U. S. DEPARTMENT OF INTERIOR
U.S. GEOLOGICAL SURVEY

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In Cooperation with the Oklahoma Water Resources Board
and Oklahoma Geological Survey

Hydrogeology, Water Quality, and Geochemistry of the Rush Springs Aquifer, Western Oklahoma

Water-Resources Investigations Report 98-4081

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Hydrogeology, Water Quality, and Geochemistry of the Rush Springs Aquifer, Western Oklahoma

By Mark F. Becker and Donna L. Runkle

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U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.305	meter (m)
mile (mi)	1.609	kilometer (km)
acre	0.404	hectare (ha)
square mile (mi^2)	2.59	square kilometer (km^2)
gallon (gal)	3.78	liter (L)

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$°F = 1.8(°C) + 32$$

°F map be converted to degree °C by using the following equation:

$$°C = (°F - 32)/1.8$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

The Rush Springs aquifer, in western Oklahoma, is equivalent to the Permian-age Rush Springs Formation. It is composed of very fine-grained to fine-grained sandstone that is massive to highly cross-bedded and is underlain by less-permeable Marlow Formation. Reported irrigation well yields exceed 1,000 gallons per minute; yields reported on 89 drillers' logs ranged from 11 to 850 gallons per minute. Transmissivities range from 670 to 1,870 feet squared per day. Specific yields for core samples range from 0.13 to 0.34. Estimates of hydraulic conductivities at one site ranged from 1.05 to 5.62 feet per day. The Rush Springs aquifer is recharged by infiltration of precipitation, ranging from 0.2 to more than 2 inches per year. Discharge is primarily to streams and rivers where the Rush Springs aquifer crops. Estimated total withdrawal was 54.7 million gallons per day in 1990. Over 42 million gallons per day, or 77.8 percent of water withdrawn, was used for irrigation of crops.

Thirty-five of the 64 wells sampled produced nitrate concentration that equaled or exceeded drinking water standards. Sulfate concentration also exceeds the drinking water standards in some areas. Two major water types occur in the aquifer, a calcium-magnesium bicarbonate type and a calcium sulfate type. Dissolved solids concentrations in water samples from the aquifer ranged from 52 to 1,840 milligrams per liter.

The chemical composition of ground water in the Rush Springs aquifer is the result of chemical reactions between the recharge waters and minerals in the overlying soils and rocks in the Rush Springs and Marlow Formations. Saturation indices of minerals were calculated for 64 water-quality analyses using the geochemical computer model WATEQF. Mass transfer rates were calculated using the mass-balance model NETPATH.

INTRODUCTION

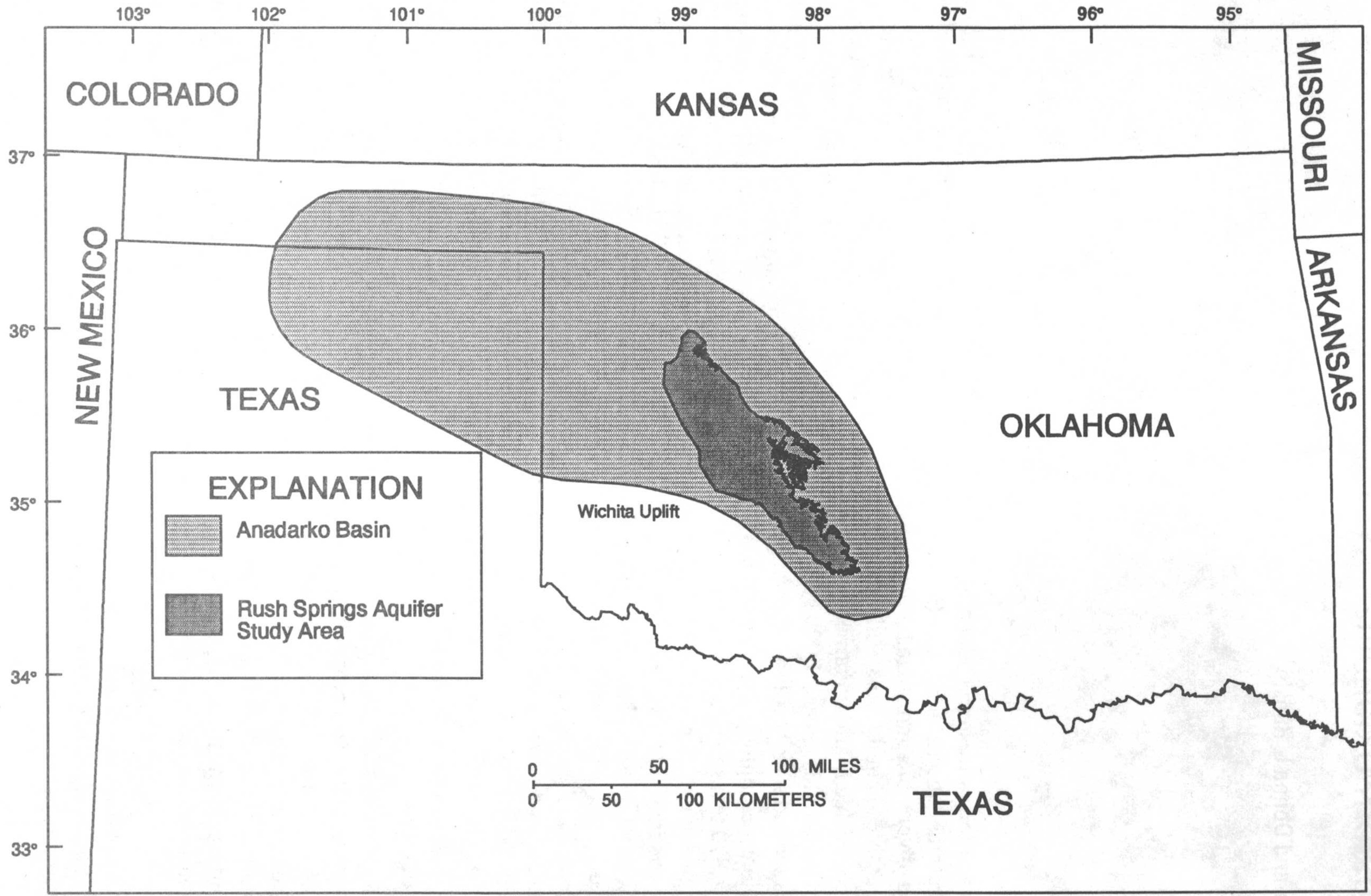
The purpose of this project was to fulfill a legislative mandate for the Oklahoma Water Resources Board (OWRB) to describe the hydrogeology, water quality, and geochemistry and to prepare a numerical model on the ground-water flow of the Rush Springs aquifer in west-central Oklahoma (fig. 1). The Rush Springs aquifer is an important source of water for irrigation, livestock, industrial, municipal, and domestic use. Agriculture is the primary industry in the study area. The Rush Springs aquifer is composed primarily of sandstone and is capable of supporting irrigated agriculture through most of the study area. Soils derived from the Rush Springs Formation are well drained and well-suited for growing crops such as cotton, peanuts, grain sorghum, wheat, alfalfa, and melons.

The study began in 1986 and data collection was completed in 1991. Information provided in this report was collected and compiled through a cooperative project between the Oklahoma Geological Survey (OGS), OWRB, and U.S. Geological Survey (USGS).

Purpose and Scope

The purpose of this report is to describe the hydrogeology, water quality, and geochemistry of the Rush Springs aquifer in western Oklahoma (fig. 1). The hydrogeology is described in terms of the aquifer boundaries, hydrologic properties, recharge, discharge, and water-use. Sources of hydrogeologic data for this report include previously published and unpublished reports, borehole geophysical logs, base-flow discharge measurements of streams, water-level measurements of existing wells, and lithologic descriptions of cores and of surficial exposures of the geologic units.

The sources of water quality and geochemical data are chemical analyses of dissolved ions in water samples taken from wells completed in the Rush Springs aquifer, petrographic descriptions of the rock matrix and cements, and analyses of minerals present in the Rush Springs Formation cores. Water samples were collected by the



(Modified from Johnson, 1989)

Figure 1. Location of the Rush Springs aquifer study area in Oklahoma.

USGS and were analyzed by the OGS laboratory for major and minor inorganic chemical constituents.

The geochemistry of the Rush Springs aquifer is described in terms of water-rock interactions described by Becker (1993). Two geochemical computer models, WATEQF (Plummer, Jones, and Truesdell, 1976) and NETPATH (Plummer, Prestemon, and Parkhurst, 1991), were used by Becker (1993) to simulate the chemical reactions in the Rush Springs aquifer. WATEQF was used to calculate the state of thermodynamic equilibrium of minerals present in the Rush Springs aquifer. A method of flow-path modeling was implemented using existing ground-water analyses and waters representing recharge waters concentrated 15-fold. NETPATH was used to calculate the mass transfer of the geochemical reactants from the time recharge waters enter the aquifer to the point where the sample was taken.

Description of the study area

The study area is located in western Oklahoma and includes most of Caddo and Custer Counties, part of western Grady County, northern Stephens County, northeastern Comanche County, northeastern Kiowa County, eastern Washita County, southern Dewey County, and southwestern Blaine and Canadian Counties (fig. 2). The study area of approximately 2,400 square miles is bounded by the erosional extent of the aquifer to the south and the east, and by the Canadian River to the north. The western boundary is the Washita River, north to Dry Creek tributary of Barnitz Creek where Dry Creek nearly intersects the Canadian River to the north.

Gould (1905), and Fenneman (1938) have described the physiography of the study area as the gypsum hills region west of the Red Bed Plains physiographic province. The gypsum hills are characterized by resistant beds composed of sandstone, dolomite, limestone, and gypsum interbedded with less competent material such as silt and clay. These interbeds of resistant and erodible material create topographic features such as escarpments and level plains. The discontinuous gypsum beds form a caprock that, where present, results in small cuestas, pronounced ledges overlooking river valleys, and small steep-sided canyons incising the Rush Springs aquifer with 150 feet or more of relief.

Most of the study area lies within the Washita River drainage basin. A small area near the northern boundary of the study area lies within the Canadian River drainage basin and a small section in the southern portion of the study area lies in the Red River drainage basin. Principal tributaries of the Washita River within the study area include the Little Washita River, Cobb Creek, and Sugar Creek (fig. 2). These are perennial streams whose flow is maintained by discharge from the Rush Springs aquifer (Tanaka and Davis, 1963). The principal tributary of the Canadian River in the study area is Deer Creek, a perennial stream that receives discharge from the Rush Springs aquifer.

The primary land use in the study area is agriculture, and the principal crops grown are cotton, peanuts, grain sorghum, wheat, oats, corn, alfalfa, and watermelons (Oklahoma Department of Agriculture, 1996). Where soils are thin and slopes are too steep to allow cultivation, the land is used for pasture. Resources in the area include oil, gas, gypsum, and limestone. Local gypsum deposits are mined for use as road ballast, soil conditioner for agricultural use, and plasterboard. The Rush Spring Formation in southeast Caddo County is diagenetically altered and is locally quarried as a lime aggregate.

The average annual precipitation in the study area, based upon records from 1954 to 1983 (Hays Haug, 1985), ranges from 26 inches to greater than 32.5 inches (fig. 3). Most of the study area falls within climatic divisions 4 and 7. Precipitation in southwestern Oklahoma from 1950 to 1995 was greatest during the study (fig. 4) based upon average annual precipitation of climatic divisions 4 and 7. The average annual precipitation from 1950 through 1995 for division 4 was 27 inches and for division 7 was 27.5 inches. From 1985 through 1995 the average annual precipitation for division 4 was 31.3 inches and for division 7 was 33.7 inches (Howard Johnson, Oklahoma Climatological Survey, oral commun., 1997). The wettest month is May, with an average monthly rainfall of more than 5 inches. The minimum mean monthly precipitation is in January and is less than 1 inch. Over 80 percent of the annual precipitation falls from March through October. Most rainfall is localized and intense, resulting in rapid runoff and local flash floods (Tanaka and Davis, 1963). Small amounts of snow are received in January and February, remaining for only brief periods of time.

Maximum mean yearly temperature at Marlow is 73.8°F and the minimum mean yearly temperature is 49.7°F (Hays Haug, 1985). The highest temperatures are in July when the daily maximum mean temperature is 94.1°F. The lowest temperatures are in January with a daily minimum mean temperature of 26.9°F. The winds are predominantly from the south, except during the winter and early spring when winds alternate from the north and the south.

HYDROGEOLOGY

Geology

The term "Rush Springs aquifer" is used in this report to focus on the hydrogeologic properties of the Rush Springs Formation. The Rush Springs aquifer is

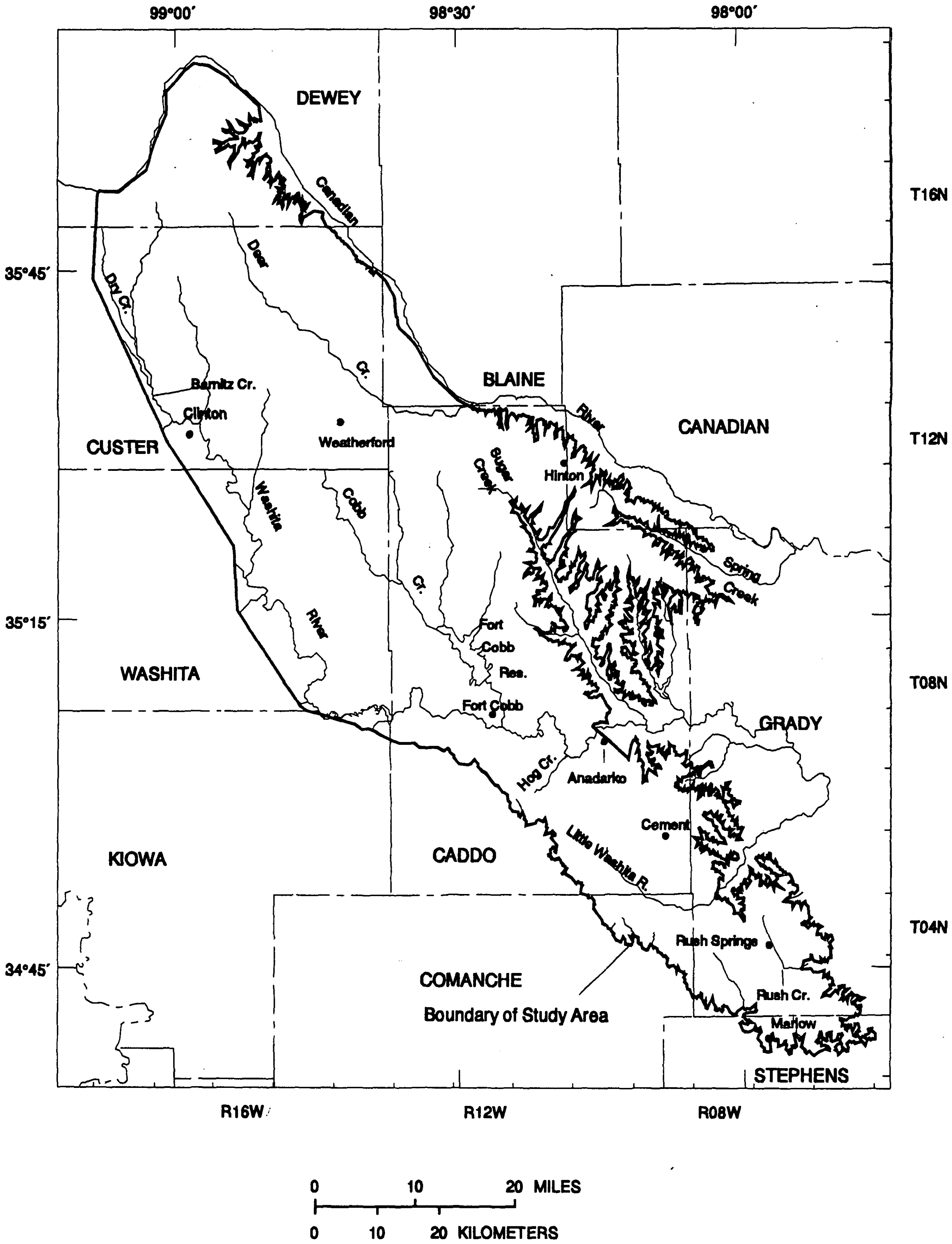


Figure 2. Geographic features within the study area.

