern Nebraska across central Kansas, the western half of Oklahoma, and into west-central Texas.

The Permian rocks in Oklahoma were deposited in a shallow embayment that was restricted, or at times cut off, from the main Permian sea. This embayment, named the Anadarko syncline, extends southeastward from Sherman County, in the Texas Panhandle, into Oklahoma along the northern side of the Wichita Mountains to its apex in south-central Oklahoma, and is the major structural feature of western Oklahoma (fig. 1). In Caddo County the Permian rocks of the basin are about 4,500 feet thick. These rocks consist of red arkose, sandstone, shale, and clay interbedded with thin limestone or dolomite lenses which tend to be local. Salt, anhydrite, and gypsum occur in thick beds at places, and as thin lentils throughout. The sediments were deposited under fluvial and shallow-sea conditions by rivers and streams flowing from nearby regions. The rocks grade laterally into deposits of different textures and lithologic characteristics. Frequent and continued small oscillations of sea level resulted in the formation of successive desiccation basins in which salt, gypsum, and anhydrite were formed.

The structure of the rocks of Permian age in the area under consideration is a large asymmetrical syncline of the Anadarko syncline. In the southern part of the area the rocks dip steeply to the northeast; in the northern part of the area they dip less steeply to the southwest.

Cloud Chief outliers conform to the configuration of the Whitehorse Group, indicating that the present attitude of the

Permian rocks in this part of Oklahoma is due to post-Cloud Chief structural movement.

PERMIAN SYSTEM

This report is concerned with ground water in the Rush Springs Sandstone and in the Marlow Formation of Permian age; however, Permian rocks underlying and overlying these units must also be considered because of their relation to the occurrence and quality of water in the principal aquifer. The discussion of the geology of rocks of Permian age will therefore be limited to the units shown in table 1.

TABLE 1.--GENERALIZED SECTION OF GEOLOGIC FORMATIONS IN THE CADDO COUNTY AREA

System	Group	Formation	Thickness (feet)	Lithology and water-bearing properties
Quaternary		Alluvium and terrace deposits	0-80	Gravel, sand, silt, and clay on the present and old flood plains of the Washita River and Pond Creek. Yields hard water. Maximum reported yield about 300 gpm.
Quaternary		High-level deposits	0-25	Unconsolidated gravel occurring as thin, scattered remnants of formerly extensive deposits; on higher ground slumped along valley slopes. Does not generally yield water.
Permian		Cloud Chief Formation	0-100	Gypsum and anhydrite, dolomitic at the base; clay shale; and silty or sandy shale, which in places resembles the underlying Rush Springs Sandstone. Base of formation marked by Weatherford Member, which in places grades into a dolomitic purple shale or into gypsum. Yields small quantities of water containing large quantities of dissolved calcium sulfate.
Permian	Whitehorse	Rush Springs Sandstone	0-340	Fine-grained, cross-bedded to even-bedded sandstone. Contains large quantities of water suitable for domestic, irrigation or industrial use. Locally, water is hard and contains large quantities of dissolved calcium sulfate. Maximum reported yield about 1,100 gpm, average yield to irrigation wells about 400 gpm.
Permian	Whitehorse	Marlow Formation	0-125	Mostly even-bedded brick-red clay shale, or sandy shale; more sandy toward the northwest. Verden Sandstone Member occurs near the upper-middle part. Emanuel Dolomite Bed at the top. Yields small quantities of highly mineralized water in the eastern part of the area, and moderate amounts of potable water locally in the western part.
Permian	El Reno	Dog Creek Shale	0-300	Mostly even-bedded dark-red gypsiferous clay shale interbedded with gypsiferous siltstone and very-fine-grained sandstone, grading into pure gypsum locally. Does not generally yield water.
Permian	El Reno	Blaine Formation	0-150	Mostly interbedded gypsum, red shale, and dolomite. Solution cavities containing large quantities of calcium sulfate may yield some water, although the formation generally does not yield water.
Permian	El Reno	Flower-pot Shale	0-150	Consists mainly of red to reddish-brown shale, and some gray shale. Generally does not yield water.
Permian	El Reno	Duncan Sand-stone	0-100	Sandstone with minor amounts of interbedded shale and intraformational siltstone conglomerates. Generally water is hard with high sulfate content. Yields 25 to 50 gpm, although the aquifer is capable of yielding more than 100 gpm. Not generally used as an aquifer in the Caddo County area.

EL RENO GROUP

The El Reno Group was named by Schweer (1937, p. 1554-1556) and includes several hundred feet of shale, siltstone, sandstone, dolomite, anhydrite, and gypsum of Permian age occupying the interval from the base of the Duncan Sandstone upward to the base of the Whitehorse Group. In the southeast end of the Anadarko syncline, in Grady County, the formations composing the group are, in ascending order, the Duncan Sandstone and Chickasha Formation. Westward, in Caddo County, the near-shore deltaic rocks of the Chickasha Formation grade into shale of the Flowerpot and the shale and evaporite sequence of the Blaine and Dog Creek, and the formations composing the El Reno Group here are the Duncan Sandstone at the base, the Flowerpot Shale, Blaine Formation, and Dog Creek Shale.

Thickness.— The thickness of the El Reno Group ranges from about 660 feet in eastern Caddo County (Davis, 1955, p. 35) to about 460 feet in eastern Washita County (Sherwood Buckstaff, oral communication, Apr. 26, 1946). It is reported to be 420 feet in southern Caddo County (Amer. Assoc. Petroleum Geologists, 1939, p. 37), but although the group is known to thicken northward across the Anadarko syncline, data on its thickness in northern Caddo County are not available.

Stratigraphic relation, character, and thickness of the formations.— The Duncan Sandstone is considered to be unconformable with the underlying Hennessey Shale and conformable with the overlying Flowerpot Shale (Freie, 1930, p. 16). The Duncan is mostly sandstone but contains minor amounts of interbedded shale and intraformational siltstone conglomerate. According to Davis (1955, p. 50) the Duncan is about 100 feet thick in the eastern part of the area. Sawyer (1929, p. 9) reported an approximate thickness of 40 feet for the Duncan in Kiowa and Washita Counties.

The Flowerpot Shale is conformable with the underlying Duncan Sandstone and with the overlying Blaine Formation. According to Sawyer (p. 9) the contact between the Flowerpot Shale and the Duncan Sandstone is gradational. The Flowerpot consists mainly of red to reddish-brown shale and of some gray shale. Its thickness is reported (Sawyer, p. 9) to be about 150 feet in Kiowa and Washita Counties and about 160 feet (Scott and Ham, 1957, p. 15) in the Carter area of Beckham County.

The Blaine Formation is conformable with the underlying

Flowerpot Shale and the overlying Dog Creek Shale, and consists of red shale interbedded with dolomite and gypsum. Sawyer (1929, p. 10) reported the thickness of the Blaine in Kiowa and Washita Counties to average 150 feet. The normal thickness of the Blaine Formation in the Carter area, as described by Scott and Ham (1957, p. 21), is 140 feet. Davis (1950, p. 7) reported a well in NW¼ sec. 5, T. 8 N., R. 12 W., drilled as a test by the Rural Electrification Administration to a depth of 506 feet, which probably flowed fresh water from solution cavities in the Blaine Formation.

The Dog Creek Shale underlies the Whitehorse Group and is the uppermost formation of the El Reno Group. It crops out as a band, generally less than a mile wide, along the southern part of the area; along the Washita River beginning about five miles downstream from Anadarko; and along the Canadian River in the northeastern part of the area. It crops out also as an inlier just southeast of Binger. The formation ranges in thickness from about 150 feet along the Kiowa-Washita County line in the southwestern part of the area to possibly 300 feet in northeastern Washita County (Sawyer, 1929, p. 317). Along the Washita River below Anadarko and from about the latitude of Fletcher eastward the Dog Creek Shale consists of red even-bedded shale interbedded with fine-grained gypsiferous sandstone locally grading into gypsum. Mudstone conglomerates are sparse. The sandy zones erode to form ledges in the softer material. Light-gray bands are common but not persistent, and normally they grade into the surrounding red shale within short distances. Westward from the above-defined exposures the mudstone conglomerates disappear and the entire formation becomes much more clayey.

Water supply. — The El Reno Group, except the Duncan Sandstone at the base, generally yields only a few gallons of water per day to wells, and the wells may be dry during periods of drought. The Duncan Sandstone, however, is an aquifer capable of yielding more than 100 gpm (gallons per minute) to some wells, although most wells produce only 25 to 50 gpm (Davis, 1955, p. 96). The Duncan Sandstone is a little-used aquifer in Caddo County. Farm wells tap water in it along the southern boundary of the outcrop area, and it furnishes the water supply for the oil refinery of Anderson-Prichard Oil Corporation at Cyril in southeastern Caddo County. There are four wells at the refinery, ranging in depth from 850 to 1,010 feet. They were completed in 1929 and 1930 and, after being pumped for about 27 years, still had yields ranging from 92 to 116 gpm in 1956.

Electric logs of wells in and near Cement indicate that the Duncan Sandstone is a good aquifer in that area. A core hole drilled in 1930 near Anadarko in SW¼ sec. 1, T. 7 N., R. 10 W., encountered water in the Duncan Sandstone at depths of about 800 to 900 feet below land surface. Artesian pressure caused the water to flow over the top of a 20-foot riser, but the flow was not measured. The well flowed for about three months before the uncased hole collapsed and choked off the well. The water was reported to be hard (Guernsey Engineering Co., written communication, 1942).

No data are available on the water-yielding potential of the Duncan Sandstone in the northern and western parts of Caddo County, but water in it probably is highly mineralized and saline because of its greater depth below land surface and greater distance from the outcrop.

WHITEHORSE GROUP

The Whitehorse Group in Oklahoma consists of the Permian strata that lie above the El Reno Group and below the Cloud Chief Formation. The strata now called Whitehorse Group were first named the Red Bluff Sandstones by Cragin (1896, p. 40), but the name Red Bluff proved to be preoccupied and Gould (1905, p. 39, 55) proposed the name Whitehorse Sandstone Member of the Woodward Formation, taken from Whitehorse Springs in northwestern Woods County. The name was restricted by Sawyer (1929, p. 11) when he called the upper part the Rush Springs Member of the Whitehorse, and the lower part the Marlow Member. Buckstaff in a written discussion (*in* Evans, 1931, p. 435) expressed a preference for classing the Whitehorse as a group rather than as a formation.

The Whitehorse Group crops out in about 80 percent of the area considered in this report and is concealed in much of the remainder by the overlying Cloud Chief Formation. The Whitehorse has been reported (Davis, 1955, p. 66-67) to be unconformable with underlying formations in the eastern end of the Anadarko syncline, but in central Caddo County and westward it is probably conformable with the underlying Dog Creek Shale of the El Reno Group. The contact with the overlying Cloud Chief Formation is unconformable locally in eastern Washita County.

The Whitehorse Group dips southwestward from Hinton about 10 feet per mile; near Sickles the dip increases to about 20 feet per mile; northeast of Alfalfa the dip flattens across the Anadarko syncline; and on the south side of the syncline northwest of Carnegie the dip has a northwesterly component which increases to about 50 feet per mile. The dip also has a westerly component of about 10 feet per mile down the plunge of the Anadarko syncline.

Marlow Formation

The Marlow Formation is the lower of two formations composing the Whitehorse Group and occupies the interval from the top of the El Reno Group to the base of the Rush Springs Sandstone. The formation consists mostly of even-bedded brick-red sandy shale, generally gypsiferous, with some very fine sand and silt loosely cemented with iron oxide and calcite. Its thickness ranges from about 90 to 128 feet and averages about 100 feet in the report area.

The Marlow Formation crops out along both limbs of the Anadarko syncline as a narrow band generally half a mile to a mile wide, although in places the outcrop area is as much as four or five miles wide.

The Verden Sandstone Member of the Marlow Formation crops out in eastern Caddo County. The Verden outcrop area, according to Bass (1939), generally is less than 1,000 feet wide and the member is about 10 feet thick. The Verden was deposited as one or more spits across the mouth of a broad, shallow bay. The presence of marine fossils in this member rules out the possibility that it is a terrestrial stream deposit. Evans (1948, p. 42-43) believed the Verden Sandstone Member to be a channel deposit laid down by tidal or salinity currents in a strait or pass. The question of its origin remains unresolved. The Verden consists of a medium- to coarse-grained sandstone containing rounded quartz grains and subangular chert grains held together by calcium carbonate cement and interbedded fine-grained sandy shale. The Verden is not an aquifer in the area of this report.