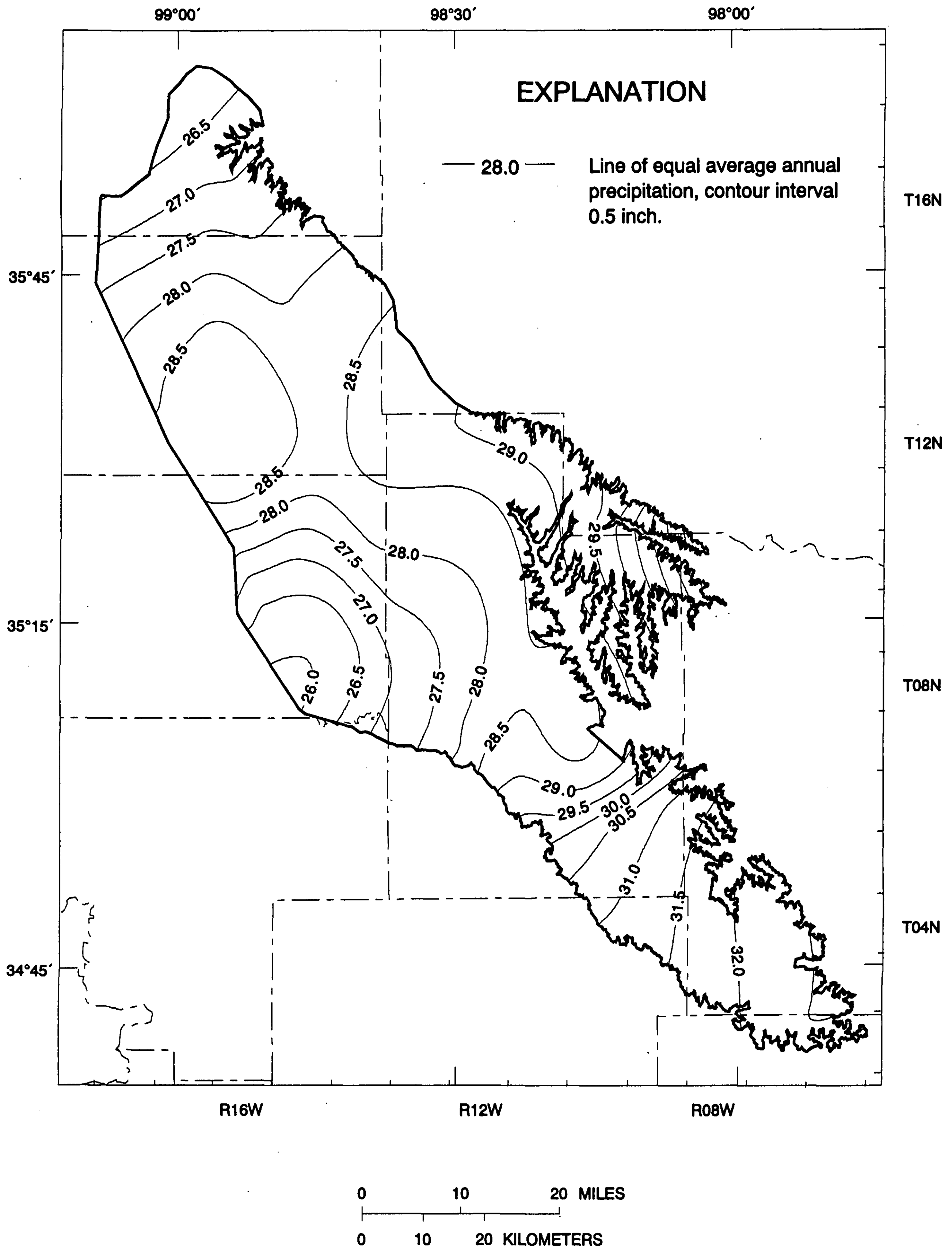


Figure 3. Average annual precipitation in inches for the study area based on a 30-year mean from 1954 to 1983.

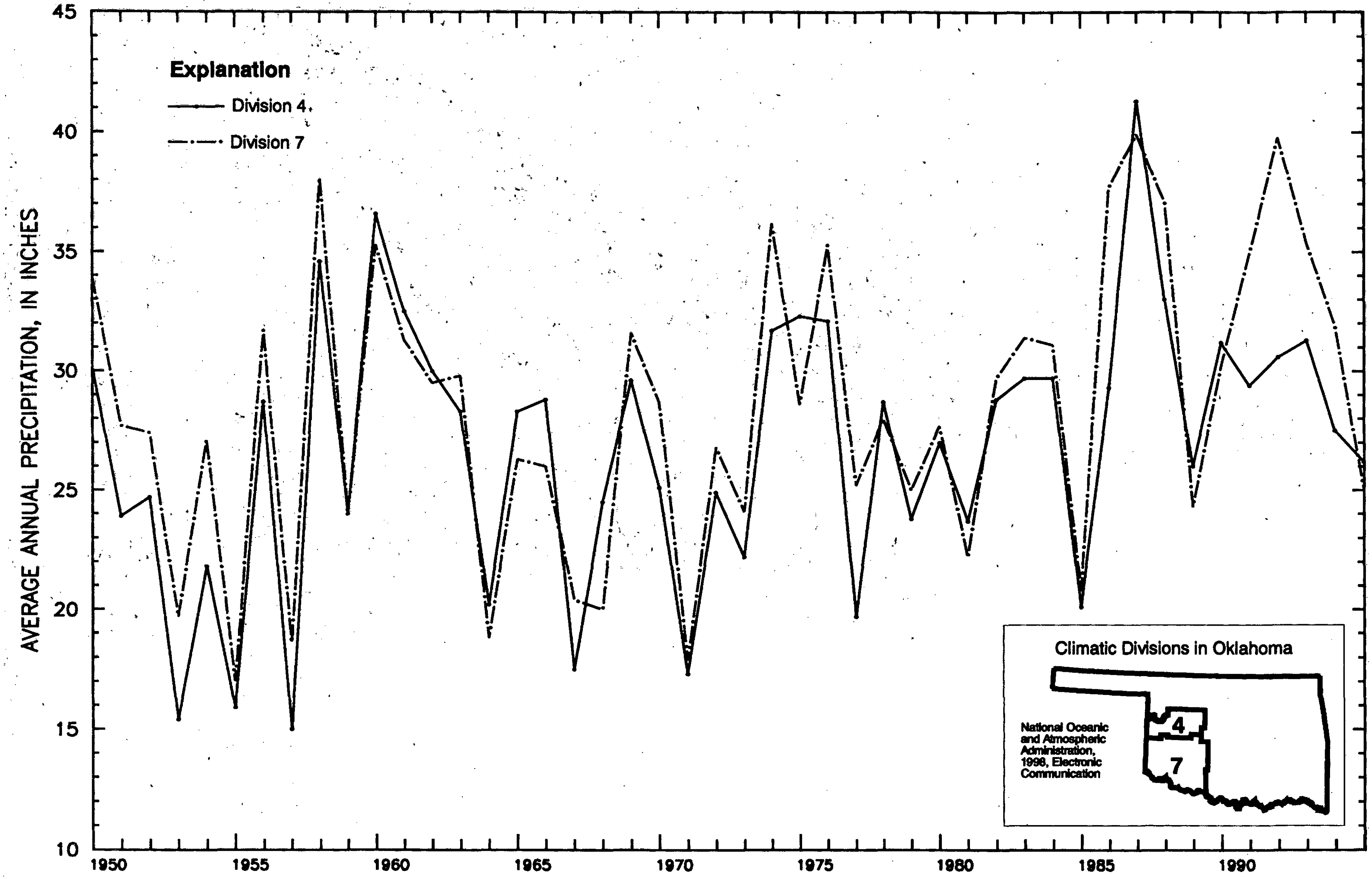


Figure 4. Average annual precipitation in climatic divisions 4 and 7 in southwestern Oklahoma showing precipitation trends over the Rush Springs study area.

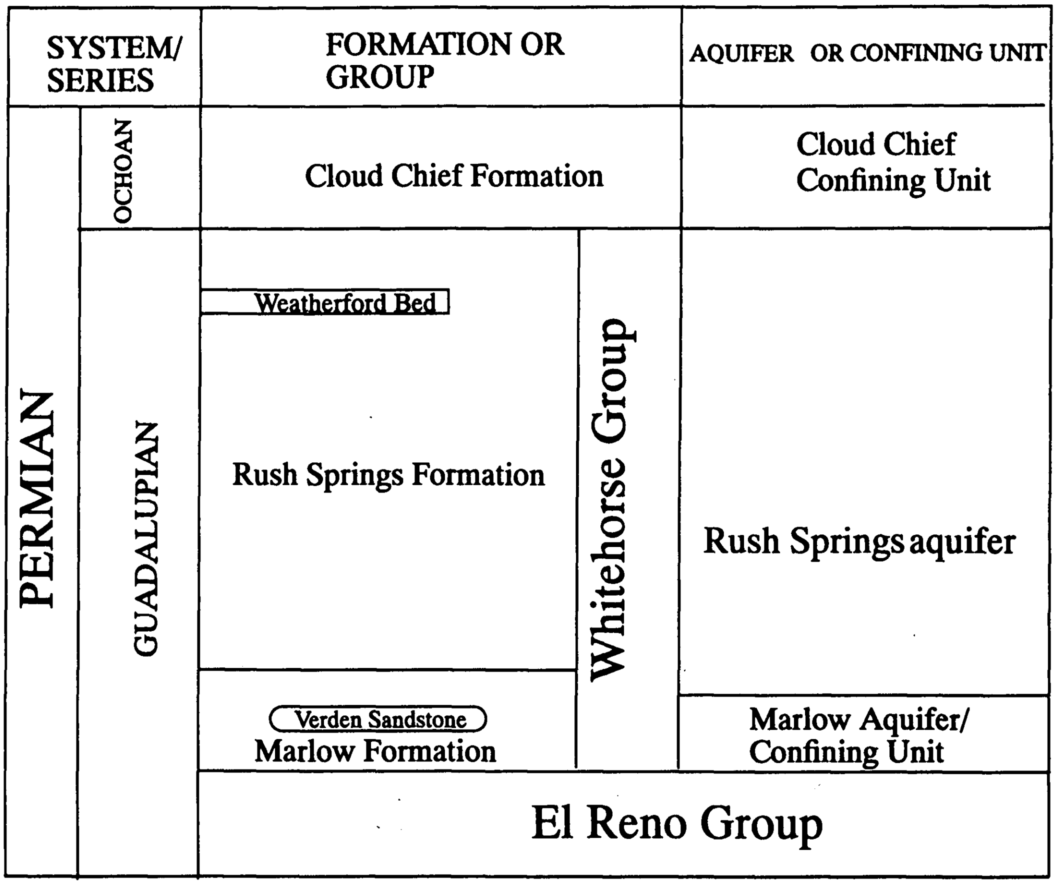


Figure 5. Stratigraphic section associated with the Rush Springs aquifer and adjoining geologic units.

equivalent to the Rush Springs Formation[1], which is part of the Whitehorse Group (fig. 5). Due to the absence of fossils within the Whitehorse Group, the exact age of the Rush Springs Formation and underlying Marlow Formation has been controversial. It is now recognized that the Whitehorse Group is of late Permian, Guadelupian age (Fay and Hart, 1978).

The study area is within the southeastern Anadarko basin, which extends from south-central Oklahoma and west-northwest into Texas (fig. 1). The regional dip of the Rush Springs on the northeastern side of the study area is approximately 20 feet per mile to the south-southwest. Along the southern boundary of the study area, the Rush Springs dips more steeply 50 to 100 feet per mile to the north-northeast.

The map of elevations of the base of the aquifer (fig. 6) was developed with elevations derived from geophysical well logs, cores, and elevations of the Rush Springs Formation-Marlow Formation contact from 1:250,000 surficial geology maps. Wells used for water-level measurements did not contain sufficient information to establish the elevation of the Rush Springs Formation-Marlow Formation contact. The contact can be gradational and difficult to establish with geophysical well logs; however, these tended to have the greatest amount of accuracy since land-surface elevations were precisely surveyed. Most water-well logs and land-surface elevations are determined from 1:24,000 topographic maps and have 5 to 10 feet of error in the study area.

Where the entire section is present, the Rush Springs Formation is more than 300 feet thick. However, it is truncated in most areas and is generally less than 250 feet thick through the central part of the study area. The Rush Springs Formation is a massive to highly cross-bedded sandstone with some interbedded dolomite or gypsum. MacLachlan (1967) and Ham, Merritt, and Frederickson (1957) describe the depositional environment as a nearshore marine environment with associated eolian deposits. The presence of authigenic feldspar in the Rush

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[1] Geologic names and stratigraphic ages in this report are accepted by the Oklahoma Geological Survey and not necessarily the same as those used by the U.S. Geological Survey.

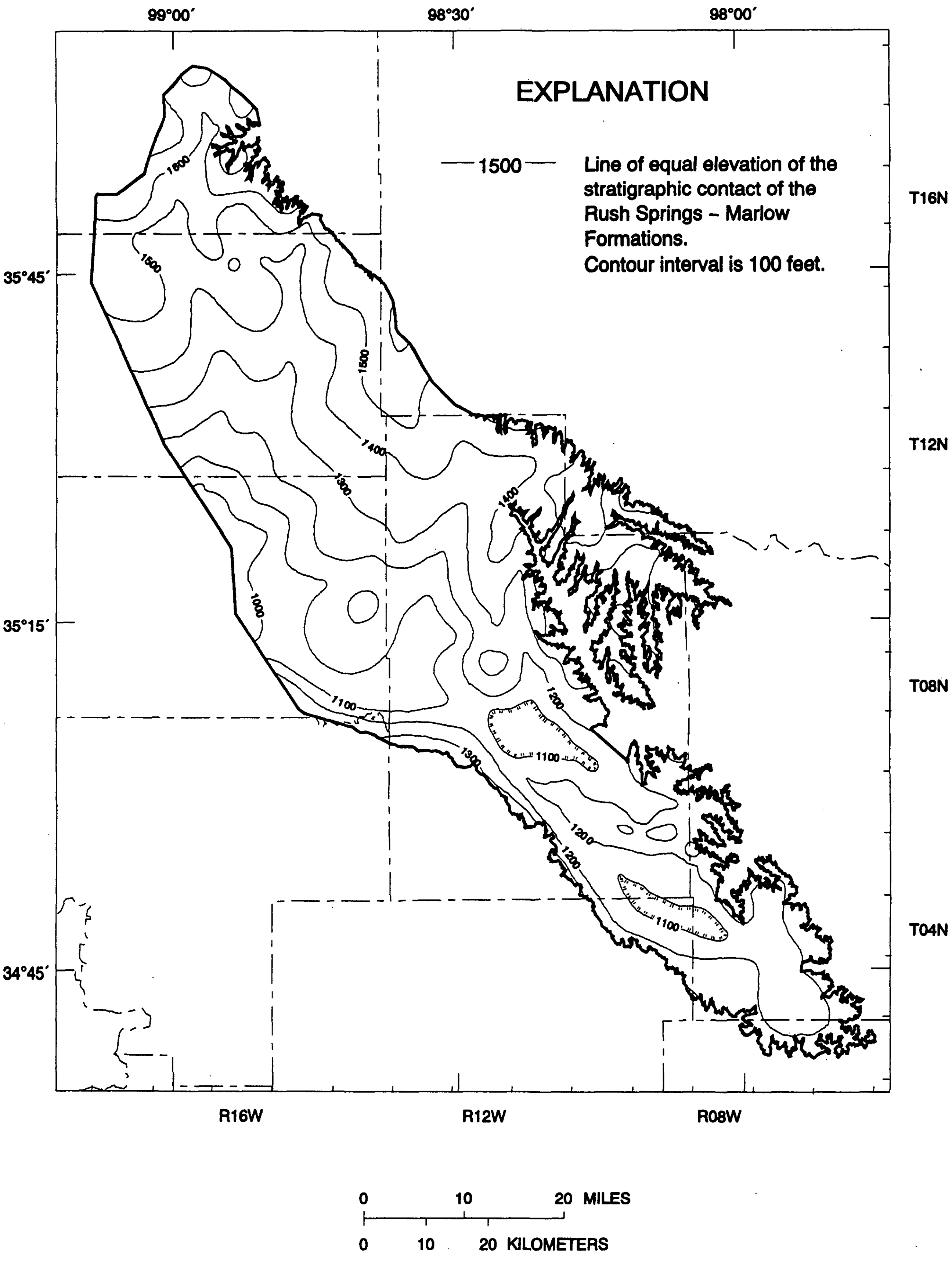


Figure 6. Elevation of the base of the Rush Springs Formation.

Springs Formation suggests occasional marine transgressions (MacLachlan, 1967). Davis (1955) concluded, based upon the textural maturity of the sand and the dip of the forset beds in Grady County, that the Rush Springs was deposited in a shallow marine bay with a distant source of sediment located northwest of the current structural setting. Field observations of high-angle cross-bedded sandstone suggest that drifted sand may have covered much of the study area at various times. The dolomite and gypsum of the Weatherford bed have the horizontal bedding and contain recrystallized nodules characteristic of a closed basin and hypersaline conditions (R.N. Donovan, Texas Tech University, oral commun., 1991).

Observations of cores and outcrops within the study area indicate that the Rush Springs Formation is generally a homogeneous sandstone through most of the study area with variable amounts and types of cementation. Cements in the Rush Springs are either calcite or gypsum, with most of the cementation occurring in the upper and lower parts of the section. Cores of the Rush Springs within the study area are primarily composed of very fine to fine-grained quartz grains that tend to be subround to subangular, moderately to poorly sorted, and frosted (Davis,1955; Tanaka and Davis, 1963; O'Brien, 1963; and Allen, 1980).

Detailed thin section analysis of the Rush Springs by Allen (1980) of samples collected near the town of Cement in southern Caddo County, indicated that the Rush Springs aquifer is composed of 50-60 percent quartz, 8-12 percent orthoclase, 2-3 percent microcline and plagioclase, less than 1 percent chert and rock fragments (mostly clay and silt), and the cement. Minerals found in trace amounts were muscovite, biotite, chlorite, zircon, and sericite. Authigenic constituents identified were illite, kaolinite, silica (in the form of quartz overgrowths), and hematite found as a microcrystalline pigment on the individual grains. The high degree of cementation described by Allen (1980) is unusual for the Rush Springs and results from alteration from underlying oil and gas deposits.

Underlying the Rush Springs Formation is the Marlow Formation, which is composed of interbedded sandstones, siltstones, mudstones, gypsum-anhydrite, and dolomite. The Marlow is approximately 90 to 100 feet thick in the study area where the entire section is present. Several authors suggest a nearshore marine depositional environment that includes (1) a brackish-water to nearshore-marine setting (Fay, 1962), and (2) a tidal flat bordering an open marine environment (MacLachlan, 1967). The Verden Sandstone within the Marlow Formation has been interpreted as a nearshore strandline deposit (Bass, 1939), whereas Evans (1948) suggests the Verden Sandstone was deposited as a channel deposit.

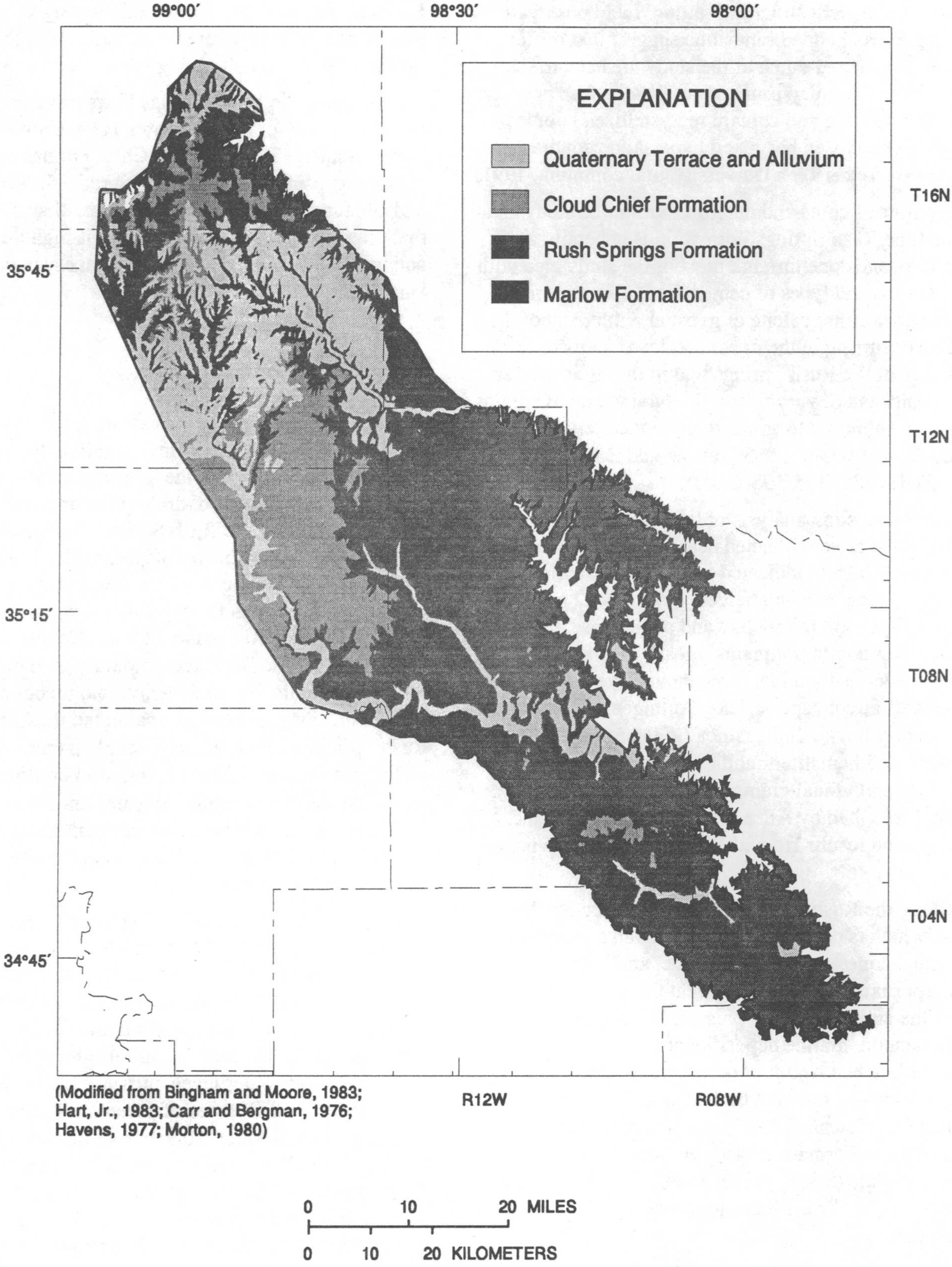
Cores show that the primary cement in the Marlow is gypsum, with minor amounts of carbonate. The Marlow Formation is moderately to well-cemented. Well-cemented units have extremely low primary permeability; cores of the Marlow were dry when extracted. Waters in the Marlow were assumed to be saturated with gypsum because of the selenite crystals in the mudstone and siltstone units, as well as bedded gypsum ranging in thickness from paper-thin to one foot. The underlying Marlow Formation acts as a confining unit that significantly retards downward movement of water from the Rush Springs aquifer to underlying units.

Overlying the Rush Springs Formation along the western portion of the study area is the Cloud Chief Formation (fig. 7). The Cloud Chief Formation is massive gypsum interbedded with reddish-brown shale and siltstone. The Cloud Chief is more than 100 feet thick in the study area but generally is highly eroded and, where gypsum is near land surface, can contain karst features.

Hydrologic system

The Rush Springs Formation extends north and west into Kansas and Texas. For this investigation, the study area was limited to areas with the largest ground-water withdrawals. Therefore, the hydrologic boundaries are the erosional extent of the Rush Springs Formation in Caddo, Comanche, Kiowa, Stephens, Grady, Canadian, Blaine, Custer, and Dewey Counties; and approximately the Canadian River in Dewey County, approximately the Washita River in Washita and Custer Counties, and approximately the Dry Creek tributary of Barnitz Creek in Custer County. Beyond the hydrologic boundaries used in this investigation, the saturated thickness of the Rush Springs aquifer, where present, is thin, with well yields generally less than 200 gallons per minute and dissolved solids in the ground water limits its use. The Rush Springs aquifer becomes increasingly more saline and more deeply buried in the Anadarko basin west of the Washita River boundary.

The Rush Springs aquifer over most of the study area is a water-table aquifer. The Rush Springs aquifer becomes confined in Washita and Custer Counties, where it is overlain by a sufficient thickness of the Cloud Chief Formation. Shallow wells in the Cloud Chief Formation indicate perched aquifers above the Rush Springs aquifer. Water levels measured in wells from 1986 to 1991 and altitudes of perennial streams were used to prepare a water-table map of the Rush Springs aquifer (fig. 8). Perennial streams are streams that flow during periods of no surface runoff. Ground water flows perpendicular to the water-level contours from highest altitudes to lowest altitudes until the flow path intercepts land surface and discharges as base flow for streams, springs, and seeps. Locally, ground-water flows to streams that incise the Rush Springs aquifer and intercept the water table.



(Modified from Bingham and Moore, 1983; Hart, Jr., 1983; Carr and Bergman, 1976; Havens, 1977; Morton, 1980)

Figure 7. Surficial geologic units in the Rush Springs study area.

Hydrographs of ground-water levels indicate that climatic conditions such as droughts and periods of higher than normal precipitation affect the overall water levels in the Rush Springs aquifer. Daily average water levels from 1947 through 1996 plotted with total precipitation for climatic division 4 (fig. 9) show the effects of daily changes in water levels in response to precipitation for a site in central Caddo County. Hydrographs of annual water-level measurements (fig. 10) show the magnitude of annual water-level changes. Water-level fluctuations measured in well 10N-12W-31 DDB2 from 1988-1990 (fig. 10) are quarterly measurements and the steep declines and recoveries are probably the result of seasonal irrigation withdrawals.

Water from the Marlow Formation, where potable, is used primarily for domestic use. Well yields are much smaller than from the Rush Springs aquifer and range from 1 to 2 gallons per minute (Tanaka and Davis, 1963). Water from the Marlow Formation, where it is overlain by a thin section of the Rush Springs Formation or exposed at land surface, is generally potable but, where deeply buried, is not used for drinking water because of the large concentration of sulfate from the dissolution of gypsum.

Hydrologic Properties

Well yields from the Rush Springs aquifer vary, but the most productive irrigation wells are reported to produce more than 1,000 gallons per minute (Tanaka and Davis, 1963). Drillers' logs for 89 wells report discharges that ranged from 11 to 850 gallons per minute, with a mean discharge of 209 gallons per minute. Specific capacity is the pumping rate divided by the water-level drawdown within the well as a result of the pumping. Specific capacities calculated for the 89 wells ranged from 0.7 to 15 gallons per minute per foot of drawdown, with a mean of 2.3.

Transmissivity, defined by Lohman and others (1972, p. 6), is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. Transmissivities estimated from four aquifer tests conducted by Tanaka and Davis (1963) ranged from 670 to 1,740 feet squared per day. Davis (1955) reported transmissivities ranging from 670 to 1,870 feet squared per day.

The storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (Lohman and others, 1972, p. 8). Storage coefficient is a term usually used when describing storage in confined aquifers. The specific yield of a rock or soil is the ratio of (1) the volume of water that the rock or soil, after being saturated, will yield by gravity, and (2) to its own volume (Lohman and others, 1972, p. 6). Tanaka and Davis (1963) reported that specific yields, from core samples of the Rush Springs aquifer, ranged from 0.13 to 0.34, with a mean of 0.25.

The 3M Company conducted a hydrologic investigation at a site in the town of Weatherford (U. S. Geological Survey files, Oklahoma City, OK, written commun., 1991). The investigation included slug and pumping tests in wells completed in the Rush Springs aquifer. Hydraulic conductivities estimated from slug tests ranged from 1.05 to 5.62 feet per day with a mean of 2.30 feet per day. Hydraulic conductivities estimated from pumping tests ranged from 3.84 to 4.41 feet per day. Calculated storage coefficients ranged from 0.0035 to 0.02.

Local variations of hydraulic conductivity are due to the degree of cementation present in the Rush Springs aquifer. One example is the area around the town of Cement, where the Rush Springs has been diagenetically altered. The Rush Springs aquifer in this area has a high degree of cementation resulting in lower estimated hydraulic conductivities than the surrounding area. No aquifer tests for this area were available at the time of the study but, based on specific capacities calculated from drillers logs for this study, hydraulic conductivities in this area were estimated to be less than 1 foot per day in some cases.

The thickness of saturation is measured from the base of the Rush Springs aquifer to the potentiometric surface, which could include the entire thickness of the Rush Springs aquifer and portions of the overlying Cloud Chief, where present. Well data used to generate the potentiometric surface or the base of the aquifers do not contain the information needed to calculate the saturated thickness. An estimate of the saturated thickness was generated (fig. 11) by subtracting the elevation of the base of the aquifer from the potentiometric surface. This was accomplished through digital processes using the geographic information system software ARC/INFO. Saturated thickness exceeding 300 feet reflect the measurement of the potentiometric surface extending into the overlying Cloud Chief Formation. The map (fig. 11) illustrates general trends of saturated thickness and should not be used to derive the saturated thickness for a specific location.

Recharge

The Rush Springs aquifer is recharged by the infiltration of precipitation. Several methods have been used to estimate recharge to the Rush Springs aquifer. Recharge estimates range from a minimum of 0. 2 inch per year to over 2 inches per year. Variations in recharge estimates can be attributed to the method used, the climatic conditions at the time the data were collected, and the area of the aquifer considered.