Two dolomite beds near the top of the Marlow were named the Upper Relay Creek Dolomite and the Lower Relay Creek Dolomite by Evans (1931, p. 416). He also indicated (p. 416) that the top of the Upper Relay Creek Dolomite was at or near the top of the Marlow. Fay (1962) revised this classification and called the Upper Relay Creek Dolomite the Emanuel Dolomite Bed, and the Lower Relay Creek Dolomite the Relay Creek Dolomite Bed. The dolomites of the Relay Creek and Emanuel, in Caddo County, range in thickness from a lamination only paper thin to a maximum of about 5 to 6 inches, and the interval between them ranges from 16 to 20 feet. Northwestward from Caddo County the two dolomite beds are as much as 4 to 5 feet thick in places, but retain approximately the same vertical separation.

About 10 to 15 inches below the Emanuel Dolomite Bed is a thin shale of a distinctive pink color. This pink shale probably is altered volcanic ash — the remains of an ash fall that can be traced long distances in western Oklahoma as a definite stratigraphic horizon. The pink shale has a maximum thickness of about a foot.

Water-bearing properties. — The Marlow Formation is not a good aquifer in eastern Caddo County — wells in it generally have maximum yields of only 1 or 2 gpm. In many areas the water has such high salinity, owing to solution of disseminated gypsum in the formation, that it is unfit even for stock use. In western Caddo County, however, the Marlow contains permeable sandy zones, 0.5 foot to 5 feet thick, that are not highly gypsiferous. Scanty data indicate that the extra 100 feet of drilling necessary to penetrate all these zones below the Rush Springs Sandstone may appreciably increase the yield of a well.

The coefficient of permeability of nine sandy beds in the Marlow Formation ranges from about 0.3 to 30 and averages 12 gpd (gallons per day) per square foot, according to analyses made by the Hydrologic Laboratory, U.S. Geological Survey. An electric log of a test hole in NW¼ sec. 23, T. 10 N., R. 12 W., indicates that this formation consists of a series of beds ranging in thickness from about 6 inches to 3 feet or more. The aggregate thickness of the permeable beds in the Marlow Formation, recorded on the log, is about 20 feet. Using 20 feet for the thickness of the aquifer and 12 as the permeability, we calculate the coefficient of transmissibility to be about 240 gpd per foot. This figure for transmissibility does not reflect the potential yield of wells tapping the formation because the irrigation wells in Caddo County are completed without casing and the permeable beds are friable. The silt and very fine sand slough into the well bore and are washed out in the water that is pumped from the well; thus, the effective diameter of the well is increased, which in turn increases the quantity of water that can be released from the formation into the well within a given period.

The Marlow Formation probably receives the major part of its recharge through the downward percolation of water from the overlying Rush Springs Sandstone. Recharge from precipitation directly on the outcrop is minor because the areal extent of the outcrop is small in comparison to the area covered by the Rush Springs Sandstone, and the relatively steep slopes and poor cover of vegetation on the outcrop permit the rapid runoff of precipitation.

Discharge from the Marlow is chiefly by seepage into the alluvium of streams crossing the outcrop. Farm wells and a few irrigation wells that penetrate beds of the Marlow below the Rush Springs Sandstone remove negligible amounts of water. However, the discharge through irrigation wells will increase in direct proportion to the number of wells that are drilled through the Marlow Formation. Because the major source of recharge to the Marlow is the overlying Rush Springs Sandstone, pumpage from the Marlow can be increased only at the expense of storage of water in the Rush Springs.

Rush Springs Sandstone

The Rush Springs Sandstone, the uppermost formation of the Whitehorse Group, conformably overlies the Marlow Formation and underlies the Cloud Chief Formation.

The Rush Springs Sandstone in Caddo County consists chiefly of reddish-brown very fine silty sandstone. A few calcareous sandy beds occur at random but they are more common in the lower part of the formation. These calcareous beds range in thickness from 6 to 12 inches and can be recognized in drill cuttings from some wells. Loose sand, through which the drill bit drops as if falling into a cavity, may represent calcareous sandy beds from which the calcium has been leached by the movement of ground water. These beds cannot be recognized with certainty in surface exposures of the Rush Springs. The formation is even bedded to highly cross-bedded and shows many of the characteristics of shallow-marine deposition, although some of the cross-bedding is subaerial in character. The sand grains composing the Rush Springs in Caddo County are subangular to subround, are remarkably homogeneous in lithologic character, and are loosely cemented with iron oxide and calcite. These sandstones probably were laid down along the eastern side of a shallow embayment that was at times cut off, or severely restricted, from the main Permian sea, because westward from Caddo County the sandstones grade laterally into anhydrite and gypsum and gypsiferous silty clay in what must have been a desiccation basin in western Oklahoma during the time of Rush Springs deposition.

The thickness of the Rush Springs Sandstone generally ranges from about 200 feet in the southern part to about 330 feet in the northern part of the area. It also becomes greater westward along the axis of the Anadarko syncline. The Rush Springs is exposed throughout the area and its structure generally conforms to the shape of the Anadarko syncline.

Water-bearing properties.—Ground water in the Rush Springs Sandstone is under water-table conditions, and the depth to water below land surface ranges from zero to about 150 feet according to the topography. The yield of wells ranges from less than 100 to more than 1,000 gpm. The amount of water that a well will yield depends upon the permeability of the aquifer, the thickness of the zone of saturation, and, most important, the presence or absence of loose or loosely cemented beds of sand in the formation. Wells encountering loose sands during drilling or wells that pump a mixture of silt, sand, and water during initial test pumping generally have specific capacities ranging from 6 to 10 gpm per foot of drawdown. Wells that encounter little or no loose sand during drilling and that pump little silt or sand generally have specific capacities ranging from 1 to 3 gpm per foot of drawdown. It is believed that the removal of fine-grained sand and silt from the aquifer during the development of a well causes a gradual increase in the effective radius of the well and thus an increase in its specific capacity. Varying amounts of sand have been pumped from nearly all the irrigation wells in the Rush Springs Sandstone. Drillers and landowners in the area have reported that several pumps and foundations have been lost because of excessive pumping of sand and subsequent collapse of the area around the well. The water in the Rush Springs is hard but is low in dissolved solids (table 8), and it generally is suitable for municipal and irrigation uses; depending upon the degree of hardness, it may require treatment for removal of hardness-causing cations for some industrial uses.

The natural discharge of ground water from the Rush

Springs Sandstone is by seepage into streams and by springs around the edge of the outcrop area and where stream channels have cut below the water table. Transpiration and evaporation remove large quantities of water from the shallow water-table areas.

The Washita River valley divides the Rush Springs Sandstone into two distinct aquifer systems. The principal difference between the two systems is that south of the Washita River are areas of silty less permeable rock containing highly mineralized water.

POST-WHITEHORSE ROCKS

Cloud Chief Formation

The Cloud Chief Formation overlies the Rush Springs Sandstone and blankets that formation west of an irregular line extending approximately from Weatherford southward to Colony. Elsewhere in the area it occurs as outliers, the largest being in the vicinity of Cyril in southeastern Caddo County. The formation was named by Gould (1924, p. 324-341) and consists of red clay shale and of red silty or sandy shale, which in places is similar to the underlying Rush Springs Sandstone. In the report area it is largely gypsum and includes the Weatherford Member at its base.

The Cloud Chief Formation was described by Ham and Curtis (1958, p. 8) as a widely distributed redbed unit in the central part of western Oklahoma. The gypsum in the Cloud Chief Formation occurs as thick and thin lenses within a sequence of sandstone and shale 250 to 300 feet thick. The thickest gypsum generally is slightly above the base of the formation and is approximately 100 feet in southeastern Washita County near the town of Cloud Chief. The gypsum grades into clastic sediments northwest of Weatherford.

The Weatherford Member at the base of the Cloud Chief is the result of the first of a series of desiccation periods during which the evaporites of the Cloud Chief were deposited. Intraformational breccias in the intervening clay shales and siltstones indicate deposition under turbulent conditions, and at some places ripple-marked, even-bedded, very fine silty sandstones similar to the underlying Rush Springs Sandstone indicate quiet-water deposition.

The Weatherford is a dolomite at most places in Caddo County, but at some places it is a dolomitic shale and at other places is anhydrite or gypsum. The variations are difficult to explain, but the most logical explanation is that the Weatherford in the Caddo County area was deposited in a near-shore environment and the variations from gypsum-anhydrite to dolomite are in some way related to the Permian sea on the west and to the landmass on the east.

A break in sedimentation, however slight, must have occurred in the Caddo County area in the change from Rush Springs to Cloud Chief sedimentation. The most direct evidence for this diastem is in a sandy phase of the Weatherford in SW¼ sec. 30, T. 12 N., R. 12 W., where casts of raindrops occur repeatedly in successive laminations near the base of the formation. At other places the beds are undulating and show evidence of flowage while in a plastic or semiplastic stage, as though deposited upon an irregular surface. In a few areas the Weatherford is broken into angular blocks and forms an intraformational or edgewise breccia. This brecciation of the Weatherford could be the result of wave action in shallow water.

A mature karst topography is developed locally on the Cloud Chief in the main outcrop area on the west and in the larger outliers to the east. Scattered buttes of the Cloud Chief occur throughout the northern part of the area and are known as the Caddo County Buttes (Gould, 1905, p. 57). The buttes are composed of the dolomitized part of the upper Rush Springs Sandstone, the Weatherford Member, and dolomitized sandy silts and siltstones of the Cloud Chief Formation. On some buttes are slump blocks of the Quartermaster Formation, which overlies the Cloud Chief to the west. The buttes were preserved by dolomitization of the rocks that compose them so that they resisted erosion more effectively than did the same strata in the surrounding areas. In the karst topography of the main outcrop area of the Cloud Chief are sinkholes which contain clearly identifiable fragments of dolomitized Cloud Chief and Quartermaster rocks, which, if the surrounding material were eroded away, would parallel in character the Caddo County Buttes. The speculative conclusion is reached that the Caddo County Buttes are remnants of indurated material such as can be seen in sinkholes in the main outcrop area of the Cloud Chief Formation.

Water-bearing properties.—The Cloud Chief is not capable of yielding more than a few gallons of water per day to wells. The karst topography has developed to the point that most solution channels and caves in the evaporite section of the formation have collapsed and have been filled with silt and clay, and the intervening beds are too clayey and silty to be permeable. At a few isolated spots, caves remain open in the more massive gypsum and yield water during periods of wet weather. Ground water in the Cloud Chief reportedly is hard and has a high sulfate content.

Quaternary System

HIGH-LEVEL GRAVELS

Coarse gravels, which are present in the area as scattered deposits and as slump on the valley slopes, are probably the remnants of a thick mantle of debris that was spread over a bedrock peneplain during late Tertiary or early Pleistocene time. These sediments were laid down by streams in a drainage system unrelated to the present drainage. The streams may have had their source in the Rocky Mountains far to the west. Most of the gravel deposits are thin and of small areal extent, but one deposit covers about 20 acres in NW¼ sec. 5, T. 8 N., R. 12 W., and has a maximum thickness of about 20 feet. Fossil bones and teeth from this gravel pit were identified as those of a horse and an elephant of Pleistocene age (J. W. Stovall, oral communication, 1954). None of these gravel deposits contains appreciable amounts of ground water.

ALLUVIUM AND TERRACE DEPOSITS

Alluvium and terrace sediments ranging in age from Pleistocene to Recent are considered together because they are both stream deposits and, in general, have similar hydrologic properties. Terrace deposits are adjacent to and topographically higher than the more recent alluvium.

The alluvium and terrace sediments along the Washita River were laid down during three cycles of erosion and deposition, two of which can be identified in the smaller stream valleys in the area. In the first cycle, the broad major valleys which were eroded in the bedrock were alluviated with sand and gravel containing an abundance of quartz, quartzite, chert, flint, jasper, and silicified wood. These materials probably came from a source in the Rocky Mountains or from the Tertiary

deposits of the High Plains. During the second cycle, the streams degraded their channels and carried away much of the older terrace deposits. The valleys then were refilled partly with material reworked from the older terrace deposits, but mostly with sand and silt derived from the surrounding bedrock. The third cycle was the shortest. Valleys were cut into younger terrace deposits and then partly filled with sand, silt, and clay, which make up the Recent alluvium.

The maximum thickness of the alluvium and terrace deposits is about 90 feet in the report area. It is likely, but not certain, to be thickest near the middle of a valley, and thicker along major streams than along small creeks.

The ground water in the alluvium and terrace deposits ranges widely in chemical character. Chemical analyses made by the Quality of Water Branch, Water Resources Division, U. S. Geological Survey, show that the alluvium generally contains water of poorer quality than that in the terrace deposits. The analyses (table 8) show that sulfate (SO_4), the principal constituent causing salinity in the area, ranges from about 336 to about 5,130 ppm (parts per million) in water from the alluvium along the Washita River, but from only about 80 to about 231 ppm in water from terrace sediments along the stream.

The difference in quality of the water contained in the alluvium and that in the terrace deposits is due to the sources of recharge to these sediments. Recharge to the alluvium is principally from seepage and runoff from adjacent, topographically higher terrace deposits. Some recharge also comes from infiltration of high-sulfate water from the Washita River during flood periods. Recharge to the terrace deposits is principally from precipitation directly on the outcrop and from runoff from adjacent high lands, which in Caddo County are underlain mostly by the sands of the Whitehorse Group. The terrace deposits are high enough above the stream channel that they are not affected directly by influent seepage of river water except during short periods of extremely high flood stage.

The alluvium and terrace deposits along the Washita River have been used as a source of public-supply, industrial, and irrigation water, and yields of as much as 300 gpm may be expected from wells constructed in favorable locations. Alluvium and terrace deposits along the tributary streams in the area are generally too silty to yield much water to wells.

GROUND-WATER RESOURCES

Hydrologic Characteristics

The quantity of water that a water-bearing material will yield and the rate at which water will move through the material are governed by its hydrologic characteristics. The hydrologic characteristics of most sediments differ from place to place, because they are dependent upon the size, shape, number, and degree of interconnection of the pore spaces within the sediments.

The amount of water that can be stored in any material depends upon the porosity of the material. Porosity is expressed as the ratio of the volume of pore spaces to the total volume of the material. A rock is saturated when all its pore spaces are filled with water. However, the amount of water that a saturated material will yield when allowed to drain by gravity is less than the porosity of the material because some of the stored water is retained in the pore spaces by capillarity. The specific yield of a water-bearing material is the ratio of the volume of water drained by gravity to the total volume of the material, and generally the ratio is stated as a percentage.

The rate at which an aquifer transmits water depends upon the permeability of the aquifer. The coefficient of permeability is defined as the volume of flow per unit time per unit hydraulic gradient through a unit area. The coefficient of permeability in meinzer units may be expressed as the rate of flow of water in gallons per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 100 percent at a temperature of 60°F (Wenzel, 1942, p. 7). The field coefficient of permeability is the same except that it is not corrected for temperature. The coefficient of transmissibility is equal to the field coefficient of permeability multiplied by the thickness (in feet) of the aquifer.

The coefficient of storage of an aquifer is defined as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. Under water-table conditions the coefficient of storage is practically the same as the specific yield.

Laboratory analyses of 27 samples from the Rush Springs

Table 2.—Laboratory Analyses of Samples from the Rush Springs Sandstone and Marlow Formation

Sample No.	Formation[1]	Location	Specific retention (percent)	Porosity (percent)	Specific yield (percent)	Permeability (meinzer units)
		T. 10 N., R. 12 W.				
1	RS	SE¼SE¼ sec. 23	9.6	30.2	20.6	8[2] •
2	RS	do.	9.0	30.6	21.6	3
3	RS	SE¼NE¼ sec. 23	10.2	35.1	24.9	11
4	RS	NW¼NW¼ sec. 24	10.2	32.1	21.9	1
5	RS	NE¼NW¼ sec. 24	12.0	32.8	20.8	8
6	RS	SW¼SE¼ sec. 26	4.7	30.6	25.9	20
		T. 10 N., R. 11 W.				
7	RS	NW¼SE¼ sec. 29	7.4	32.8	25.4	22
8	RS	do.	5.2	35.5	30.3	36[2]
9	RS	do.	5.5	35.5	30.0	35[3]
10	RS	do.	7.0	34.7	27.7	34
11	RS	do.	7.7	32.8	25.1	1
12	RS	do.	5.6	33.6	28.0	70
13	RS	do.	11.3	30.6	19.3	10
14	RS	do.	10.9	30.9	20.0	100[3]
15	RS	do.	6.4	30.9	24.5	66
16	RS	do.	10.6	29.4	18.8	8[2]
17	RS	SE¼SW¼ sec. 29	8.1	32.1	24.0	52
18	RS	SW¼SE¼ sec. 30	10.0	34.3	24.3	65
19	RS	NW¼SE¼ sec. 30	4.8	43.4	38.6	100
20	RS	NE¼SW¼ sec. 30	11.9	33.6	21.7	27
21	RS	NW¼NW¼ sec. 34	10.1	29.4	19.3	43
22	M	NW¼SE¼ sec. 27	7.2	32.5	25.3	12[3]
23	RS	do.	5.5	31.7	26.2	19
24	M	SE¼SE¼ sec. 27	5.4	43.0	37.6	10[2] •
25	M	NW¼SW¼ sec. 26	11.3	24.5	13.2	0.3
		T. 10 N., R. 10 W.				
26	M	NW¼SW¼ sec. 31	3.4	40.8	37.4	18[3]
		T. 10 N., R. 11 W.				
27	RS	NW¼SE¼ sec. 27	4.1	38.9	34.8	8[3]
		T. 9 N., R. 10 W.				
28	M	SE¼NE¼ sec. 4	.....	.....	.....	27
		T. 11 N., R. 10 W.				
29	M	NE¼NE¼ sec. 11	.....	.....	.....	0.4
		T. 8 N., R. 10 W.				
30	M	NE¼NW¼ sec. 4	.....	.....	.....	11.0
31	M	NE¼NE¼ sec. 10	.....	.....	.....	30.0
32	M	do.	.....	.....	.....	1

[1] RS, Rush Springs; M, Marlow.
[2] Particle-size distribution curve on figure 3.
[3] Sample repacked; porosity and specific yield percentages are probably high.

Sandstone and upper part of the Marlow Formation in Caddo County indicate that porosity ranges from 24 to 43 percent and averages 32 percent. Specific yield ranges from 13 to 38 percent and averages about 25 percent. Permeability (meinzer units) ranges from 0.3 to 100 and averages about 30 (table 2).

Particle-size analyses of four samples of the Rush Springs Sandstone show that, in general, the sandstone is composed of very fine to fine sand, the silt and clay sizes averaging a little more than 20 percent of the total. The two analyses of the Marlow Formation indicate that it contains a higher percentage of material of silt and clay sizes than does the Rush Springs (fig. 3).

A two-week aquifer test was conducted on well 10N-12W-23bb1 on the C. E. Smith farm near Sickles, Caddo County, during April 1956. The irrigation well was pumped at a constant measured rate of 730 gpm from April 8 to 14, during which time the drawdown of ground-water levels in nine observation wells was measured by continuous automatic water-level recorders and by steel tapes. The pumping level of the irrigation well reached a maximum depth of about 142 feet below land surface. The depth to water before pumping began was 56 feet. The drawdown in the observation wells ranged from about 80 feet in a well 100 feet from the pumped well to less than 2 feet in a well 1,080 feet distant. A well approximately 1,500 feet away did not show a measurable drawdown. Transmissibility and storage coefficients computed by the Theis nonequilibrium formula, the Thiem formula, and the Jacob modified nonequilibrium formula ranged from 11,000 to 14,000 gpd per foot. The storage coefficient ranged from 0.01 to 0.03 and averaged 0.02.

A second aquifer test in the Rush Springs Sandstone was conducted on well 10N-13W-2dd1, four miles north of Eakly in March 1959. Drawdown of water levels was measured in two observation wells by steel tape and in one by automatic water-level recorder. The static water level before pumping began was 62 feet. The pumping level of the irrigation well varied between 166 and 185 feet below land surface owing to a fluctuation in the rate of pumping between 175 and 246 gpm during the test. The drawdown of water level was 8.5 feet in an observation well 740 feet northeast of the pumped well and 6 feet in a well 950 feet distant. No appreciable drawdown occurred in an observation well 165 feet from the pumped well, and so it was assumed to be plugged. Inasmuch as the rate

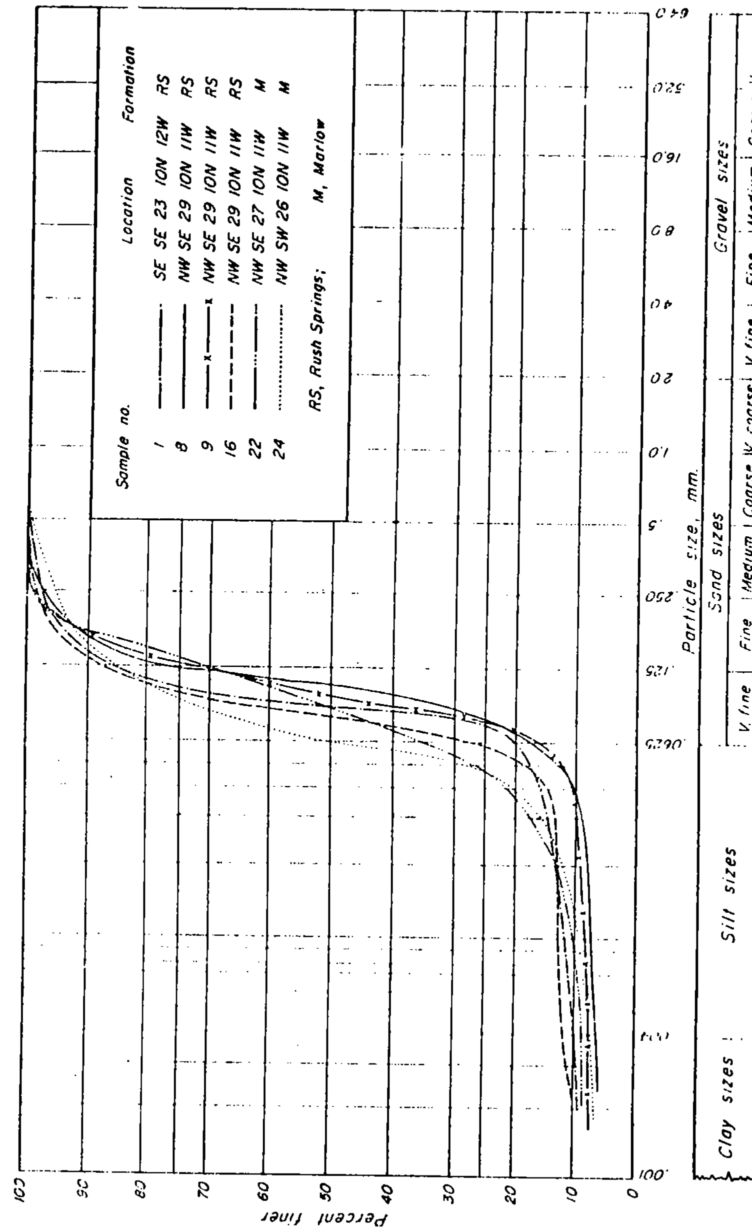

Figure 3. Particle-size distribution curves of six samples from the Rush Springs Sandstone and Marlow Formation

of pumping varied considerably during the test, only recovery data were used in computing transmissibilities. The coefficient of transmissibility determined by the Jacob modified nonequilibrium formula was 13,000 gpd per foot.

Before this investigation, L. V. Davis made two aquifer tests in the Rush Springs Sandstone. One was made in 1948 on the water well of the Magnolia Petroleum Co. in sec. 3, T. 4 N., R. 7 W., in Grady County, and the other in 1949 on well 11N-13W-22cd1 in Caddo County. The coefficients of transmissibility computed from these tests were 13,000 gpd per foot at the well in Grady County and 5,000 gpd per foot at well 11N-13W-22cd1.