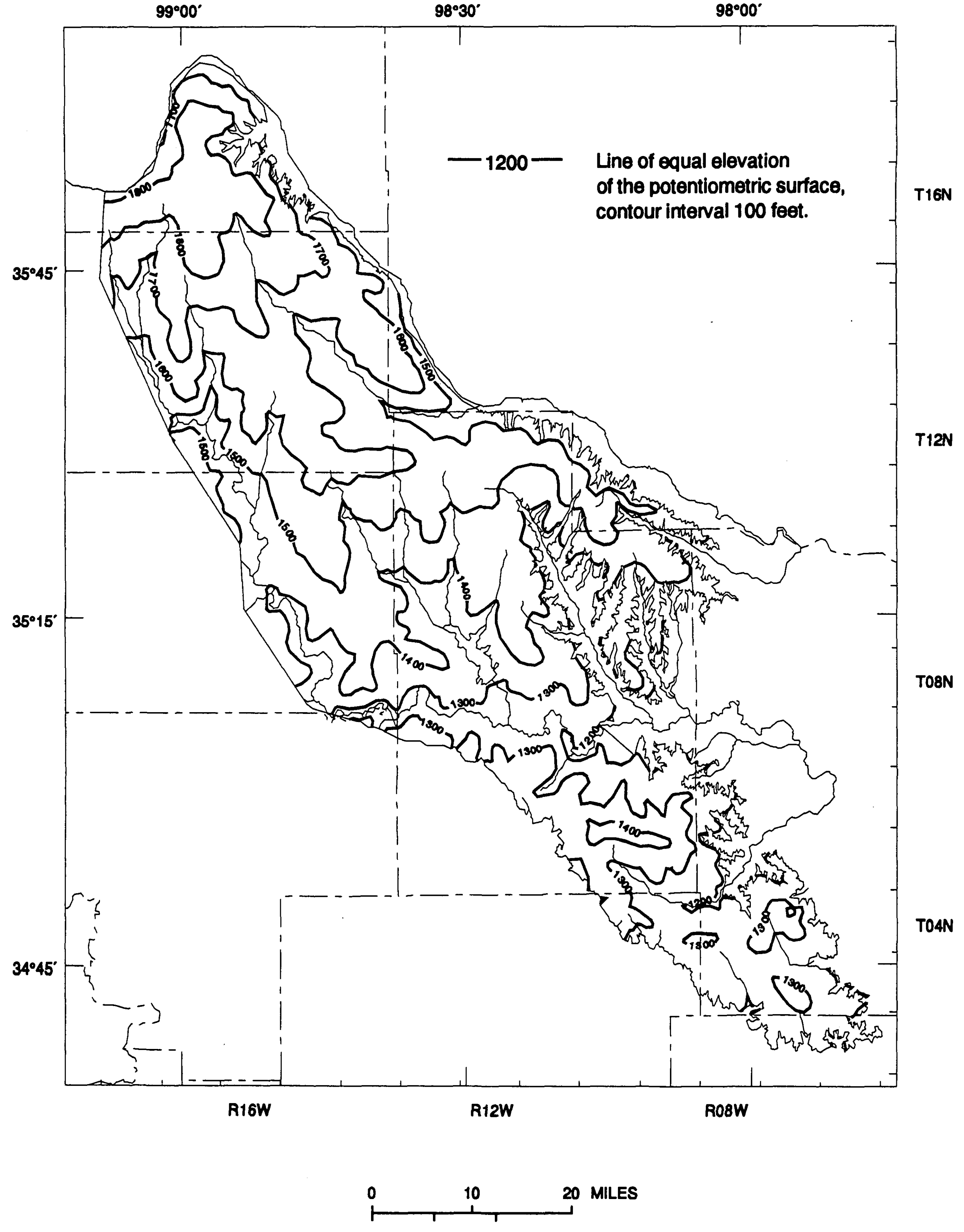


Figure 8. Contours showing the elevation of the potentiometric surface from water-level measurements in 1986 to 1991.

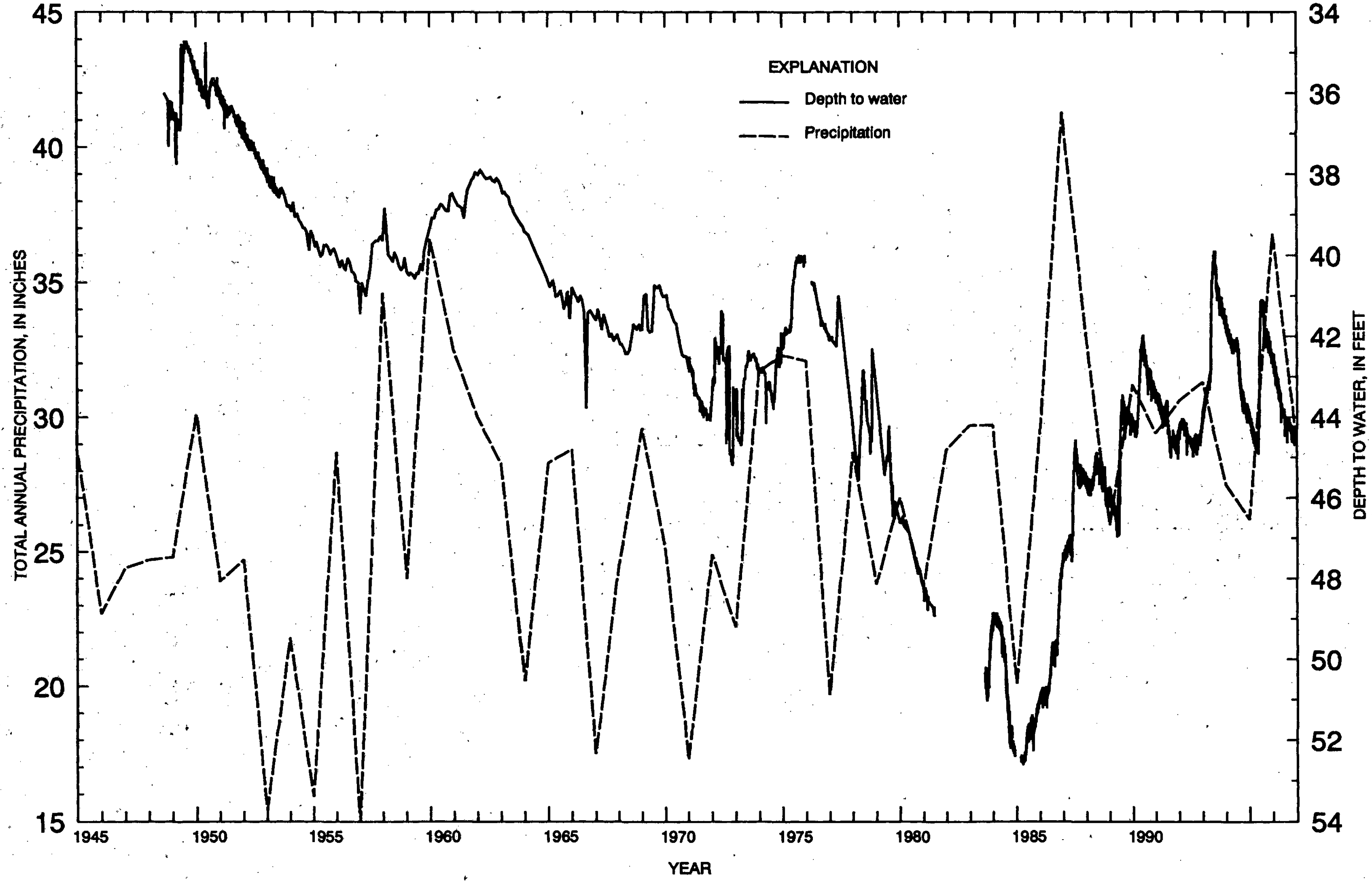


Figure 9. Depth to water recorded in well at 9N-13W-28 D in Caddo County and total annual precipitation in climatic division 4.

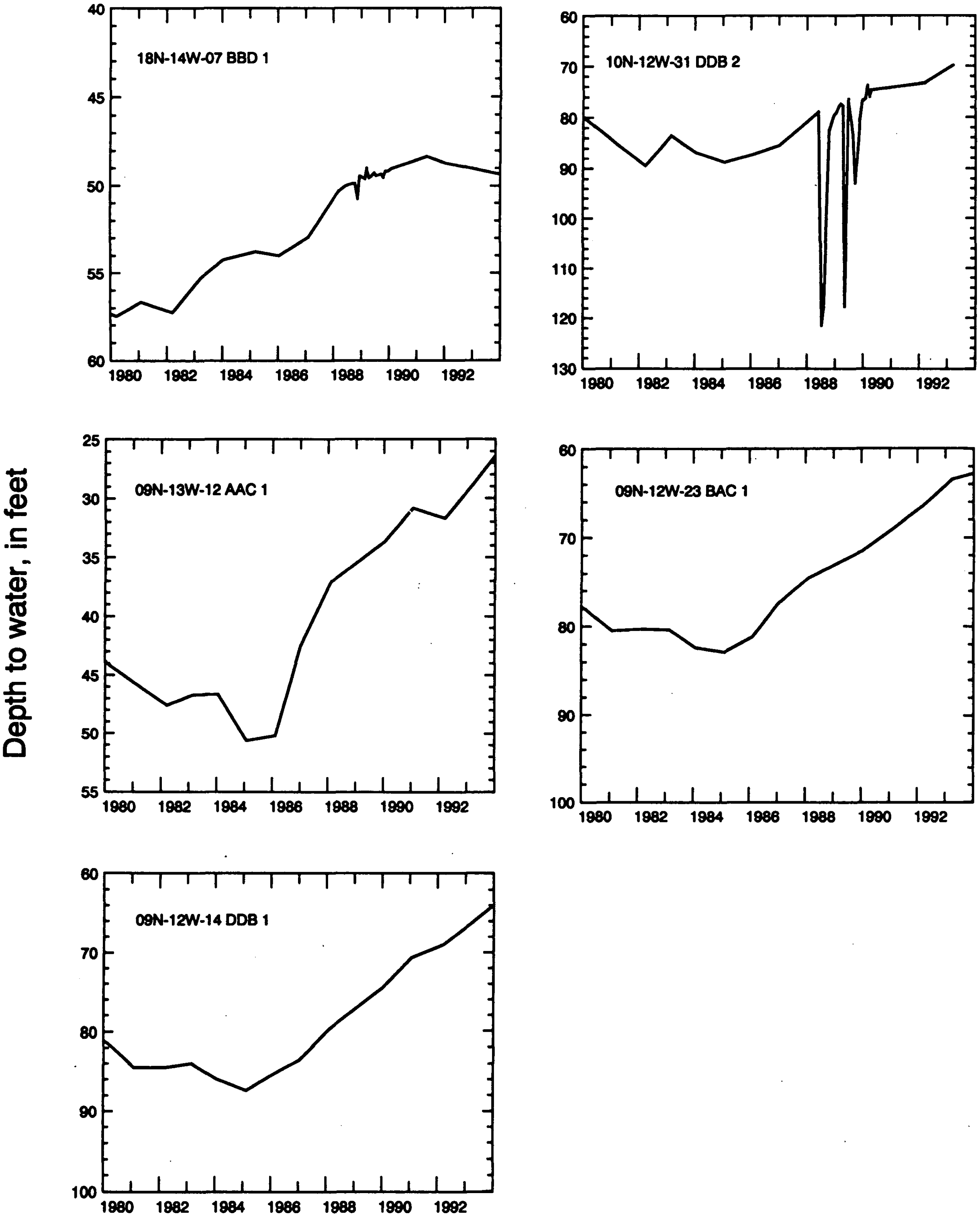


Figure 10. Depth to water measured in wells in the Rush Springs aquifer. Measurements show annual changes in depth to water in the Rush Springs aquifer.

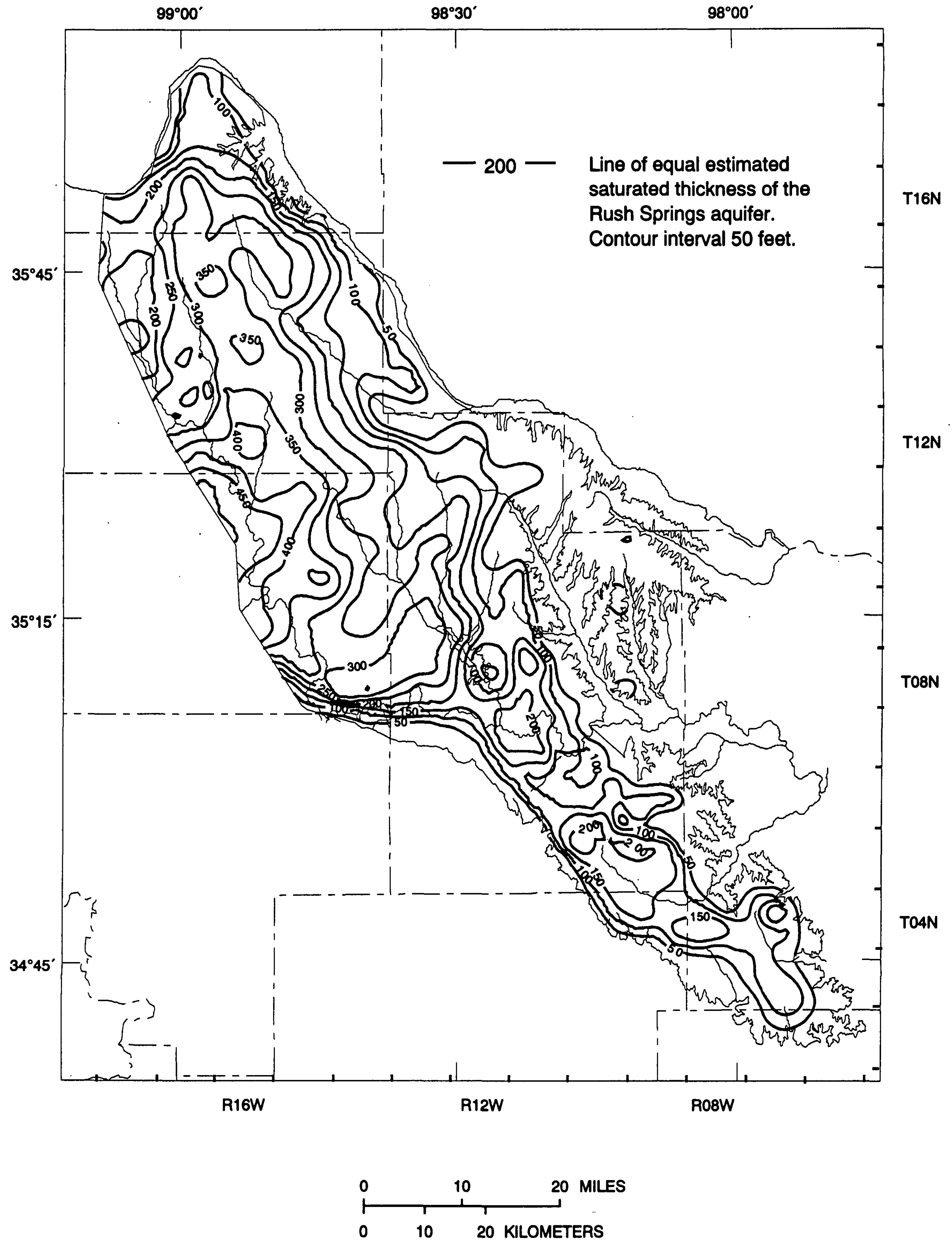


Figure 11. Estimated saturated thickness of the Rush Springs aquifer and the Cloud Chief Formation.

A water-level rise in the Rush Springs aquifer that corresponded to rainfall was used by Tanaka and Davis (1963) and Davis (1955) to estimate recharge. They correlated the water-level rise in wells to the amount of rainfall and estimated recharge. The amount of recharge estimated by Tanaka and Davis (1963) for the Cobb Creek basin ranged from 1.5 to 3.5 inches per year for the years from 1953 to 1956.

A regional recharge rate was estimated by Pettyjohn, White, and Dunn (1983) by separating stream discharge hydrographs from data collected on major streams and tributaries for 1970 to 1979 into surface runoff and ground-water seepage components. Using that method, the recharge estimated for the Rush Springs aquifer study area ranges from greater than 0.2 to 1 inch per year.

For this investigation, the initial estimate of recharge was made by assuming that the system was in dynamic equilibrium with discharge; therefore, recharge was approximately equal to discharge. Stream base flow is defined as stream discharge that is sustained only by ground-water discharge and when evapotranspiration is at a minimum. Base flow measurements taken in March 1989 and February 1991 were used to estimate the minimal annual recharge. There were no significant differences between values at sites measured in 1989 and those measured in 1991 (Blazs and others, 1991). The estimate of minimal annual recharge is based on: (1) measurements within each stream basin normalized by drainage area to estimate a mean yield per square mile for that individual basin; (2) the surface area of 2,400 square miles of study area; (3) a mean annual rainfall for the study area of 29 inches, and (4) the estimated annual ground water withdrawal of 50,000 acre-feet for the study area, including withdrawals for domestic, irrigation, public supply, industrial, and commercial users. The estimated recharge is approximately 7.0 percent of the average annual rainfall, and equaling 310,000 acre feet per year or 0.369×10^8 cubic feet per day for the entire study area. This amount equals about 1.80 inches per year evenly distributed over the outcrop of the aquifer in the study area.

Discharge

Most of the discharge from the Rush Springs aquifer, not attributed to pumping of wells, is to streams and rivers, primarily the Washita River. Springs and seeps also are points of discharge and generally occur where the Rush Springs aquifer is deeply incised by streams and the water table intersects valley walls. The Marlow Formation impedes downward flow from the Rush Spring aquifer and redirects water to springs and seeps where the Rush Springs Formation-Marlow Formation contact is near land surface. Springs and seeps are near Hinton, in northern Caddo County, within the town of Rush Springs in Grady County, along the Canadian River, Spring Creek, and Sugar Creek drainage basins, and within valleys along the southern and eastern outcrop of the Rush Springs aquifer. In areas where the aquifer is in equilibrium, the rate of ground water discharges to streams equals the rate of recharge. Stream base flows were measured in 1989 and 1991 (Blazs and others, 1992) to estimate recharge.

Water Use

Most ground water withdrawn from the Rush Springs aquifer is in Caddo County. In 1990, Caddo County had the fourth largest annual ground-water withdrawal amount among counties in Oklahoma, estimated at more than 36 million gallons per day (Lurry and Tortorelli, 1995). Estimated withdrawal from the Rush Springs aquifer was 54.70 million gallons per day in 1990 (fig. 12). The largest-water use category was irrigation; it accounted for 42.57 million gallons per day, or 77.8 percent of the water withdrawn from the Rush Springs aquifer.

WATER QUALITY AND GEOCHEMISTRY

Water quality can be defined by the suitability of water chemistry for a particular use. The chemical analysis of ground-water samples collected in 1986 from wells completed in the Rush Springs aquifer are shown in Appendix A. All samples were analyzed by the Oklahoma Geological Survey laboratory. Sixty-four samples were used to describe the water quality and geochemistry of the Rush Springs aquifer. The water quality and geochemical analysis focused on the most extensively used part of the Rush Springs aquifer. All 64 sample sites are located east of longitude 098°36′15″ (fig. 13).

Summary statistics of the water-quality data in Appendix A are listed in table 1. The summary statistics include the minimum, maximum, mean, and selected percentiles for the chemical constituents analyzed in the 64 ground-water samples from the Rush Springs aquifer. Many trace elements contained censored data, data that are reported below the analytical detection limit. Percentiles and means for trace elements containing censored data were calculated using a method described by Helsel (1990), where a log-probability regression is used to estimate the distribution and mean of data containing censored data.

The Oklahoma drinking water standards for public water supplies (table 2) are used as a standard for the suitability of the drinking water (Oklahoma Department of Environmental Quality, 1994) from the Rush Springs aquifer. Two concentration levels for public water supplies are used for

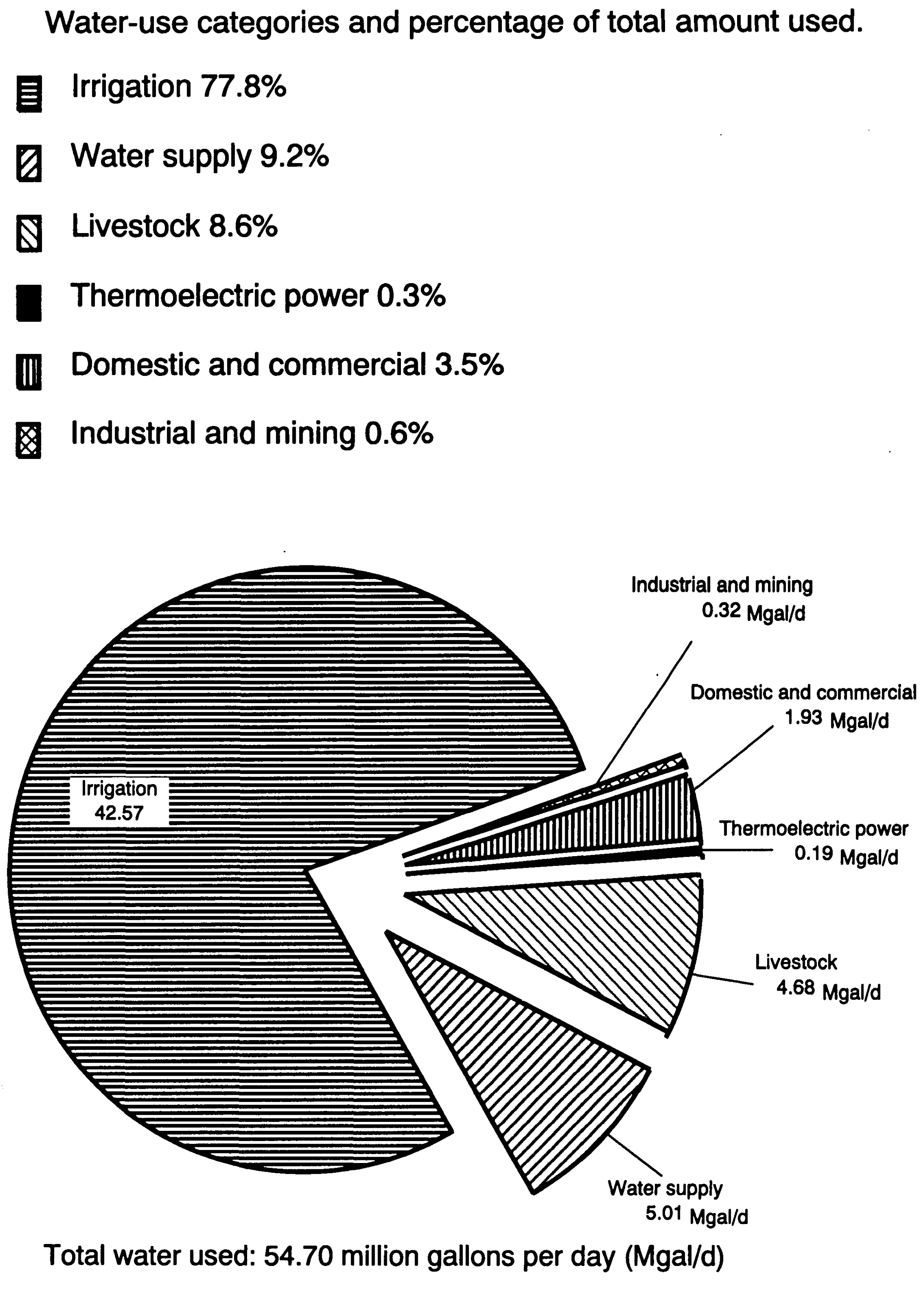


Figure 12. Estimated ground-water withdrawals by water-use category from the Rush Springs aquifer in 1990 (Lurry and Tortorelli, 1995).

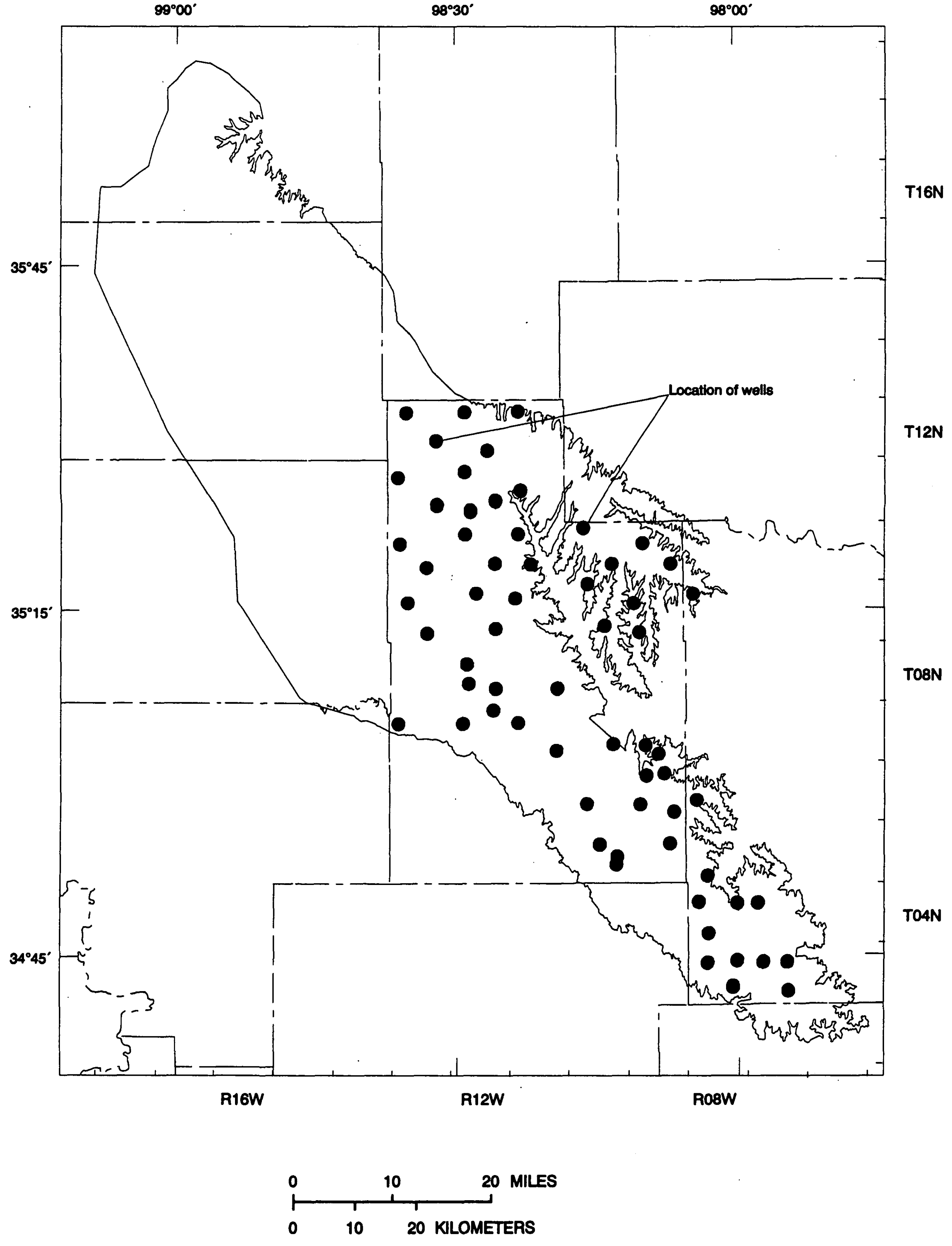


Figure 13. Location of 64 wells completed in the Rush Springs aquifer that were sampled in 1986.

Table 1. Summary statistics for field water-quality measurements, dissolved chemical constituents, saturation indices for calcite, dolomite, and gypsum, and the log of the partial pressure of carbon dioxide for 64 analyses for samples collected from June to August 1986 from wells completed in the Rush Springs aquifer. Analysis provided by the Oklahoma Geological Survey, Norman, Oklahoma.

[Specific conductance is in microsiemens per centimeter at 25° C, Temperature is in degrees Celsius; pH is in standard units; *, are presented in milligrams per liter; **, are presented micrograms per liter; Residue on evaporation at 180° C in milligrams per liter; ++, analyses were less than the analytical detection limit and statistics could not be estimated; calcite, dolomite, and gypsum saturation indices (SI) and Log P_{CO2} were calculated by WATEQF; __, indicates exceeds Maximum Allowable Level or the Recommended Maximum Level for Oklahoma public water supplies (Oklahoma Department of Environmental Quality, 1994)]

Parameter	Mean	Minimum	Maximum	Number of samples	Percentile		
					25	50	75
Specific conductance	763	330	2,450	64	492	645	853
Temperature	19.1	17	24	64	18	19	20
pH	7.2	6.1	7.8	64	6.9	7.1	7.3
Dissolved solids residue on evaporation at 180° C	511	52	1,840	64	298	374	550
Calcium*	100.4	30	360	64	53.2	73	110
Magnesium*	21.6	5.5	150	64	10.2	17	20.7
Sodium*	28.1	4.1	110	64	15	20.5	35.5
Potassium*	1.2	0.3	9.6	64	0.6	0.95	1.3
Bicarbonate*	251	82.9	612.4	64	193	242.10	309.2
Sulfate *	125.9	6.2	840	64	16	27.5	93.7
Chloride*	20.1	2.2	200	64	6.7	12	24.7
Fluoride*	0.3	0.1	1.1	61	0.2	0.2	0.4
Bromide*	0.19	0.04	0.74	64	0.10	0.17	0.23
Silica*	25.8	14	45	64	21.2	25	27.7
Nitrate as N*	14.3	0.2	88	64	4.9	11	18.7
Aluminum**	++	<140	200	64	++	++	++
Arsenic**	^{1}14.9	<10	16	63	^{1}2.1	^{1}3.3	^{1}5.2
Barium**	137.3	10	600	64	60	100	207.5
Boron**	65.1	10	340	64	30	50	80
Cadmium**	^{1}1.3	<0.5	3.3	64	^{1}0.70	^{1}1.20	^{1}1.8
Chromium**	++	++	++	64	++	++	++
Copper**	^{1}15.6	<10	37	64	^{1}1.3	^{1}2.9	^{1}6.5
Iron**	^{1}48.5	<10	1,600	64	^{1}1.4	^{1}10.0	^{1}17.5
Lead**	++	++	++	64	++	++	++
Manganese**	^{1}21.0	<10	890	64	^{1}0.01	^{1}0.13	^{1}1.76
Zinc**	^{1}83.6	<11	1,000	64	^{1}11.0	^{1}30.5	^{1}69.7
Calcite SI	-0.20	-1.67	0.56	64	-0.39	-0.13	0.05
Dolomite SI	-1.39	-4.05	0.32	64	-1.76	-1.36	-0.99
Gypsum SI	-1.92	-2.79	-0.35	64	-2.45	-2.09	-1.48
Log P_{CO2}	-1.79	-2.38	-0.79	64	-2.08	-1.76	-1.57

[1] Statistic was estimated using the method described by Helsel (1990).

Table 2. Oklahoma drinking water standards Recommended Maximum Level and Maximum Allowable Level for public supply for some selected inorganic constituents

.[**, mean and maximum concentrations are reported in micrograms per liter; *, mean and maximum concentration are reported as milligrams per liter; NA, analyses were less than the analytical detection limit and statistics could not be estimated]

Constituent	Recommended maximum level in mg/L	Maximum allowable level in mg/L	Mean concentration found in Rush Springs aquifer	Maximum Concentration found in the Rush Springs aquifer
Total dissolved solids	500		589	1,939
Aluminum**	.05-.2		NA	200
Arsenic**		.05	[1]14.9	16
Barium**		2	.13	.6
Cadmium**		.005	[1]<1.3	3.3
Chloride*	250		20.1	200
Chromium**		0.1	<10	<10
Copper**		1	[1]15.6	37
Fluoride*	2.	4	.3	1.1
Iron**	0.3		[1]48.5	1,600
Manganese**	0.05		[1]21	890
Sulfate*	250		125.9	840
Zinc**	5		[1]83.6	1,000
Nitrate as N*		10	14.3	88

[1] Statistic was estimated using the method described by Helsel (1990).

comparison, the maximum allowable level (primary standard) and the recommended maximum level (secondary standard). The maximum allowable level is the permissible level for public water supplies and is set at levels to safeguard public health.