In summary, the results of the two aquifer tests described in this report and the two tests made by Davis in 1948 and 1949 indicate transmissibility coefficients of the Rush Springs Sandstone ranging from 5,000 to 14,000 gpd per foot and field permeability coefficients ranging from 19 to 62 gpd per square foot. The value for storage or specific yield, which averages 2 percent in the Smith test, is believed to be too low for water-table conditions and probably results from incomplete drainage of the aquifer. Analyses of samples sent to the Hydrologic Laboratory indicate an average specific yield of about 25 percent for the Rush Springs Sandstone.

Laboratory determinations of specific yield are based on complete saturation and drainage of a material and therefore represent ideal conditions. These conditions are seldom met in the field because water-level fluctuations in response to recharge and discharge are too rapid to permit complete saturation and drainage, especially of fine-grained material. Therefore for this report an estimated value of 10 percent is used. This value is believed to represent more nearly the specific yield for the Rush Springs Sandstone under actual field conditions. Computations given later in the report are based on this value.

TABLE 3.—SUMMARY OF FOUR AQUIFER TESTS IN THE RUSH SPRINGS SANDSTONE

DATE OF TEST	WELL NUMBER	COEFFICIENT OF TRANSMISSIBILITY (GPD PER FOOT)[1]
December 1948	T4N-R7W-3ab1	13,000
April 1949	T11N-R13W-22cd1	5,000
April 1956	T10N-R12W-23bb1	12,000[2]
March 1959	T10N-R13W-2dd1	13,000

[1] Gallons per day per foot.
[2] Coefficient of storage, 0.02.

Two of the aquifer tests (near Sickles and Eakly) are in heavily irrigated areas where the average yield of irrigation wells is high. The coefficients of transmissibility computed from these two aquifer tests probably are higher than the average transmissibility of the Rush Springs Sandstone. On the basis of the permeabilities derived from analysis of samples from the Rush Springs and the computations of transmissibility and permeability from four aquifer tests, it is concluded that a reasonable average coefficient of transmissibility for the Rush Springs Sandstone in this area is about 10,000 gpd per foot, and that the average coefficient of permeability is about 35 gpd per square foot. The results of the four pumping tests are summarized in table 3.

MOVEMENT OF GROUND WATER

Ground water moves slowly through the pore spaces in the rocks from areas of high head to areas of low head. The general direction of movement is toward points of discharge, such as springs, streams, pumping wells, or swamps, and is indicated by the direction of the hydraulic gradient. The rate of ground-water movement depends upon the hydraulic gradient and the permeability of the formation. The volume of ground-water movement depends upon the rate and the cross-sectional area through which the water moves. Contour maps of the water table or piezometric surface show the direction of ground-water movement, which is at right angles to the contours.

A contour map of the water table in the Caddo County area (pl. II) shows that the water table is an irregular surface that generally corresponds with the topography. These irregularities in the shape of the water table not attributed to topography are caused by differences in permeability, thickness, or recharge and discharge conditions of the aquifer. Ground water moves from the points of high heads toward points of lower heads. Movement is generally southward and southeastward toward the Washita River, but locally toward Cobb and Sugar Creeks and their main tributaries, which receive ground-water discharge in the form of seepage.

RECHARGE

Recharge is the addition of water to the ground-water reservoir. It may be accomplished by seepage from streams, ponds, and reservoirs; by underflow from adjacent areas; by infiltration of excessive irrigation water; or by infiltration of precipitation. Of these sources, precipitation is the most important in this area.

Ground-water recharge due to seepage from streams will occur in those parts of the stream channels that are above the water table and will occur only briefly after heavy rains. Thus stream recharge in the Caddo County area can be considered as part of the recharge due to precipitation. Part of the water in small ponds and reservoirs may infiltrate to the water table. However, the amount of recharge probably is small because ponds become sealed by silt in a few years and most of the water in small ponds and reservoirs is lost by evaporation. The water-table map (pl. II) indicates that subsurface flow of water into the area north of the Washita River is limited by the ground-water divide of the Cobb Creek basin. Thus inflow from the topographically higher areas to the north and west is relatively insignificant. The amount of water that returns to the ground-water reservoir by infiltration of excessive irrigation water probably is small because application of water over most of this area is by sprinkler system, which wets only the upper few inches of the soil.

The amount of recharge by precipitation is governed not only by the total amount of precipitation but also by its intensity and distribution. The average annual precipitation in the Caddo County area is about 28.10 inches; only a small part of this water infiltrates to the zone of saturation, the remainder being lost through evaporation, transpiration, and surface runoff.

A quantitative estimate of recharge in the area is obtained by analyzing the recharge derived from precipitation in the Cobb Creek basin. Cobb Creek drains an area of about 320 square miles above the gaging station near Fort Cobb (pl. II). Although it represents only about 20 percent of the report area, the Cobb Creek basin forms a single and complete drainage basin within this larger area, and thus the amount of water that enters and leaves the basin can be measured. The rate of recharge over the rest of the report area is approximately equal to that in the Cobb Creek basin because the

physical and hydrologic conditions that control recharge are similar.

The effect of precipitation on ground-water levels in the Cobb Creek basin was computed by using four wells that were believed to be hydrologically representative of the basin and that were away from the influence of irrigation wells. The average depth to water in the four wells was determined and plotted by months against corresponding average monthly precipitation (fig. 4).

Because the amount of water recharged to or discharged from the ground-water zone is reflected in fluctuations of water levels in wells, ground-water recharge can be estimated from figure 4. However, when ground-water levels rise after periods of significant rainfall, the rise does not reflect total recharge because ground water is being discharged at the same time. To account for this part of the recharge, the slope of the hydrograph prior to the rise was projected to the month in which the peak of the rise occurred. This projection represents the natural recession in ground-water stage had there been no recharge. The amount of ground-water recharge is equal to the difference between the peak and the recession stages, multiplied by the specific yield of the saturated section, which in this area is estimated to be 10 percent. The annual total recharge in the Cobb Creek basin for 1953-1956 is shown in table 4.

Recharge ranged from a high of 3.5 inches during 1953 to

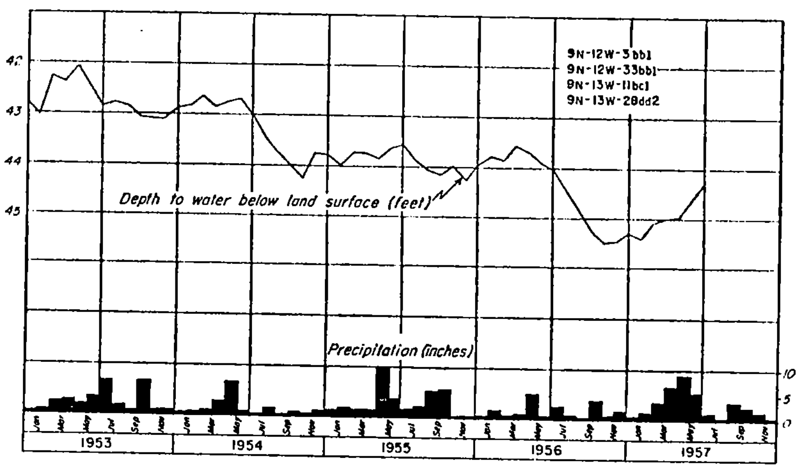

Figure 4. Hydrograph of average ground-water level of four wells and average monthly precipitation at Fort Cobb, Carnegie, Lookeba, and Weatherford.

a low of 1.5 inches during 1956 and averaged 2.4 inches for the 4-year period. Because 1954 and 1956 were unusually dry years, it is believed that a recharge rate of 2.8 inches would be about the average over a long period. Recharge of 2.8 inches per year is about 10 percent of the annual precipitation of 28.10 inches. This recharge figure can be projected over the entire project area as representative of recharge to the Rush Springs Sandstone where it crops out, and would be equivalent to more than 150,000 acre-feet of water annually.

TABLE 4.—ANNUAL RECHARGE IN COBB CREEK BASIN

YEAR	RISE IN WATER LEVELS (INCHES)	RECHARGE (INCHES)
1953	35	3.5
1954	21.5	2.1
1955	25	2.5
1956	15.5	1.5

DISCHARGE

NATURAL DISCHARGE

Ground water is discharged under natural conditions through transpiration by plants, by evaporation, by flow of streams and springs, and by underflow into adjacent areas. The rate of discharge varies yearly and seasonally, as it is dependent upon weather conditions and the altitude of the water table. Under natural conditions, or before large quantities of ground water are withdrawn by pumping, the perennial ground-water discharge and recharge are approximately in balance.

Transpiration and evaporation. — Discharge by transpiration and evaporation from the zone of saturation or capillary fringe is negligible over most of the area of this report because the average depth to the water table in the upland area is more than 40 feet. Only where the water table is close to the land surface, such as along the major drainage systems, does discharge through evaporation and transpiration (evapotranspiration) become significant.

The losses due to evaporation and transpiration are large, however, for that part of precipitation that does not infiltrate to the water table. The magnitude of this loss is illustrated by

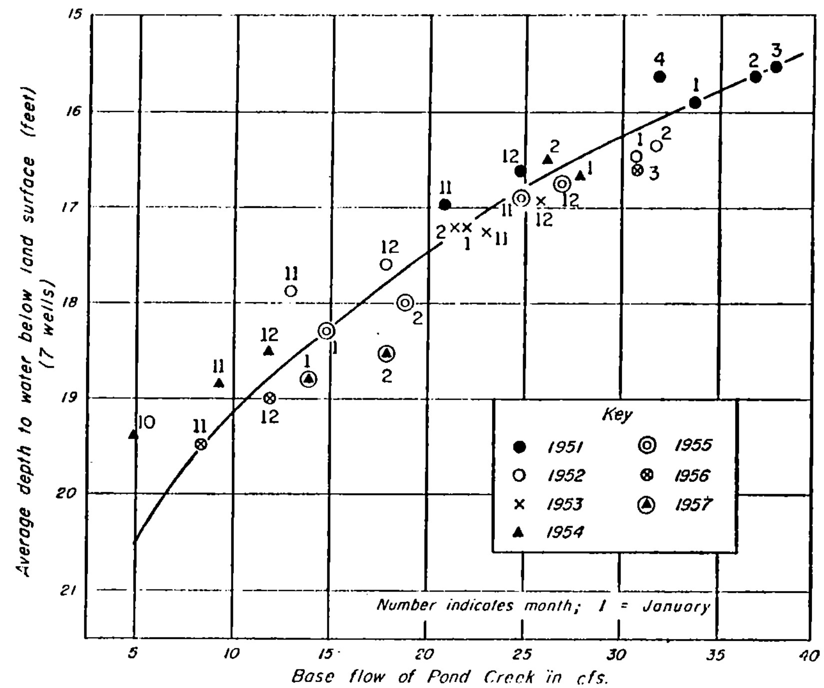

Figure 5. Base-flow rating curve of mean ground-water stage compared with base flow of Cobb Creek.*

the data obtained for the Cobb Creek basin.* The average annual precipitation over the basin is 28.10 inches, which is most of the water that enters the basin. If the yearly recharge to the aquifer is 2.8 inches and surface runoff of Cobb Creek is 2.1 inches, evaporation and transpiration must account for about 23 inches, or 80 percent of the total water that enters the basin. This figure for evaporation and transpiration probably would apply over the project area.

Ground-water discharge by streams and springs. — The rate of ground-water movement varies with the gradient of the water table if transmissibility and storage in the aquifer are assumed to remain about constant. Water levels measured over a period of years in the report area indicate that ground water moves toward the larger streams at a fairly constant rate. No significant yearly change occurs in the ground-water gradient except near the major drainage areas, where ground-water

* Also known as Pond Creek and so referred to by Clark (1956) and Davis (1950). The Board on Geographic Names has officially accepted the name Cobb Creek.

TABLE 5.—MONTHLY GROUND-WATER DISCHARGE OF COBB CREEK COMPUTED FROM BASE-FLOW RATING CURVE, 1953-1956

MONTH	AVERAGE DEPTH TO WATER OF SEVEN WELLS[1] (FEET)	AVERAGE GROUND-WATER DISCHARGE (CFS)	GROUND-WATER DISCHARGE (CFS DAYS)	GROUND-WATER DISCHARGE (INCHES OVER BASIN)
		1953		
Jan.	17.22	21.5	666	0.07
Feb.	17.20	21.5	600	.07
Mar.	17.09	22.5	700	.08
Apr.	16.61	26.5	800	.09
May	16.90	24.0	745	.08
June	18.04	16.0	480	.06
July	16.88	24.0	745	.08
Aug.	17.30	21.0	650	.08
Sept.	18.23	15.0	450	.05
Oct.	17.53	19.5	605	.07
Nov.	17.24	21.5	645	.07
Dec.	16.92	24.0	745	.08
		1954		
Jan.	16.68	26.0	805	.09
Feb.	16.50	28.0	785	.09
Mar.	16.56	27.0	835	.09
Apr.	16.50	27.5	825	.09
May	16.08	32.0	990	.11
June	17.05	23.0	690	.08
July	18.20	15.0	465	.05
Aug.	18.88	11.5	355	.04
Sept.	19.41	9.0	270	.03
Oct.	19.38	9.5	294	.03
Nov.	18.85	12.0	360	.04
Dec.	18.51	13.5	420	.05
		1955		
Jan.	18.31	14.5	450	0.05
Feb.	18.01	16.5	460	.05
Mar.	17.99	16.5	510	.06
Apr.	17.70	18.5	555	.06
May	16.53	27.5	850	.10
June	16.47	28.0	840	.10
July	17.66	18.5	570	.06
Aug.	17.91	17.0	527	.06
Sept.	18.32	14.5	435	.05
Oct.	17.03	23.0	714	.08
Nov.	16.94	24.0	720	.08
Dec.	16.78	25.0	775	.09
		1956		
Jan.	16.73	25.5	790	.09
Feb.	16.66	26.5	740	.08
Mar.	16.61	26.5	822	.09
Apr.	16.65	26.5	795	.09
May	17.18	22.0	680	.08
June	17.84	17.5	525	.06
July	18.57	13.5	418	.05
Aug.	19.19	10.0	310	.03
Sept.	19.99	6.5	195	.02
Oct.	19.91	7.0	217	.02
Nov.	19.45	9.0	270	.03
Dec.	19.02	11.0	340	.04

[1] 8N-12W-5bc1, -9cc1, -15cd1, -16dd1; 9N-12W-19dc1, -28cc1, -30cd1.

discharge is affected mainly by evaporation and transpiration by plants during the summer months.

Ground-water discharge was computed by Meinzer and Stearns (1929) in their study of the Pomperaug Basin, Connecticut, by relating stream base flow to the average water level in several wells. A similar approach is used in this report to compute ground-water discharge by relating average water levels in wells near Cobb Creek to its base flow.

The depths to water in seven wells near Cobb Creek were averaged. Ground-water stages were selected only during the

season when evaporation and transpiration losses were low (November through February) so that the effects of evaporation and transpiration on stream base flow would be at the minimum, and the selection was further restricted to periods when the flow in Cobb Creek consisted only of ground-water flow, as indicated by stream hydrographs and precipitation records.

From these selected points a base-flow rating curve was constructed by plotting mean ground-water stages against stream-discharge rates in corresponding months (fig. 5). From this curve approximations of the monthly and yearly base flow of Cobb Creek between 1953 and 1957 were obtained by using average water levels of the seven wells. The results are given in table 5. Ground-water discharge into Cobb Creek was computed as equivalent to 0.9 inch over the basin, or approximately 15,000 acre-feet per year. Data are not available to compute ground-water discharge for the entire report area.

The amount of ground water discharged by springs is relatively small. Most springs occur near the heads of the tributary streams that flow into Cobb and Sugar Creeks. The Oklahoma State Mineral Survey in 1937 listed 20 springs draining into the Sugar Creek basin at that time. Many of these springs now have stopped flowing. The yields of springs in the report area were not measured.

Subsurface flow. — Some discharge occurs by subsurface flow of ground water into underlying formations and adjacent areas. Subsurface flow out of the Cobb Creek basin occurs near the southeast corner of T. 8 N., R. 12 W., and most of this flow is intercepted eventually by the Washita River. South of the Washita River most of the ground-water flow is intercepted by the Washita River and its larger tributaries. South of the ground-water divide between the Washita and Red River basins, ground water moves toward the south out of the report area.

PUMPAGE

Irrigation use. — Computations of irrigation pumpage are based on estimates of normal irrigation requirements of various crops at Carnegie (Garton and Criddle, 1955), crop acreages from the yearly Irrigation Survey Summary, and a correction factor. The correction factor is necessary because normal requirements are based on normal precipitation for the area. The correction factor was computed by comparing the normal requirement for peanuts to the actual amount of water used to irrigate peanuts in the vicinity of Eakly, less than 25 miles north of Carnegie. J. E. Garton (written communication, 1960) supplied the figures for the water used to irrigate peanuts at Eakly for the years 1956-1959. The correction factor thus reflected the rainfall, temperature, and humidity of the growing season and was applied to the other crops of the area. The estimated irrigation pumpage by crops for the years 1956-1959

TABLE 6.—IRRIGATION PUMPAGE IN CADDO COUNTY, 1956-1959

CROP	ACREAGE[1]	NORMAL WATER REQUIREMENT (INCHES)	CORRECTION FACTOR	ACRE-FEET
		1956		
Cotton	6,500	10.2	1.3	7,200
Sorghum	6,575	8.8	1.3	6,200
Alfalfa	1,500	17.3	1.3	2,800
Peanuts	13,000	14.0	1.3	20,000
Other	2,925	10.2	1.3	2,500
	30,500			38,700
		1957		
Cotton	1,400	10.2	0.43	510
Sorghum	866	8.8	.43	280
Alfalfa	1,200	17.3	.43	750
Peanuts	18,000	14.0	.43	9,200
Other	735	10.2	.43	270
	22,201			11,010
		1958		
Cotton	4,925	10.2	0.75	3,200
Sorghum	2,600	8.8	.75	1,400
Alfalfa	1,000	17.3	.75	1,100
Peanuts	20,000	14.0	.75	17,500
Other	2,475	10.2	.75	1,600
	31,000			24,800
		1959		
Cotton	5,000	10.2	.64	2,750
Sorghum	1,350	8.8	.64	630
Alfalfa	1,500	17.3	.64	1,400
Peanuts	20,000	14.0	.64	15,000
Other	450	10.2	.64	240
	28,300			20,020

[1] Irrigation Survey Summary, Oklahoma State University.

are given in table 6. The table shows that yearly pumpage for irrigation ranged from about 11,000 acre-feet in 1957 to 39,000 acre-feet in 1956 and averaged about 24,000 acre-feet.

The above computation of irrigation pumpage for 1956 was checked by using acreage and discharge estimates of 29 irrigators in Caddo County who were interviewed in the field during the fall of 1956. The results show that the total number

TABLE 7.—MUNICIPAL WATER SUPPLIES FOR THE CADDO COUNTY AREA

CITY OR TOWN	POPULATION (1960)	AQUIFER[1]	NUMBER OF WELLS	DEPTH RANGE OR AVG. (FT)	ELEVATED STORAGE (1,000 GALS)	PUMPAGE (1960) DAILY AVG. (1,000 GALS)	PUMPAGE (1960) YEARLY (ACRE-FT)
Caddo County							
Anadarko	6,299	A	5	41-46	2,115	670	750
Apache	1,455	ER RS	6	41-700	50	230	260
Binger	603	RS	3	160-225	100	30	34
Carnegie	1,500	RS	10	160-300	50	200	220
Cement	959	RS	4	185-500	250	50	57
Cyril	1,284	RS	5	150-200	50	216	240
Fort Cobb	687	RS	4	135-145	55	45	50
Hinton	907	RS	4	125-325	60	60	67
Hydro	697	RS	4	140-185	50	100	110
Comanche County							
Elgin	540	ER	8	60	—	12	13
Fletcher	884	ER	2	932	50	39	44
Sterling	562	ER	3	140-200	—	29	34
Custer County							
Weatherford	4,499	RS	15	130-250	785	850	950

[1] A, alluvium; RS, Rush Springs Sandstone; ER, El Reno Group.

of days crops were irrigated in 1956 ranged from 15 to 90 and averaged 52, and the estimated yield of the wells ranged from 225 to 800 gpm and averaged 520 gpm. Although the average well yield is 520 gpm, Liles (1960, p. 14), in his study of irrigation leases in Caddo County, found that the actual yield of wells was approximately 80 percent of the irrigators' estimate. Using the same percentage in this report, the average well yield is estimated to be 420 gpm or 604,800 gpd (gallons per day).

If the preceding average figures are applied to the estimates of the 340 irrigators in Caddo County during 1956, total pumpage in the irrigated area is computed to be about 34,000 acre-feet, which compares reasonably well with the 38,700

acre-feet obtained for 1956 by the crop water-requirement method (table 6).

Public-supply use. — Thirteen towns and cities in the Caddo County area have municipal water wells, storage reservoirs, and distribution systems. Municipal wells generally are cased with 8-inch or larger steel pipe and are equipped with electrically driven turbine pumps. Annual municipal use of water totals about 2,800 acre-feet—from the Rush Springs Sandstone about 1,700 acre-feet, and from all other groundwater sources about 1,100 acre-feet (table 7).

Industrial use. — Large industrial water supplies are used by the oil refinery in Cyril, which pumps more than 700 acre-feet of water annually from the Duncan Sandstone, and the Western Farmers Electric Cooperative in Anadarko, which pumps more than 1,100 acre-feet of water annually from the alluvium of the Washita River. The smaller business establishments and industries in the area obtain their water from municipal supplies. The total self-supplied industrial use is about 1,800 acre-feet per year.

Rural use. — Most water for domestic and stock use in the area is obtained from small-diameter wells equipped with pumps which are operated by electricity, by windmill, or by hand. The yields of these wells generally are less than 5 gpm. On the basis of the estimated rural population, probably about 2,000 acre-feet is pumped annually from domestic and stock wells.

Summary. — The following table summarizes the pumpage in the Caddo County area by use of the water. Irrigation pumpage is based on the average of 1956 to 1959. Other pumpage is based on estimates for 1960.

USE	PUMPAGE (ACRE-FT)
Irrigation	24,000
Public supply	2,800
Industrial	1,800
Rural	2,000
TOTAL	30,600

FLUCTUATIONS OF WATER LEVELS

Fluctuations of water levels, except those caused by atmospheric pressure changes, are caused by imbalances in the recharge-discharge relationship of an aquifer. The water level rises in response to an increase in storage resulting from recharge by rainfall, seepage from surface-water bodies, or underflow from adjacent areas which exceeds discharge. Discharge by evaporation, transpiration by plants, pumping from wells, seepage into surface streams, and underflow into adjacent areas causes depletion of ground-water storage and a decline of water levels when it exceeds recharge.

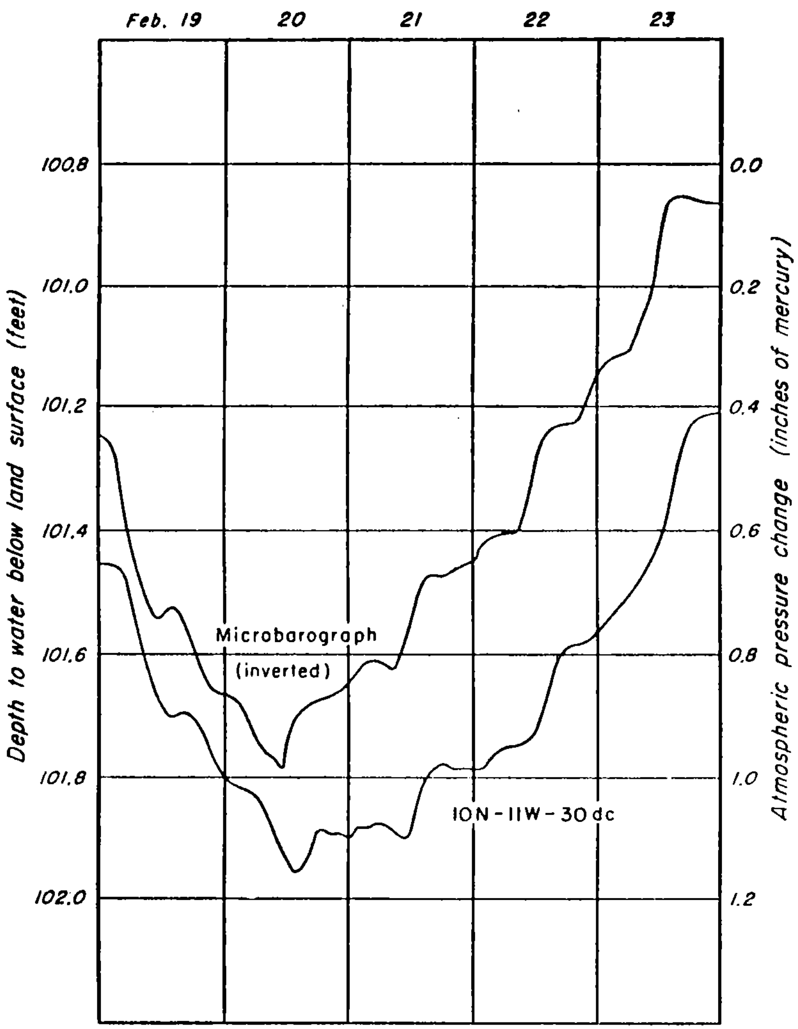

Figure 6. Water-level fluctuations in well 10N-11W-30dc1 caused by changes in atmospheric pressure during February 1956.