The recommended maximum level is a nonmandatory guideline. Common water-quality characteristics such as hardness, taste, and discoloration of fixtures or laundry are concerns but pose no health threat. Based upon the scale for hardness in Hem (1970, p. 225), using the mean concentrations of calcium and magnesium, the waters from the Rush Springs aquifer would be considered very hard. This results in premature failure of water heaters, incrustations on fixtures, and can reduce the effectiveness of soaps.

Total dissolved solids represent the sum of all dissolved constituents in the water. Specific conductance is an indirect qualitative estimate of total dissolved solids. The recommended maximum level for total dissolved solids (500 milligrams per liter) is based upon its effect on taste and hardness. In areas where gypsum is present, the total dissolved solids can exceed 1,000 milligrams per liter.

Arsenic has many industrial sources including agricultural chemicals. Arsenic can also occur naturally under appropriate geochemical conditions but is generally stable. Arsenic was less than the maximum allowable levels in all wells sampled.

Barium concentration is less than the maximum allowable level in the Rush Springs Aquifer. The source of barium is from natural deposits such as barite.

Cadmium is associated with natural mineral deposits and is used in paints, batteries, agricultural chemicals and other industrial products. The maximum allowable level of cadmium is0.005 milligrams per liter. The mean concentration estimated in waters analyzed from the Rush

Springs aquifer is 1.3 micrograms per liter and the maximum concentration is 3.3 micrograms per liter.

Aluminum can affect the taste of water and is derived from naturally occurring minerals. Iron and manganese are naturally occurring and affect taste, create staining, scaling, and discoloration of the water. Zinc is from plumbing materials and can be associated with industrial contamination. High concentrations of zinc will affect the taste of water. Aluminum, iron, manganese, and zinc concentrations are measured below the recommended allowable levels in waters from the Rush Springs aquifer.

Chloride has a recommended maximum level of 250 milligrams per liter. The most common sources of chloride in the study area are evaporite deposits, precipitation, and brines. Chloride can affect the taste of water, create discoloration, cause corrosion, and is toxic to plants. The mean chloride concentration in the Rush Springs aquifer is 20.1 milligrams per liter and the maximum chloride concentration is 200 milligrams per liter.

Chromium is associated with natural deposits and industrial processes such as leather tanning and petroleum refining. Chromium was not detected above the maximum allowable level of 1 milligram per liter in the Rush Springs aquifer.

Sulfate is related to the presence of gypsum. The recommended maximum level for sulfate is 250 milligrams per liter. This concentration can be exceeded if gypsum is in equilibrium with water. High sulfate will effect the taste of the water and acts as a laxative. The mean sulfate concentration in the Rush Springs aquifer is 125.9 milligrams per liter and the maximum sulfate concentration is 840 milligrams per liter.

Fluoride is the exception to the recommended maximum level guidelines. Fluoride is added to some drinking water supplies due to the benefits for the development of teeth and bones; however, elevated concentrations result in a mottled discoloration of teeth. Fluoride concentrations in the Rush Springs aquifer are well below the recommended maximum level of 2 milligrams per liter. There is a maximum allowable level for community public water supply systems 4 milligrams per liter. The mean fluoride concentration in the Rush Springs aquifer is .3 milligrams per liter and the maximum is 1.1 milligrams per liter.

The mean concentration for nitrate detected in waters from the Rush Springs aquifer is 14.3 milligrams per liter, which exceeds the maximum allowable level of 10 milligrams per liter. Nitrate exceeding 10 milligrams per liter can result in methemoglobinemia, or "blue baby syndrome," and has been tentatively linked to other health problems. Several potential sources of nitrate are present, including commercial fertilizer, animal waste, and treated sewage. The presence of elevated nitrate in ground water can indicate other potential contaminants such as agricultural pesticides.

The chemical composition of ground water in the Rush Springs aquifer is the result of chemical reactions between the recharge waters and minerals in the soils and rocks. The mass transfer between the solid phase and water was modeled using dominant geochemical reactions along the flow paths of the Rush Springs aquifer (Becker, 1993), the computer program NETPATH (Plummer and others, 1992), rainfall chemical analyses, and the 64 chemical analyses of well water. NETPATH calculates the mass transfer of ions exchanged between the mineral phases present and the ground water at points along a flow path. Two water chemistries must be known to use the flow path model, that of the initial water and that of the final water. In this case, the initial water used was an analysis of rainwater that had been concentrated up to 15 times its initial concentration to simulate the effects of evapotranspiration. The final water chemistry was derived from the 64 water analyses.

Chemical reactions that produce the water-quality characteristics were identified by the minerals in the greatest abundance and solubility within the flow paths such as gypsum, calcite, and dolomite. The dissolution of halite and cation exchange are additional reactions that account for the water quality. The following geochemical reactions were used in the mass-balance model (Becker, 1993) to account for the presence of the detected dissolved common ions.

$$\mathrm{CaCO_{3(Calcite)}} \text{ -------> } \mathrm{Ca^{++} + CO_3^{=}} \tag{1}$$

$$\mathrm{CaMg(CO_3)_{2(Dolomite)}} \text{ -------> } \mathrm{Ca^{++} + Mg^{++} + 2CO_3^{=}} \tag{2}$$

$$\mathrm{CaSO_4 \cdot 2H_2O_{(Gypsum)}} \text{ ------> } \mathrm{Ca^{++} + SO_4^{=} + 2H_2O} \tag{3}$$

$$\mathrm{Na\text{-}clay + 0.5Ca^{++}} \text{ ------> } \mathrm{0.5Ca\text{-}clay + Na^{+}} \tag{4}$$

$$\mathrm{Na\text{-}clay + 0.5Mg^{++}} \text{ ------> } \mathrm{0.5Mg\text{-}clay + Na^{+}} \tag{5}$$

$$\mathrm{NaCl_{(Halite)}} \text{ ------> } \mathrm{Na^{+} + Cl^{-}} \tag{6}$$

Equilibrium indices, referred to as saturation indices, were calculated using the computer program WATEQF (Plummer and others,1976) for the common mineral phases in the Rush Springs aquifer (Becker, 1993). Saturation indices indicate the state of equilibrium of a mineral in a solution. The status of equilibrium is expressed as either saturated, undersaturated, or equilibrium. Saturation indices indicating undersaturation with respect to a mineral indicates that the mineral will not precipitate and may dissolve. Conversely, saturation indices indicating a saturation of a mineral indicates that the mineral will not dissolve and may precipitate. A solution at equilibrium with a mineral means the mineral will dissolve, precipitate, or remain inert to maintain equilibrium.

The mass-balance model and saturation indices indicate what elements have been added or removed from the solution along the flow path and what specific minerals are in equilibrium with the water. The saturation indices calculated by WATEQF indicate that all 64 water analyses were undersaturated with gypsum and halite. Calcite saturation was found in 19 water analyses and two analyses indicated dolomite saturation. All water analyzed was saturated with quartz The mass-balance model indicates that in all waters dolomite and gypsum had dissolved and in 15 water analyses calcite was shown to have precipitated. Halite was the only mineral phase selected to account for chloride in the mass-balance model. The chloride and sodium concentrations required for halite precipitation are higher than those found in the Rush Springs aquifer that halite precipitation could not occur.

The two most common water types are a calcium-magnesium bicarbonate type and calcium-sulfate type. The large concentration of calcium in ground water is from the dissolution of calcite, dolomite, and gypsum (eqs. 1-3). Dolomite is the primary source of magnesium (eq. 2). Calcium concentration ranged from 30 to 360 milligrams per liter with a median of 73 milligrams per liter. Magnesium concentration ranged from 5.5 to 150 milligrams per liter.

Potassium is present but occurs in relatively small concentration of less than 0.3 to 9.6 milligrams per liter, with a median of 0.95 milligrams per liter; therefore, potassium was not included in the mass-balance model. The mineral sources of potassium in clastic deposits are orthoclase, biotite, and muscovite; even though the sand of the Rush Springs Formation is composed primarily of quartz, Allen (1980) identified those potassium-bearing minerals in thin section analysis of the Rush Springs Formation. Illite, a potassium-rich clay, is another source of potassium in the Rush Springs aquifer.

Sodium concentrations ranged from 4.1 to 110 milligrams per liter, with a median of 20.5 milligrams per liter. A potential mineral source of dissolved sodium is cation exchange with sodium-rich clay minerals such as montmorillonite (eqs. 4-5). Chloride, which is often associated with sodium, ranged in concentration from 2.2 to 200 milligrams per liter with a median of 12 milligrams per liter. Halite is another possible source of sodium and chloride (eq. 6), however, there is no record of halite in the Whitehorse Group (fig. 4) within the study area. Halite may be present in very small amounts in microcrystalline form associated with evaporite deposits such as gypsum. Other sources of sodium and chloride could be septic systems, brines from oil and gas operations, inclusions within the rock cement and matrix bearing residual brines, precipitation, and fertilizers such as potash (potassium chloride).

Bicarbonate and sulfate are the anions occurring in the largest concentration in the Rush Springs aquifer. Because the pH of the water samples ranged from 6.1 to 7.8 with a median of 7.1, the dominant carbonate ion is bicarbonate, the primary buffer in solution. Bicarbonate concentration ranges from 83 to 612 milligrams per liter, with a median of 242 milligrams per liter. Bicarbonate concentrations accounted for greater than 50 percent of the total anion concentration in 42 of the 64 samples analyzed. Sources of bicarbonate in ground water are the atmosphere, soil gases, and dissolution of carbonate minerals. Sulfate concentrations ranged from 6.2 to 840 milligrams per liter, with a median of 27.5 milligrams per liter. The sulfate concentration accounted for greater than 50 percent of total anion concentrations in 9 of 64 water analyses. Sulfate exceeded 250 milligrams per liter in 10 of the 64 sites analyzed (fig. 14). Gypsum, the most probable source of sulfate, is present in the Marlow Formation, the Rush Springs Formation in places, and the overlying Cloud Chief Formation.

Background concentrations of nitrate in ground water are generally less than 2.0 milligrams per liter (Mueller and Helsel, 1996). When nitrate concentrations exceed background, particularly by an order of magnitude, anthropogenic sources are suspected. Nitrate as nitrogen concentrations in the Rush Springs aquifer for this study ranged from 0.2 to 88 milligrams per liter with a median concentration of 11 milligrams per liter. Figure 15 shows locations where nitrate concentrations equal or exceed 10 milligrams per liter. Common natural and anthropogenic sources of nitrate are precipitation, sewage, fertilizer, animal waste, and the decomposition of organic material. Agriculture is the primary industry in the study area and nitrogen fertilizers are used extensively. Most of the wells sampled for this investigation are rural domestic wells and all the dwellings have septic systems. Several anthropogenic and natural sources exist in proximity to the sampled wells so it was not possible with the data available to identify specific origins of the nitrate.

Knowledge of the flow paths, distribution of the abundant soluble minerals, and equilibrium conditions of these minerals make it possible to predict the type of water in the study area. If gypsum is encountered anywhere along the flow path, the water will be of the calcium sulfate type or contain substantial concentrations of calcium and sulfate. This would include areas where there is gypsum on the surface or where wells penetrate the Marlow Formation. If gypsum is not present in sufficient quantities along a flow path, the water will be of a calcium-magnesium bicarbonate type.

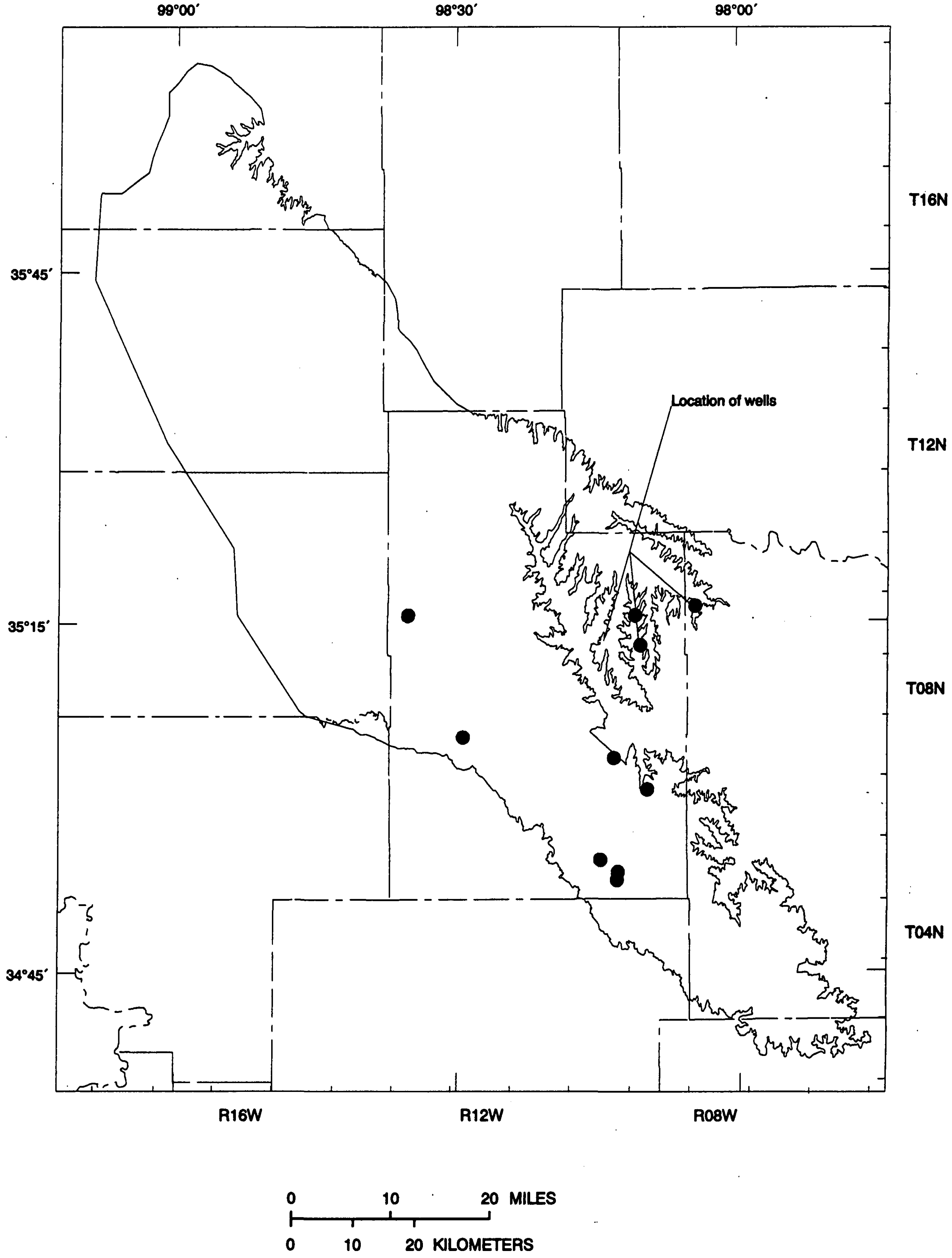


Figure 14. Location of 10 wells sampled in 1986 where sulfate concentration was greater than 250 milligrams per liter.