Fluctuations due to changes in atmospheric pressure may occur in artesian or water-table wells if the pressure changes that immediately affect the water surface in wells are retarded or diminished before reaching the water in the formation. The water level in such a well will rise when the atmospheric pressure falls and will decline when the pressure rises (fig. 6). These fluctuations represent no changes in ground-water storage. The Rush Springs Sandstone is considered a water-table aquifer because it is not confined by an overlying impermeable formation. However, water levels in wells fluctuate as a result of atmospheric-pressure changes throughout the general area of study because of the very fine-grained composition of the aquifer.

Hydrographs of the water levels in four wells are shown on figure 7. Wells 12N-14W-31bb1, 10N-14W-35dd1, 9N-14W-5da1, and 9N-13W-28dd2 are in areas where withdrawals of ground water for irrigation are small. The hydrographs indicate that the amount of ground water in storage at those points is relatively unchanged during the irrigation season (June through September).

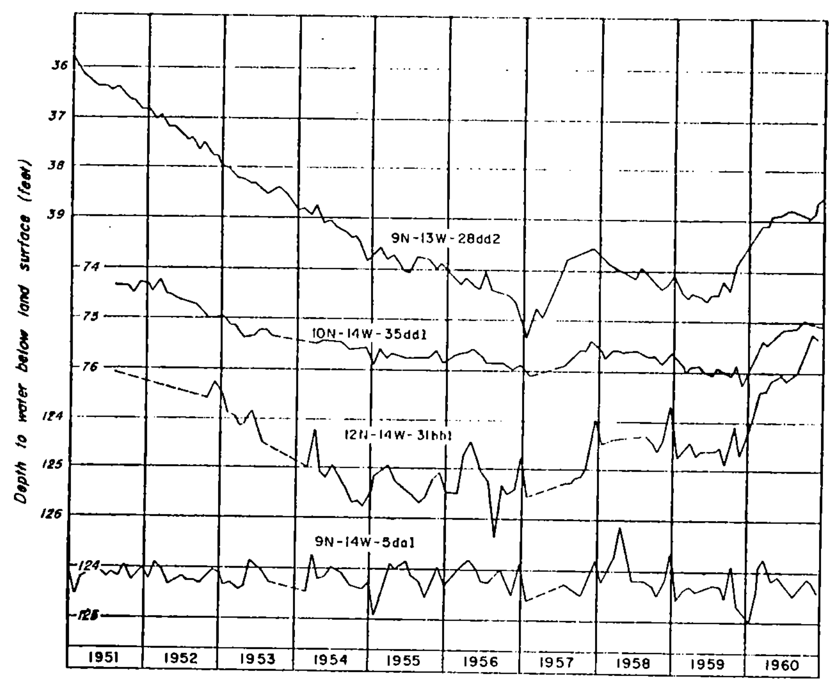

Figure 7. Hydrographs of four wells in Caddo, Washita, and Custer Counties.

Ground-water levels near heavily irrigated areas show a pattern of fluctuation that follows definite seasonal water demands and reflects the discharge from pumping. Water levels in well 10N-12W-23bb2 (fig. 8), which is in a heavily irrigated area and 1,080 feet from an irrigation well, show the result of large withdrawals of ground water for irrigation between June and September each year, the usual period of intensive irrigation. The hydrograph of this well shows an accelerated decline of water level beginning in July or August each year.

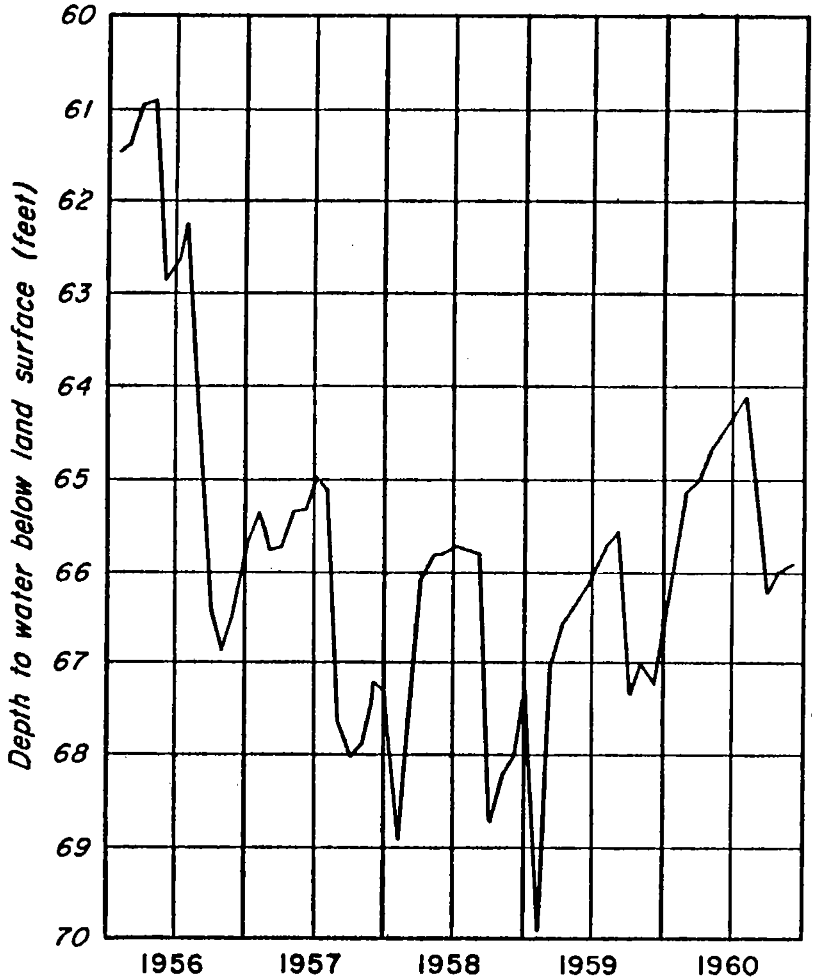

Figure 8. Hydrograph of well 10N-12W-23bb2 showing the effect of pumping on water-level fluctuations.

The water level reaches its lowest point between October and February, after which it usually begins to recover as irrigation pumping stops. Figure 9 is a hydrograph of the same well, scaled in days to illustrate the fluctuation of the water level during intermittent periods of pumping.

During periods of normal precipitation in areas not affected by pumping, the average annual recharge is about equal to discharge, and little or no change occurs in ground-water storage. During periods of above- or below-normal precipitation the hydrographs of the same wells show an increase or decrease in ground-water storage indicated by a rise or decline in water levels. Wells 9N-13W-28dd2, 10N-14W-35dd1, and 12N-14W-31bb1 in figure 7 show declines in water levels ranging from 1.7 to 5.5 feet from 1951 through 1956. Precipitation during this same interval averaged about 6 inches below the normal 28.10 inches. From 1957 through 1960 precipitation averaged about 5 inches above normal and the same wells showed rises

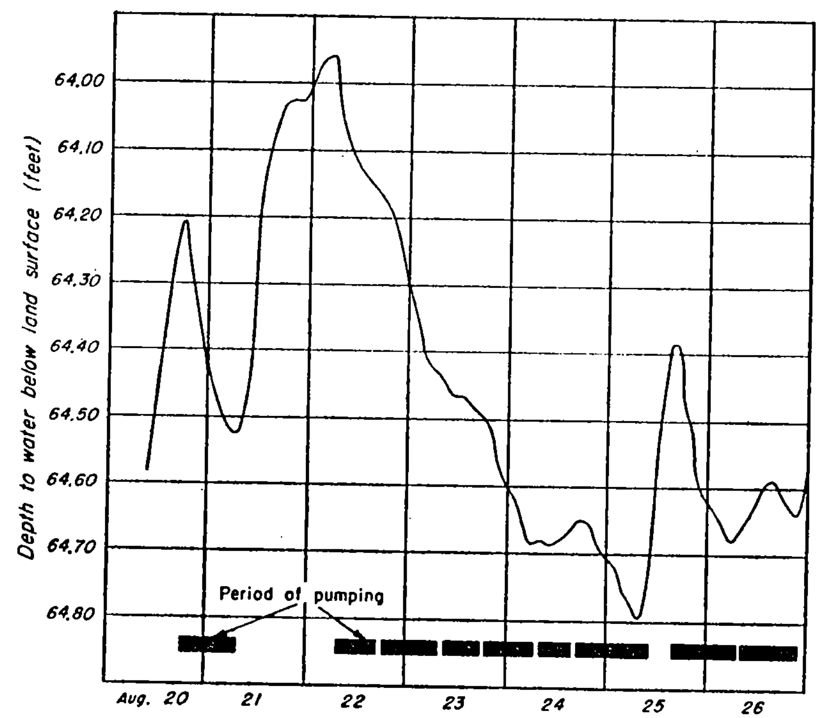

Figure 9. Hydrograph of well 10N-12W-23bb2 showing the effect of intermittent pumping on water-level fluctuations.

in water levels ranging from 1 to 3 feet. A close correlation is indicated between fluctuations in ground-water levels and departures from normal precipitation.

Water-level fluctuations, except those caused by changes in atmospheric pressure, are a measure of changes in ground-water storage. The volume of water involved in this change can be determined by multiplying the total volume of material in the zone of fluctuation by the specific yield of the aquifer. The change in storage can be observed for any selected period by superposing a water-level contour map for the beginning upon one for the end of the period under consideration, and constructing therefrom a new contour map showing the net change in ground-water storage. The total volume of material that has been dewatered or saturated is determined by meas-

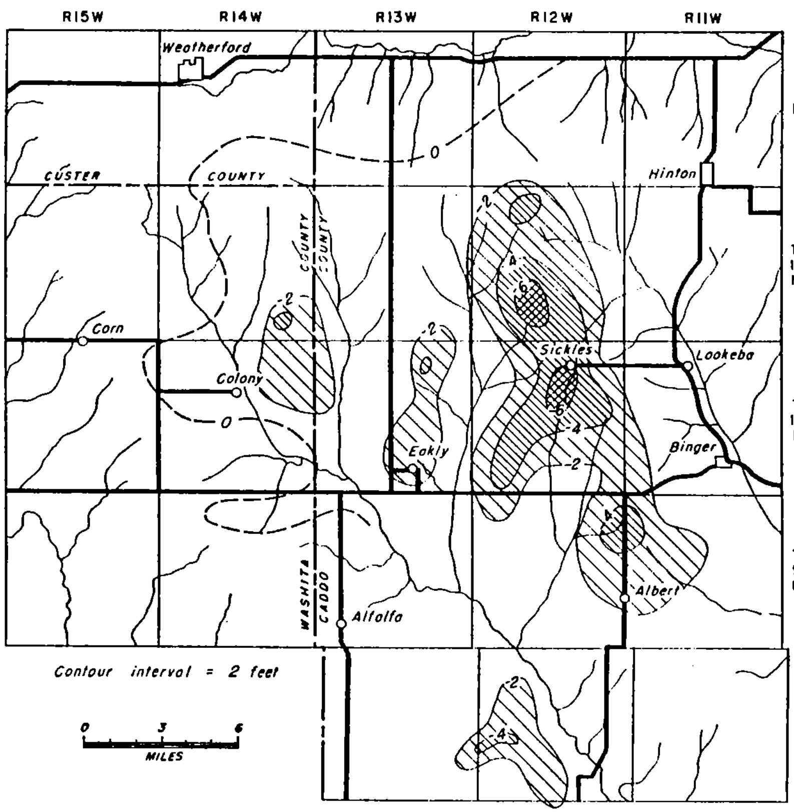

Figure 10. Map of Caddo County area showing lines of equal change in water level from June 1956 to April 1959.

uring the areas of the net-change contours and multiplying by the contour interval and specific yield of the aquifer. Figure 10 shows the net change in water level for the main irrigated area of this report. The decrease in ground-water storage from June 1956 to April 1959 is equivalent to about 20,000 acre-feet of water, and the area of decline corresponds closely with the area of concentrated pumping for irrigation.

Chemical Quality

The analyses of 54 water samples collected from five geologic sources in the area during 1945-1957 are shown in table 8. Included are 6 samples from the alluvium, 3 from the terrace deposits, 42 from the Rush Springs Sandstone, 1 from the Marlow Formation, and 2 from the Duncan Sandstone.

RECENT ALLUVIUM

The water in the alluvium is hard, high in mineral content, and in most places has a "gyppy" taste. The hardness of water, as measured by concentration of calcium and magnesium, ranges from 478 to 4,940 ppm and averages about 2,300 ppm. The quantity of dissolved solids is determined as the residue on evaporation at 180°C of a given quantity of water. It ranges from 772 to 7,960 ppm and averages about 4,100 ppm. Sulfate, which is dissolved as water moves through gypsum or other sulfate rocks, ranges from 336 to 5,130 ppm and averages 2,254 ppm.

TERRACE DEPOSITS

The three samples collected from wells in the terrace deposits indicate that the water is not so hard as and is lower in dissolved solids and sulfate content than the water in the alluvium. Hardness ranges from 282 to 568 ppm and averages 396 ppm, dissolved-solids content ranges from 390 to 766 ppm and averages 529 ppm, and sulfate content ranges from 80 to 231 ppm and averages 130 ppm.

RUSH SPRINGS SANDSTONE

The chemical analyses of the 42 samples of water collected from wells and springs in the Rush Springs Sandstone indicate

TABLE 8.—CHEMICAL ANALYSES OF GROUND WATER IN THE CADDO COUNTY AREA

(Analyses by U. S. Geological Survey. Results in parts per million except as indicated)

Aquifer: A, alluvium; D, Duncan Sandstone; M, Marlow Formation; R, Rush Springs Sandstone; T, terrace deposit.

Location and Well No.	Depth of well (feet)	Aquifer	Date of Collection	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na) + Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved Solids *	Hardness as $CaCO_3$: Calcium Magnesium	Hardness as $CaCO_3$: Noncarbonate	Sodium adsorption ratio	Specific Conductance (Micromhos at 25° C)	pH
5N- 9W- 3dd1	200	R	8-16-56	22	62	5.2	4	122	0	28	28	0.0	20	236	180	80	0.1	388	7.7
- 3aa1[a]		R	8- 3-51	22	385	80	396	264	0	201	1,160	1.0	65	3,160	1,290	1,070	4.8	4,290	7.1
-18cc1[b]	1,010	D	8-16-56	18	87	41	183	236	0	504	44	.4	.7	1,000	384	190	4.1	1,420	7.9
-35dd1	300	R	8-12-48		54	12	39	212	0	41	20		30	310	184	10	1.3	490	
5N-10W- 1da1	140	R	8-23-51	22	92	17	15	272	0	78	11	.3	15	407	300	76	.4	610	8.1
- 1da2	170	R	8-16-56	24	100	12	16	274	0	7	37	.0	50	399	298	74	.4	640	7.3
- 2ba1[c]	175	R	12-11-46	16	141	33	12	258	0	261	15	.0	7.2	646	488		1.7	890	7.3
7N-10W-10bb1	80	R	3-23-48		605	83	28	159	0	1,690	14	.4	2.0	2,700	1,850	1,720	.3	2,630	
-13dd1	40	A	3-23-48		430	822	281	273	25	4,300	225	.7	3.0	6,530	4,450	4,190	1.8	6,210	
-15db1		T		23	124	53	36	400	0	231	26	.5	50	766	568	240	.6	1,100	7.5
-21dd1	40	T	3-23-48		80	20	28	173	20	60	13	.2	20	432	282	107	.8	659	
-23ab1	45	T	3-23-48		84	31	2	22	34	80	5	.6	14	390	337	100	.1	532	
-27aa1	106	A	3-23-48		460	922	376	282	10	5,130	115	.6	1.0	7,960	4,940	4,650	2.3	6,990	
-27dc1		A	4-23-48		535	129	28	218	0	1,630	34	1.0	.2	2,800	1,870	1,690	.3	2,750	
-27dc2		A	4-23-48		578	35	72	96	0	1,590	16	.2	1.0	2,600	1,590	1,510	.3	2,470	
7N-11W-30		R	8-22-49		246	6.6	39	216	0	476	8	.3	50	966	64	464	.7	1,200	
7N-12W- 2cc1		R	2- 7-57		37	7.7	16	132		10	3		50	186	124	16	.5	310	7.7
- 2dd1		R	8-23-51	24	74	3.5	14	189	0	79	7	.3	7.0	318	220	64	.4	477	7.5
- 5bb1	.32	R	3-17-48		12	4.4	38	107	0	16	6		20	174	48	0	2.3	237	
-11cd1	17	A	7-18-47		132	36	55	182	0	336	55	.0	7.0	772	478	328		106	
-34ad1	57	R	3-17-48		21	.2	49	158	0	12	10	.0	4.0	154	54	0	3.0	222	
7N-13W- 3ba1	18	A	7-17-47		206	59	35	294	0	540	105		15		556	516		161	
5N-10W- 4bc1		R	3-23-46		57	51	17	218	0	190	7	.5	.5	555	352			849	
6N-12W- 5bc2	250	R	3-24-48		24	12	2	99	0	10	14	.0	4.0	192	109	0	1.0	296	
-11ab1	200	R	6-18-45		66	9.2	8	236	0	7	15				203				7.7
-12bc1		R	12- 5-45		35	15		216	0	15	11								7.1
-13cc1	120	R	12- 5-45		36	15		215	0	12	11								7.2
-14	200	R	12- 5-45		36	12		418	0	32	11		.0						7.5
6N-13W- 1ab1	40	R	3-17-48		27	13	29	110	0	16	11	.0	75	273	121	31	1.1	393	
- 1cc1	250	R	11- 8-49		448	45	29		0	1,270	26		.0	2,020	1,310	1,310	.3	2,110	
9N-10W- 4dd1	57	R	3-23-48		40	19	25	196	10	23	10	.2	20	287	170	1	.8	515	
-16ab1	85	R	3-23-48		65	27	32	250	13	0	6	.2	90	343	276	25	.9	626	
9N-11W-36ca1	67	D	3-23-48		182	72	28	168	0	547	50	.7	40	1,220	750	612	.4	1,600	
9N-12W- 1aa1	80	R	3-18-48		17	7.5	16	72	0	12	12	.2	25	144	74	15	.3	204	
-12aa1	90	R	3-18-48		47	13	16	206	12	[illegible]	[illegible]	.4	15	202	191	2	.5	339	
-19dd1	62	R	3-17-46		20	10	13	99	0	10	11	.0	10	145	91	10	.5	217	
-24dd1	120	R	3-24-48		36	16	103	316	0	21	4	.0	50	448	157	0	3.3	742	

a 0.10 ppm iron.
b 0.01 ppm iron.
c 0.02 ppm iron.

TABLE 8.—Continued

Aquifer: R, Rush Springs Sandstone; M, Marlow Formation.

Location and Well No.	Depth of well (feet)	Aquifer	Date of Collection	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na) + Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved Solids *	Hardness as $CaCO_3$: Calcium Magnesium	Hardness as $CaCO_3$: Noncarbonate	Sodium adsorption ratio	Specific Conductance (Micromhos at 25° C)	pH
9N-13W- 3ba1		R	3-24-48		47	8.7	47	239	0	12	9	.4	40	296	153	0	1.6	455	
-28dd2	335	R	3-16-48		54	13	15	168	0	20	9		40	282	182	34	.5	407	
10N- 9W-24ba1	29	M	3-17-48		92	19	14	370		4	21	.4	.0	423	308	4	.4	724	
10N-11W- 5da1		R	3-24-48		12	7.3	8	75		10	3	.4	.0	73	60	0	.4	149	
-32cc1	225	R	5-23-56		47	9.4	14	210	0	4	8		1.3	220	156	0	.5	356	7.0
-33ba1		R	5-24-56		53	2.9	21	170	0	38	6		6.5	270	144	4	.8	414	8.0
10N-12W-23bb1[b]	288	R	4-13-55	30	48	7.3	11	185	0	13	5	.0	1.2	204	150	0	.4	325	7.4
-31dd1	67	R	3-19-48		57	19	21	260	0	15	25	.1	1.0	280	221	7	.5	477	
10N-13W- 4ad1		R	3-17-48		37	5.2	16	145	0	8	14	.0	3.0	156	114	0	.7	268	
11N-11W- 3ba1[d]		R	3-23-48		59	13	31	349	11	8	14	.2	3.0	292	200	0	.6	455	
-22ad1[d]		R	8-29-47		48	13	20	172	10	11	16		[illegible]	244	173	16	.6	383	
-22cc1	280	R	4- 5-49		64	18	16	304	0	6	7		4.5	286	234	0	.4	489	
11N-12W- 3bb1	110	R	3-19-48		73	9.2	22	210	18	6	14	.0	50	290	220	179		465	
12N-11W-31cb1	155	R	3-19-48		45	9.0	59	283	0	4	12	.3	.6	252	149	0	1.8	447	
-34bc2	225	R	8-29-47					240		17	35		30					580	
12N-13W- 4bb1	150	R	9-26-51	24	54	13	26	256	0	9	8	.0	1.9	259	188	0	.8	476	7.6
-33aa1	80	R	3-18-48		70	6.0	39	325	0	6	11	.0	8.0	339	200	0	1.2	554	

[b] 0.01 ppm iron.
[d] Spring.

that, except for samples from three wells, the quality of water generally is suitable for irrigation and domestic use. Water from wells 7N-10W-10bb1 and 8N-13W-1cc1 is a calcium sulfate type, highly mineralized, and extremely hard. The poor quality of this water is the result of solution of gypsum from the Marlow Formation in the first well and from the Cloud Chief Formation in the second well. The water from well 5N-9W-3aa1 contains 1,160 ppm chloride and probably was contaminated by surface seepage as a result of ponding of oil-field brine nearby.

The following concentrations of selected chemical constituents of water in the Rush Springs Sandstone do not apply to samples from the three wells mentioned and probably are more representative of the quality of water in the formation. Hardness ranges from 48 to 488 ppm and averages 179 ppm; dissolved solids ranges from 79 to 1,220 ppm and averages 260 ppm; sulfate ranges from 4.1 to 476 ppm and averages 45 ppm; and chloride ranges from 3.2 to 49 ppm and averages 14 ppm.

MARLOW FORMATION

Although the one sample of water from the Marlow Formation from well 10N-9W-24ba1 shows a close similarity to water from the Rush Springs Sandstone, it probably is not typical of most of the water in the Marlow. In the southern and eastern parts of the report area, the Marlow Formation generally contains much disseminated gypsum, and as a result the water is harder and has higher sulfate and dissolved-solids concentrations than does water in the Rush Springs Sandstone.

DUNCAN SANDSTONE

The two samples of water from the Duncan Sandstone indicate that the water is high in dissolved solids and relatively high in sulfate. The hardness is 384 and 750 ppm; dissolved solids, 1,000 and 1,220 ppm; and sulfate, 504 and 547 ppm, respectively. The concentrations of dissolved solids and sulfates in these two samples exceed the maximum limits recommended by the U. S. Public Health Service for drinking water.