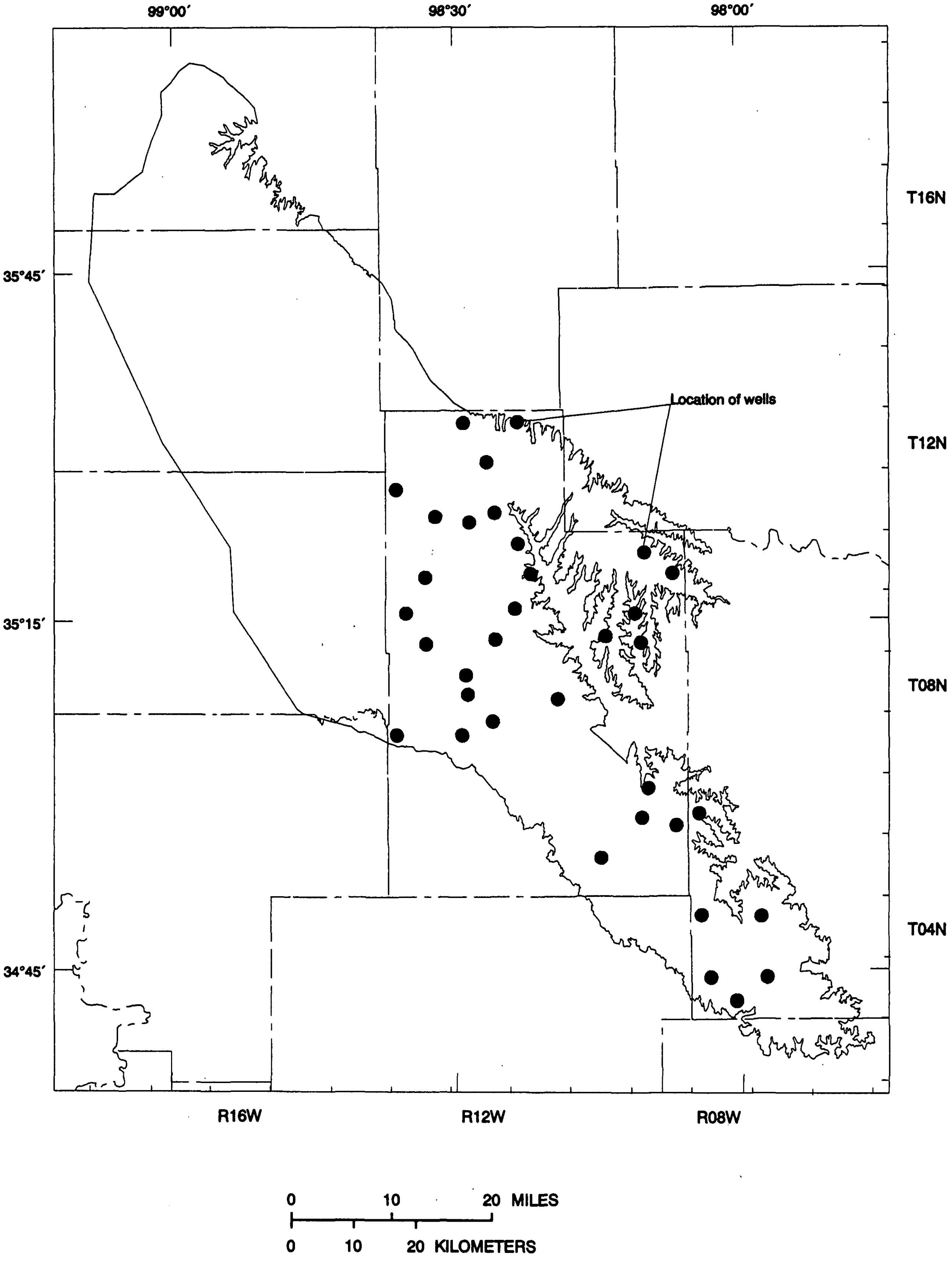


Figure 15. Location of wells sampled in 1986 where nitrate concentration was greater than 10 milligrams per liter as nitrogen.

Summary and Conclusions

The purpose of this report is to describe the hydrogeology, water quality, and geochemistry of the Rush Springs aquifer. The Rush Springs aquifer is equivalent to the Rush Springs Formation. Generally less than 250 feet thick in the central part of the study area, it is a massive to highly cross-bedded sandstone with some interbedded dolomite and gypsum. Well yields from the Rush Springs aquifer vary, but the most productive irrigation wells are reported to yield more than 1,000 gallons per minute. Drillers' logs for 89 wells report discharges ranging from 11 to 850 gallons per minute, with a mean discharge of 209 gallons per minute. Transmissivities estimated from four aquifer tests performed for earlier investigations ranged from 670 to 1,870 feet squared per day. Reported specific yields for core samples of the Rush Springs aquifer ranged from 0.13 to 0.34, with a mean of 0.25. Hydraulic conductivities from slug tests ranged from 1.05 to 5.62 feet per day, with a mean of 2.30 feet per day. Hydraulic conductivities estimated from pumping tests ranged from 3.84 to 4.41 feet per day. Calculated storage coefficients ranged from 0.0035 to 0.02. Ground water from the Rush Springs aquifer discharges to streams and rivers, primarily the Washita River. Springs and seeps also are points of discharge and generally occur where the Rush Springs aquifer is deeply incised and the water table intersects steep valley walls. The underlying Marlow Formation impedes downward flow of water from the Rush Springs and redirects water to springs and seeps where the Rush Springs Formation Marlow Formation contact is near land surface. The Rush Springs aquifer is recharged by the infiltration of precipitation. The annual recharge estimated for this investigation is approximately 1.80 inches per year, over the outcrop of the study area.

Estimated total withdrawal from the Rush Springs aquifer was 54.70 million gallons per day in 1990. The largest-water use category was irrigation, which accounts for greater than 42 million gallons per day or 77.8 percent of the water withdrawn from the Rush Springs aquifer.

Water from the Rush Springs aquifer is very hard. Concentrations of most selected inorganic constituents were less than the Oklahoma drinking water standard maximum allowable and recommended maximum levels. The maximum concentration for sulfate was 840 milligrams per liter, exceeding the recommended maximum level of 250 milligrams per liter. The mean concentration for nitrate in waters from the Rush Springs aquifer was 14.3 milligrams per liter, which exceeds the maximum allowable level of 10 milligrams per liter. The most common types of water found in the study area are calcium-magnesium bicarbonate and calcium-sulfate.

The chemical composition of ground water in the Rush Springs aquifer is the result of geochemical reactions between the recharge waters and minerals in the soils and rocks. The saturation indices calculated by WATEQF indicate that all 64 water analyses were undersaturated with gypsum and halite, whereas 19 water analyses were saturated with calcite, and 2 water analyses were saturated with dolomite. All water analyses were saturated with quartz. Saturation of calcite is indicated in 15 mass-balance analyses. The mass balance of all 64 waters indicate dolomite and gypsum undersaturation.

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Appendix A

Appendix A. Chemical analyses of 64 ground-water samples collected from June to August 1986 from wells completed in the Rush Springs aquifer

[--, indicates no data available;<, indicates concentration is less than the specified value; µg/L, micrograms per liter; mg/L, milligrams per liter, °C, degrees Celsius; specific conductance, pH, temperature, and alkalinity were measured in the field; FET, fixed endpoint titration; µS/cm, microsiemens per centimeter; all samples were collected by U.S. Geological Survey; all samples were analyzed by the Oklahoma Geological Survey laboratory, Norman, Oklahoma]

Site identifier	Local number	Latitude	Longitude	County	Date sampled	Specific conductance µS/cm	pH, FSU, whole water	Water temperature (°C)	Total alkalinity, whole water, FET (mg/L as $CaCO_3$)	Dissolved solids residue at 180°C (mg/L)
345448098071401	05N-09W-11 CDD 1	345448	0980714	Caddo	06-26-1986	710	7.1	18.0	213	532
345342098105201	05N-09W-19 AAD 1	345342	0981252	Caddo	07-30-1986	1,820	6.1	21.5	198	1,540
345302098125801	05N-10W-26 AAA 1	345302	0981258	Caddo	07-30-1986	1,030	6.8	20.5	241	612
345445098144301	05N-11W-14 ABB 1	345445	0981443	Caddo	07-02-1986	2,450	7.0	19.0	304	1,700
350043098094301	06N-09W-09 BCB 1	350043	0980943	Caddo	07-08-1986	1,480	7.0	19.5	162	1,210
350053098074901	06N-09W-10 DDC 1	350053	0980749	Caddo	07-08-1986	460	7.0	19.0	184	288
345732098064801	06N-09W-26 DDB 1	345732	0980648	Caddo	06-25-1986	554	7.0	19.0	239	322
345812098102401	06N-09W-29 BAA 1	345812	0981024	Caddo	06-27-1986	469	7.4	19.0	174	330
345815098160601	06N-10W-28 BBB 1	345815	0981606	Caddo	06-30-1986	529	7.4	19.0	184	292
350320098094701	07N-09W-28 BBC 1	350320	0980947	Caddo	07-08-1986	547	6.9	18.0	212	358
350235098082401	07N-09W-34 BAB 1	350235	0980824	Caddo	07-07-1986	330	7.4	17.5	100	210
350327098131401	07N-10W-26 AAB 1	350327	0981314	Caddo	07-08-1986	2,250	6.8	21.0	502	1,840
350519098232501	07N-11W-07 DDD 1	350519	0982325	Caddo	07-15-1986	452	7.1	18.0	183	284
350254098191801	07N-11W-26 DAD 1	350254	0981918	Caddo	07-16-1986	393	6.6	18.0	162	224
350626098260401	07N-12W-02 CAD 1	350626	0982604	Caddo	07-10-1986	537	7.5	19.0	138	308
350516098292001	07N-12W-08 CDD 1	350516	0982920	Caddo	07-17-1986	1,570	6.9	17.5	170	1,330
350516098361501	07N-13W-07 DDD 1	350516	0983615	Caddo	07-24-1986	960	6.9	21.0	309	490
350819098191101	08N-11W-26 DAA 1	350819	0981911	Caddo	07-21-1986	500	7.6	19.0	180	304
350819098254701	08N-11W-26 DBA 1	350819	0982547	Caddo	07-23-1986	400	7.3	19.5	148	234
351027098285301	08N-12W-17 AAB 1	351027	0982853	Caddo	07-22-1986	535	6.8	19.5	72	344

Appendix A. Chemical analyses of 64 ground-water samples collected from June to August 1986 from wells completed in the Rush Springs aquifer —Continued

Site identifier	Local number	Latitude	Longitude	County	Date sampled	Specific conductance µS/cm	pH, FSU, whole water	Water temperature (°C)	Total alkalinity, whole water, FET (mg/L as $CaCO_3$)	Dissolved solids residue at 180°C (mg/L)
350845098284101	08N-12W-29 AAA 1	350845	0982841	Caddo	07-23-1986	385	7.4	20.0	139	254
351542098105901	09N-09W-17 BBB 1	351542	0981059	Caddo	08-12-1986	692	7.2	22.0	275	1,320
351311098102401	09N-09W-26 DCC 1	351311	0981024	Caddo	07-17-1986	1,400	7.0	18.0	245	1,070
351724098155501	09N-10W-04 BAB 1	351724	0981555	Caddo	08-19-1986	584	7.4	21.0	257	320
351345098140601	09N-10W-26 BBC 1	351345	0981406	Caddo	07-17-1986	715	7.2	19.5	116	458
351610098234001	09N-11W-07 ADD 1	351610	0982340	Caddo	08-12-1986	440	7.3	19.0	172	52
351637098275101	09N-12W-03 CCC 1	351637	0982751	Caddo	08-13-1986	580	6.9	18.0	216	296
351332098254701	09N-12W-26 DAA 1	351332	0982547	Caddo	07-22-1986	870	6.9	18.0	254	500
351548098351301	09N-13W-09 CCC 1	351548	0983513	Caddo	08-07-1986	865	6.5	20.5	79	628
351308098330801	09N-13W-26 CCC 1	351308	0983308	Caddo	07-24-1986	750	7.1	17.5	288	426
352056098095901	10N-09W-08 DDD 1	352056	0980959	Caddo	08-13-1986	1,050	6.7	20.5	195	748
351907098070101	10N-09W-26 AAB 1	351907	0980701	Caddo	08-11-1986	535	7.1	21.0	144	330
352216098162101	10N-10W-05 ADD 1	352216	0981621	Caddo	08-13-1986	350	7.3	17.5	114	202
351909098131901	10N-10W-26 AAB 1	351909	0981319	Caddo	08-13-1986	688	7.1	23.0	257	380
352145098232101	10N-11W-08 BAB 1	352145	0982321	Caddo	08-12-1986	365	7.3	19.0	98	222
351908098220101	10N-11W-28 AAB 1	351908	0982201	Caddo	08-13-1986	755	7.1	17.5	261	362
352145098290201	10N-12W-08 AAA 1	352145	0982902	Caddo	08-12-1986	490	7.2	19.0	204	278
351914098255101	10N-12W-23 DDD 1	351914	0982551	Caddo	08-07-1986	420	7.3	17.5	189	234
352056098360301	10N-13W-08 CDC 1	352056	0983603	Caddo	08-12-1986	610	7.1	19.0	252	318
351852098331201	10N-13W-27 ADA 1	351852	0983312	Caddo	08-08-1986	620	7.3	18.0	141	418
352517098230401	11N-11W-17 DCC 1	352517	0982304	Caddo	08-14-1986	385	7.4	18.0	157	212
352338098283001	11N-11W-27 DDA 1	352338	0982830	Caddo	08-14-1986	670	7.1	21.0	189	412

Appendix A. Chemical analyses of 64 ground-water samples collected from June to August 1986 from wells completed in the Rush Springs aquifer —Continued

Site identifier	Local number	Latitude	Longitude	County	Date sampled	Specific conductance µS/cm	pH, FSU, whole water	Water temperature (°C)	Total alkalinity, whole water, FET (mg/L as $CaCO_3$)	Dissolved solids residue at 180°C (mg/L)
352655098290501	11N-12W-08 AAA 1	352655	0982905	Caddo	08-14-1986	675	7.1	18.0	317	322
352427098254801	11N-12W-23 DDD 1	352427	0982548	Caddo	08-19-1986	675	7.1	19.0	146	410
352626098361501	11N-13W-08 CBC 1	352626	0983615	Caddo	08-05-1986	687	7.8	18.5	245	370
352407098320601	11N-13W-26 ADA 1	352407	0983206	Caddo	08-06-1986	585	7.5	22.0	230	312
353211098232001	12N-11W-08 BAB 1	353211	0982320	Caddo	08-05-1986	896	7.7	18.5	343	558
353208098290501	12N-12W-08 AAB 1	353208	0982905	Caddo	08-05-1986	1,380	7.4	24.0	286	838
352846098263601	12N-12W-26 CCD 1	352846	0982636	Caddo	08-19-1986	1,050	7.0	19.5	254	580
353206098352101	12N-13W-08 AAD 1	353206	0983521	Caddo	08-11-1986	625	7.1	19.0	267	350
352937098320701	12N-13W-23 DDD 1	352937	0983207	Caddo	08-05-1986	666	7.4	21.0	278	378
344433097572501	03N-07W-08 DCB 1	344433	0975725	Grady	06-26-1986	440	7.2	17.5	120	398
344433097545301	03N-07W-10 DDA 1	344433	0975453	Grady	06-26-1986	530	7.4	17.5	205	304
344211097544601	03N-07W-26 CBB 1	344211	0975446	Grady	06-30-1986	820	7.0	19.5	378	490
344431098031801	03N-08W-08 DDA 1	344431	0980318	Grady	07-09-1986	700	7.0	18.0	178	448
344442098001001	03N-08W-11 DAD 1	344442	0980010	Grady	07-09-1986	500	7.7	18.0	196	280
344234098003601	03N-08W-26 ABB 1	344234	0980036	Grady	07-08-1986	740	7.0	17.0	206	464
344939097575601	04N-07W-08 CCC 1	344939	0975756	Grady	07-01-1986	470	6.3	17.0	79	320
344946098041101	04N-08W-08 CCB 1	344946	0980411	Grady	07-03-1986	490	6.7	17.5	68	290
344939098000701	04N-08W-11 DDD 1	344939	0980007	Grady	07-02-1986	890	7.0	19.5	230	556
344701098031101	04N-08W-28 CCC 1	344701	0980311	Grady	07-02-1986	670	7.2	19.5	199	382
345201098031601	05N-08W-29 DCD 1	345201	0980316	Grady	07-10-1986	815	6.9	18.0	222	582
345833098042401	06N-08W-20 CBB 1	345833	0980424	Grady	06-25-1986	606	6.6	23.0	167	410
351630098043701	09N-08W-08 BBB 1	351630	0980437	Grady	08-12-1986	1,860	7.0	20.0	240	1,580