TABLE 9.—SUMMARY OF WATER QUALITY IN THE RUSH SPRINGS SANDSTONE COMPARED WITH STANDARDS OF THE U. S. PUBLIC HEALTH SERVICE AND THE STATE DEPARTMENT OF HEALTH

CONSTITUENT (PPM)	MAXIMUM ALLOWABLE (PPM)	CONTENT OF SAMPLES FROM RUSH SPRINGS SANDSTONE (PPM) MAXIMUM	MINIMUM	AVERAGE	NUMBER OF SAMPLES	NUMBER OF SAMPLES EXCEEDING STANDARD
Iron	0.3	.10	.0	.03	5	0
Nitrate	44	90	0	20.3	37	8
Magnesium	125	83	.3	17.0	41	0
Sulfate	250	1,690	4	112	42	3
Chloride	250	1,160	3	41	42	1
Fluoride	1.5	.6	.0	.15	27	0
Dissolved solids	500[1]	3,160	79	487	37	6

[1] 1,000 permitted.

SUITABILITY FOR DOMESTIC AND INDUSTRIAL USES

Water having hardness in the range of 1 to 60 ppm is considered soft. It is satisfactory for all domestic and most industrial uses. Hardness in the range 61 to 120 ppm may be considered moderately hard. Water in this range generally is satisfactory for domestic use, but may be objectionable for some industrial use. Hardness in the range 121 to 180 ppm may be considered hard. Near the upper limit, softening of the water may be desirable for domestic and many industrial uses. Water having a hardness greater than 180 ppm is considered to be very hard. Such waters are objectionable for many domestic and industrial uses and commonly are softened.

Waters having less than 500 ppm of dissolved solids generally are satisfactory for domestic and many industrial uses. Waters with more than 1,000 ppm of dissolved solids are likely to contain enough of certain constituents to make them unsuitable for many domestic and industrial uses.

SUITABILITY FOR DRINKING

The drinking-water standards of the U. S. Public Health Service have had general acceptance as criteria for public and domestic supply. The recommended maximum concentrations of certain chemical constituents are given in table 9. In addition to the Federal standards, the Oklahoma State Department of Health has recommended a maximum concentration of 44 ppm of nitrate for such water. In general, the quality of water in the Rush Springs Sandstone meets the standards set by both Federal and State agencies. Results of the analyses of water in the Rush Springs Sandstone as compared with the standards are summarized in table 9.

SUITABILITY FOR IRRIGATION

The suitability of water for irrigation depends not only on the chemical character of the water but also on the chemical and physical character of the soil, the method and amount of water applied, and the amount and distribution of rainfall. The following paragraphs on this subject have been adapted from Wilcox (1948).

Any method for the interpretation of the analysis of water to be used for irrigation is based on the presumption that the water will be used under average conditions as related to quantity, soil, permeability, drainage, climate, and crops.

All water used for irrigation contains varying quantities of chemicals that are referred to as dissolved salts. If their concentration is not too great, some dissolved salts favor the

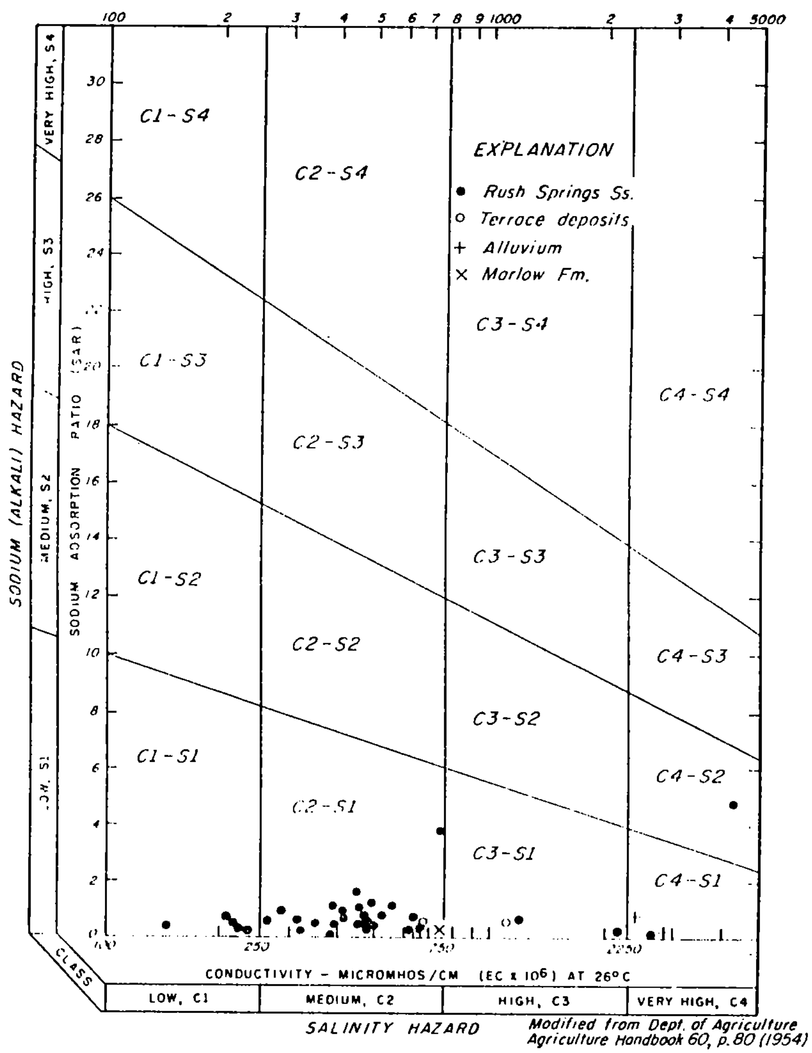

Figure 11. Classification of waters in the Caddo County area for irrigation use.

growth of plants; others are harmful to plant growth and to soils. The concentration of dissolved salts may vary from a few to many thousand parts per million, but in most waters used for irrigation the range is from 100 to 1,500 ppm. The principal constituents of these waters are the cations: calcium, magnesium, and sodium; and the anions: bicarbonate, sulfate, and chloride. Potassium, carbonate, nitrate, silica, and boron normally are present, but only in low concentrations. Small quantities of other substances may be found in some waters, but their effect on the quality of the water for irrigation is not important, and usually they are not considered in an analysis for this purpose.

The diagram in figure 11 can be used to estimate the suitability of a water for irrigation. One method of classifying irrigation waters is based on the sodium-adsorption ratio and the electrical conductivity of water (U. S. Salinity Laboratory Staff, 1954). The sodium-adsorption ratio (SAR) is related to the adsorption of sodium by the soil and is used as an index of the sodium or alkali hazard of the water.

The sodium adsorption ratio is a number derived by dividing the square root of one-half the sum of the concentrations of calcium and magnesium ions into the concentration of sodium ions, all expressed in equivalents per million. The SAR is reported in table 8 for 45 of the samples analyzed.

Electrical conductivity is related to the total concentration of soluble salts in water and is used as an index of the salinity hazard. According to *Agriculture Handbook 60* (U. S. Salinity Laboratory Staff, 1954, p. 79, 81), a low-salinity water (C1) is generally suitable for irrigation under normal irrigation practice; medium-salinity water (C2) can be used if a moderate amount of leaching occurs; high-salinity water (C3) cannot be used on soils with restricted drainage; very high-salinity water (C4) is not suitable for irrigation under ordinary conditions. Low-sodium water (S1) can be used for irrigation on almost all soils if the salinity does not restrict its use. The diagram (fig. 11) indicates that most water in the Caddo County area has a medium-salinity hazard and a low-sodium hazard (Class C2-S1); thus water suitable for irrigating the well-drained, sandy soil is generally found in this area. This is supported by about 10 years of irrigation in the area with no resulting problem of soil salinity.

Construction and Operation of Wells

Most wells in the Caddo County area have been drilled by rotary or cable-tool methods. The large-diameter irrigation and public-supply wells range in depth from 128 to 400 feet and average about 280 feet; they range in diameter from 10 to 20 inches and commonly are cased only in the upper 20 or 30 feet to prevent caving.

Irrigation wells generally are drilled completely through the Rush Springs Sandstone into the upper part of the Marlow Formation. Most irrigation wells are not gravel packed, and as a result they initially pump very fine sand; this causes the development of cavities or channels in the more friable zones of the aquifer. Generally, in this area, the wells that pump the most sand during the initial test are the wells that have the highest ultimate yields.

Most domestic and stock wells in the Caddo County area are equipped with cylinder pumps and are powered by windmills or electric motors, or are operated by hand, although some domestic wells are equipped with jet pumps. The larger irrigation and public-supply wells are commonly equipped with deep-well turbine pumps and are powered by electric motors or internal-combustion engines. Fuel for the latter is some form of liquefied petroleum gas. Most irrigation wells in this area are drilled 150 feet or more below the water table, and minor water-level fluctuations do not seriously affect their yields. Distribution of water for irrigation is almost entirely by sprinkler systems.

Table 10.—Rate of Irrigation-well Installation in the Caddo County Area

Year	Number of wells installed	Cumulative total
Prior to 1951	8	8
1951	4	12
1952	13	25
1953	19	44
1954	77	121
1955	172	293
1956	84	377
1957	108	485
1958	45	530
1959	5	535
1960	2	537

Dates of well construction in this area were obtained from water-rights applications, which are submitted to the Oklahoma Water Resources Board by the well owners before completion of each well. Table 10 shows the number of irrigation wells in the Caddo County area from 1951 through 1960. The greatest number of wells (172) was installed in 1955, and since then the number of installations has decreased to 2 in 1960. Although the decline in the rate of well installation may have resulted from above-normal rainfall between 1957 and 1960, it may be due also to the control legislation on peanuts, which is the principal irrigated crop in this area.

Conclusions

The rapid development of irrigation in the Caddo County area north of the Washita River resulted in local decline of the water table between 1956 and 1959, a period in which the average water level in nonirrigated areas of the Rush Springs Sandstone rose slightly because precipitation was above normal. The greatest decline of the water table (about 6 feet) is around Sickles (fig. 10), where the concentration of irrigation wells is the greatest and local overdevelopment seems to have occurred. A continual decline of the water table by pumping for irrigation in excess of natural recharge may require deepening of some domestic and stock wells or a deeper resetting of pump bowls on irrigation wells to maintain desired yields. Although the saturated thickness of the Rush Springs Sandstone probably is greater than 200 feet over much of the irrigated area, drawdowns of water levels during pumping are large, and a continued decline of the water table eventually will affect well yields and result in increased pumping costs. If drought conditions become prevalent, water-level declines will be accelerated owing to a decrease in the rate of recharge by precipitation and an increase in the rate of discharge by pumpage.

Decline of the water table will eventually reduce the ground-water discharge into the main stream systems of the area by altering the natural recharge-discharge relationship of the aquifer. The amount of ground-water discharge into streams is directly proportional to the hydraulic gradient. Decline of the water table will decrease the hydraulic gradient, and ground-water discharge will be reduced by an amount approximately equal to the consumptive use for irrigation. This change, however, will be gradual because most wells are distant from the principal drainage areas, and the effect of their pumping will be apparent only after a long time.

The Rush Springs Sandstone and the upper part of the Marlow Formation contain a large quantity of ground water in storage. The average annual recharge from precipitation in the project area is estimated to be more than 150,000 acre-feet. Possibilities for large-scale irrigation are slight in much of the area south of the Washita River and east of the Cobb Creek basin, because of the lower permeability or smaller saturated thickness of the aquifer. Within the Cobb Creek basin, further ground-water development is possible, generally, in those areas where irrigation wells are spaced more than half a mile. Moderate irrigation development may be possible south and east of Hinton, for about seven miles along State Highway 37, thence generally south near the drainage divide separating Sugar and Boggy Creeks, to State Highway 52 near sec. 18, T. 10 N., R. 9 W. East of this area the Rush Springs Sandstone thins rapidly. Additional ground-water development is possible, generally, north of T. 8 N. along the western edge of the basin, where the overlying Cloud Chief Formation is relatively thin and the maximum thickness of the underlying Rush Springs Sandstone is available for development. West of the Cobb Creek basin the Rush Springs Sandstone dips beneath and is overlain by a thicker section of the Cloud Chief Formation, and the water in the aquifer may be too highly mineralized to be suitable for domestic or irrigation use.

Although the ground-water supply in the Caddo County area is great and is being replenished continually, the concentration of wells of high yield in a small area can result in local overdevelopment. A program to measure water levels and inventory withdrawals periodically is necessary to insure the safe development and conservation of the ground-water resources. The program should be a continuing one and should be reviewed and revised regularly to provide adequate data on the relation of the ground-water supply to its dvelopment and use.

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