Appendix A. Chemical analyses of 64 ground-water samples collected from June to August 1986 from wells completed in the Rush Springs aquifer —Continued

Site identifier	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Silica, dissolved (mg/L as SiO_2)	Nitrate, dissolved (mg/L as N)
345448098071401	100	20.0	22.0	1.4	140.0	25.0	0.4	0.21	21	1.8
345342098105201	360	17.0	15.0	0.4	820.0	10.0	0.2	0.10	22	2.6
345302098125801	190	10.0	17.0	1.0	270.0	7.4	0.4	0.10	21	4.9
345445098144301	320	86.0	76.0	1.0	460.0	200.0	0.8	0.74	14	88.0
350043098094301	270	35.0	18.0	1.3	580.0	19.0	0.3	0.15	24	27.0
350053098074901	73	11.0	13.0	1.4	35.0	4.2	0.6	0.10	37	6.1
345732098064801	75	11.0	45.0	0.9	22.0	14.0	0.5	0.23	27	19.0
345812098102401	84	5.8	7.1	0.4	29.0	7.6	0.1	0.06	24	16.0
345815098160601	78	10.0	20.0	0.6	74.0	2.2	1.1	0.12	20	3.3
350320098094701	73	18.0	10.0	9.4	52.0	10.0	0.4	0.08	29	2.8
350235098082401	30	12.0	17.0	0.4	24.0	8.6	0.5	0.18	35	7.4
350327098131401	190	150.0	100.0	1.1	840.0	23.0	0.3	0.21	21	2.0
350519098232501	54	12.0	25.0	<0.3	15.0	12.0	0.3	0.13	25	7.3
350254098191801	68	7.0	4.1	0.3	23.0	5.2	0.2	0.14	38	2.7
350626098260401	64	7.6	15.0	0.7	40.0	5.4	0.3	0.20	25	11.0
350516098292001	340	14.0	19.0	<0.3	700.0	8.6	0.3	0.14	22	12.0
350516098361501	120	26.0	36.0	1.1	44.0	35.0	0.4	0.17	19	22.0
350819098191101	65	9.7	16.0	1.4	6.2	3.6	0.3	0.17	26	14.0
350819098254701	50	8.8	12.0	0.7	13.0	5.3	0.4	0.10	24	5.8
351027098285301	52	16.0	21.0	1.3	81.0	14.0	0.2	0.14	26	16.0
350845098284101	51	6.9	14.0	0.7	7.0	3.6	0.3	0.14	21	11.0
351542098105901	240	51.0	34.0	0.4	440.0	48.0	0.7	0.46	33	39.0
351311098102401	260	58.0	30.0	0.3	580.0	6.8	--	0.17	37	10.0
351724098155501	76	20.0	6.4	0.3	15.0	8.6	0.6	0.21	42	3.1

Appendix A. Chemical analyses of 64 ground-water samples collected from June to August 1986 from wells completed in the Rush Springs aquifer —Continued

Site identifier	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Silica, dissolved (mg/L as SiO_2)	Nitrate, dissolved (mg/L as N)
351345098140601	100	20.0	22.0	0.8	210.0	17.0	--	0.21	33	14.0
351610098234001	52	10.0	20.0	1.2	9.7	2.8	0.2	0.06	25	11.0
351637098275101	46	21.0	38.0	1.3	18.0	14.0	0.2	0.19	25	8.8
351332098254701	130	11.0	18.0	1.6	25.0	26.0	0.2	0.44	25	28.0
351548098351301	110	25.0	19.0	1.5	270.0	13.0	0.2	0.24	22	18.0
351308098330801	87	17.0	34.0	3.3	26.0	12.0	0.3	0.13	21	14.0
352056098095901	99	39.0	28.0	1.2	44.0	44.0	0.3	0.36	29	54.0
351907098070101	56	16.0	13.0	0.7	20.0	15.0	0.2	0.26	34	13.0
352216098162101	32	12.0	13.0	0.7	12.0	2.8	0.2	0.11	26	9.0
351909098131901	110	9.5	18.0	0.6	83.0	11.0	0.2	0.15	40	1.3
352145098232101	35	12.0	13.0	0.7	16.0	6.8	0.2	0.12	26	13.0
351908098220101	82	18.0	40.0	0.9	18.0	11.0	0.2	0.26	26	23.0
352145098290201	67	8.0	18.0	1.5	10.0	4.9	0.2	0.06	23	9.3
351914098255101	52	8.1	16.0	1.2	17.0	5.3	0.2	0.06	26	0.4
352056098360301	64	19.0	32.0	1.1	16.0	9.4	0.1	0.06	21	8.6
351852098331201	69	17.0	16.0	0.7	9.0	17.0	0.1	0.37	22	30.0
352517098230401	43	9.6	15.0	0.8	9.0	3.8	0.2	0.10	23	4.9
352338098283001	74	18.0	23.0	2.5	16.0	32.0	0.1	0.48	25	22.0
352655098290501	67	23.0	39.0	1.0	9.9	12.0	0.2	0.04	26	2.3
352427098254801	60	28.0	19.0	9.6	36.0	29.0	0.2	0.31	21	27.0
352626098361501	73	5.5	50.0	1.0	17.0	14.0	0.1	0.22	19	15.0
352407098320601	72	16.0	11.0	0.4	12.0	5.8	0.2	0.11	20	10.0
353211098232001	58	29.0	93.0	1.7	36.0	36.0	0.4	0.19	21	15.0
353208098290501	100	54.0	58.0	1.0	150.0	67.0	0.2	0.34	18	31.0
352846098263601	140	24.0	48.0	3.8	23.0	84.0	0.1	0.46	19	41.0

Appendix A. Chemical analyses of 64 ground-water samples collected from June to August 1986 from wells completed in the Rush Springs aquifer —Continued

Site identifier	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Silica, dissolved (mg/L as SiO_2)	Nitrate, dissolved (mg/L as N)
353206098352101	75	10.0	39.0	1.4	17.0	8.4	--	0.06	22	9.2
352937098320701	61	12.0	56.0	1.1	13.0	15.0	0.2	0.06	23	7.8
344433097572501	33	20.0	22.0	0.5	26.0	28.0	1.1	0.26	20	13.0
344433097545301	68	16.0	13.0	0.9	49.0	6.7	0.3	0.07	22	2.4
344211097544601	53	20.0	110.0	1.7	26.0	11.0	0.2	0.22	22	7.8
344431098031801	100	12.0	25.0	0.7	79.0	41.0	0.2	0.13	24	13.0
344442098001001	46	18.0	26.0	0.9	14.0	4.0	0.6	0.08	25	7.4
344234098003601	75	20.0	42.0	1.0	43.0	30.0	0.5	0.22	27	26.0
344939097575601	39	17.0	20.0	1.4	22.0	35.0	0.2	0.26	38	22.0
344946098041101	39	20.0	12.0	0.5	90.0	8.6	0.2	0.13	25	11.0
344939098000701	120	20.0	26.0	0.8	95.0	62.0	0.3	0.37	28	4.5
344701098031101	110	8.5	9.1	0.6	120.0	4.1	0.2	0.09	24	2.9
345201098031601	120	16.0	23.0	0.6	200.0	12.0	0.2	0.18	45	2.4
345833098042401	46	36.0	24.0	1.3	53.0	24.0	0.4	0.22	29	29.0
351630098043701	280	48.0	46.0	0.4	790.0	18.0	0.2	0.32	30	0.2

Appendix A. Chemical analyses of 64 ground-water samples collected from June to August 1986 from wells completed in the Rush Springs aquifer—Continued

Site Identifier	Aluminum, dissolved (μg/L as Al)	Arsenic, dissolved (μg/L as As)	Barium, dissolved (μg/L as Ba)	Boron, dissolved (μg/L as B)	Cadmium, dissolved (μg/L as Cd)	Chromium, dissolved (μg/L as Cr)	Copper, dissolved (μg/L as Cu)	Iron, dissolved (μg/L as Fe)	Lead, dissolved (μg/L as Pb)	Manganese, dissolved (μg/L as Mn)	Zinc, dissolved (μg/L as Zn)
345448098071401	<140	<10	30	80	1.7	<10	<10	140	<100	140	74
345342098105201	<140	<10	10	110	3.3	<10	<10	10	<100	<10	35
345302098125801	<140	<10	100	80	2.6	<10	<10	10	<100	<10	63
345445098144301	<140	<10	80	80	0.9	<10	16	240	<100	140	240
350043098094301	<140	<10	30	120	1.3	<10	<10	30	<100	<10	53
350053098074901	<140	<10	60	60	1.4	<10	18	<10	<100	40	57
345732098064801	<140	<10	540	110	1.4	<10	<10	10	<100	<10	43
345812098102401	<140	<10	300	30	1.0	<10	<10	<10	<100	<10	<12
345815098160601	<140	<10	80	50	0.8	<10	<10	30	<100	<10	19
350320098094701	<140	12	210	50	<0.5	<10	<10	<10	<100	<10	16
350235098082401	<140	<10	60	30	<0.5	<10	12	10	<100	<10	17
350327098131401	<140	<10	10	340	1.1	<10	16	10	<100	20	210
350519098232501	<140	<10	100	40	1.0	<10	<10	<10	<100	<10	16
350254098191801	<140	<10	90	30	1.0	<10	<10	<10	<100	<10	<12
350626098260401	<140	<10	60	30	0.5	<10	14	<10	<100	<10	11
350516098292001	<140	<10	<10	60	0.8	<10	<10	20	<100	<10	<12
350516098361501	<140	<10	220	70	<0.5	<10	<10	<10	<100	<10	35
350819098191101	<140	<10	260	40	1.8	<10	<10	10	<100	<10	30
350819098254701	<140	<10	60	30	0.5	<10	<10	<10	<100	<10	<12
351027098285301	<140	<10	60	30	0.7	<10	<10	20	<100	<10	<12
350845098284101	<140	<10	50	30	<0.5	<10	<10	10	<100	<10	95
351542098105901	200	<10	50	110	1.9	<10	<10	10	<100	<10	<12
351311098102401	<140	<10	30	100	1.8	<10	<10	20	<100	10	59
351724098155501	<140	<10	200	70	3.2	<10	<10	40	<100	30	<12
351345098140601	<140	<10	40	40	0.6	<10	<10	<10	<100	<10	16

Appendix A. Chemical analyses of 64 ground-water samples collected from June to August 1986 from wells completed in the Rush Springs aquifer —Continued

Site Identifier	Aluminum, dissolved (μg/L as Al)	Arsenic, dissolved (μg/L as As)	Barium, dissolved (μg/L as Ba)	Boron, dissolved (μg/L as B)	Cadmium, dissolved (μg/L as Cd)	Chromium, dissolved (μg/L as Cr)	Copper, dissolved (μg/L as Cu)	Iron, dissolved (μg/L as Fe)	Lead, dissolved (μg/L as Pb)	Manganese, dissolved (μg/L as Mn)	Zinc, dissolved (μg/L as Zn)
351610098234001	<140	<10	60	80	1.2	<10	<10	<10	<100	<10	26
351637098275101	<140	<10	50	30	1.6	<10	<10	<10	<100	<10	41
351332098254701	<140	<10	190	30	1.2	<10	<10	10	<100	<10	<12
351548098351301	<140	<10	50	30	1.7	<10	<10	<10	<100	<10	120
351308098330801	<140	<10	210	60	0.6	<10	<10	<10	<100	<10	1,000
352056098095901	<140	<10	280	60	2.2	<10	28	<10	<100	10	97
351907098070101	<140	<10	600	40	1.6	<10	<10	<10	<100	<10	790
352216098162101	<140	<10	50	40	2.3	<10	<10	20	<100	<10	<12
351909098131901	<140	<10	90	40	2.1	<10	<10	10	<100	<10	40
352145098232101	<140	<10	40	30	0.7	<10	<10	<10	<100	<10	28
351908098220101	<140	<10	190	100	2.9	<10	<10	<10	<100	<10	15
352145098290201	<140	10	140	30	1.5	<10	<10	10	<100	<10	220
351914098255101	<140	16	380	30	1.7	<10	<10	10	<100	<10	31
352056098360301	<140	<10	130	50	0.6	<10	<10	<10	<100	<10	28
351852098331201	<140	<10	80	10	1.0	<10	<10	10	<100	<10	42
352517098230401	<140	--	210	40	1.6	<10	<10	<10	<100	<10	<12
352338098283001	<140	<10	120	40	2.2	<10	<10	<10	<100	<10	98
352655098290501	<140	<10	120	50	1.9	<10	<10	<10	<100	<10	60
352427098254801	<140	<10	60	90	0.7	<10	<10	20	<100	<10	36
352626098361501	<140	<10	120	120	1.0	<10	<10	10	<100	<10	<12
352407098320601	<140	<10	100	20	1.1	<10	<10	<10	<100	<10	40
353211098232001	<140	10	170	160	1.8	<10	<10	<10	<100	<10	22
353208098290501	<140	<10	70	130	1.0	<10	<10	10	<100	<10	270
352846098263601	<140	<10	300	110	0.7	<10	12	10	<100	<10	72
353206098352101	<140	<10	230	120	1.4	<10	<10	<10	<100	<10	430

Appendix A. Chemical analyses of 64 ground-water samples collected from June to August 1986 from wells completed in the Rush Springs aquifer—Continued

Site Identifier	Aluminum, dissolved (µg/L as Al)	Arsenic, dissolved (µg/L as As)	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)	Copper, dissolved (µg/L as Cu)	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Zinc, dissolved (µg/L as Zn)
352937098320701	<140	<10	280	110	1.7	<10	<10	20	<100	<10	<12
344433097572501	<140	<10	120	70	1.9	<10	<10	<10	<100	<10	<12
344433097545301	<140	<10	130	60	1.6	<10	<10	30	<100	<10	<12
344211097544601	140	<10	180	50	2.5	<10	<10	610	<100	20	230
344431098031801	<140	<10	110	40	0.6	<10	<10	10	<100	<10	57
344442098001001	<140	<10	250	50	<0.5	<10	<10	<10	<100	10	13
344234098003601	<140	<10	190	60	1.6	<10	<10	<10	<100	<10	75
344939097575601	<140	<10	90	30	0.6	<10	<10	<10	<100	<10	55
344946098041101	<140	<10	70	20	1.2	<10	<10	20	<100	<10	19
344939098000701	<140	<10	40	70	0.9	<10	<10	<10	<100	<10	<12
344701098031101	<140	<10	220	40	0.9	<10	<10	20	<100	<10	<12
345201098031601	<140	<10	210	30	<0.5	<10	37	<10	<100	<10	11
345833098042401	<140	<10	100	70	1.8	<10	34	10	<100	10	180
351630098043701	<140	10	20	110	<0.5	<10	<10	1,600	<100	890	17

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