GEOHYDROLOGY OF ALLUVIUM AND TERRACE DEPOSITS OF THE CIMARRON RIVER FROM FREEDOM TO GUTHRIE, OKLAHOMA

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OKLAHOMA GEOLOGICAL SURVEY

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To Obtain
inch (in)	2.540	centimeter
foot (ft)	0.3048	meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8\ (°C) + 32$$

Abbreviated water-quality units and terms used in report:

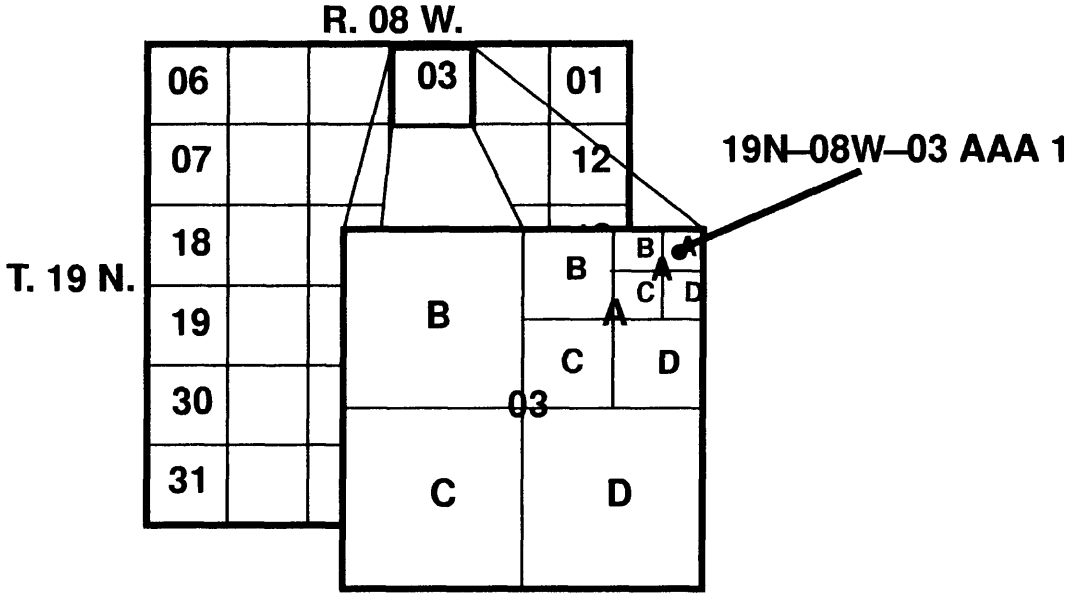
micrograms per liter	(μg/L)
milligrams per liter	(mg/L)
micrograms per kilogram	(μg/kg)
picocuries per liter	(pCi/L)
polychlorinated biphenyls	(PCB's)

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

EXPLANATION OF THE SITE-NUMBERING SYSTEM

The standard legal method of describing locations of data-collection sites by fractional section, section, township, and range is replaced in this report by the method illustrated in the diagram below. By the legal method, the location of the site indicated by the dot is described as NE 1/4 NE 1/4 NE 1/4 sec. 3, T. 19 N., R. 8 W. The method used in this report indicates quarter subdivisions of the section by letters and reverses the order of presentation of the subdivisions. By this method, location of the site is given as 19N–08W–03 AAA 1. The final digit (1) is the sequence number of the site within the smallest fractional subdivision. For example, if three data collection sites were located within the same quarter-quarter-quarter section, they would be uniquely identified as AAA 1, AAA 2, and AAA 3.

Each site identification number or station number in this report is assigned a unique identification number. This number is unique in that it applies specifically to a given station and to no other. The number usually is assigned when a station is first established and is retained for that station indefinitely.



GEOHYDROLOGY OF ALLUVIUM AND TERRACE DEPOSITS OF THE CIMARRON RIVER FROM FREEDOM TO GUTHRIE, OKLAHOMA

By Gregory P. Adams and DeRoy L. Bergman

Abstract

Ground water in 1,305 square miles of Quaternary alluvium and terrace deposits along the Cimarron River from Freedom to Guthrie, Oklahoma, is used for irrigation, municipal, stock, and domestic supplies. As much as 120 feet of clay, silt, sand, and gravel form an unconfined aquifer with an average saturated thickness of 28 feet. The 1985–86 water in storage, assuming a specific yield of 0.20, was 4.47 million acre-feet. The aquifer is bounded laterally and underlain by relatively impermeable Permian geologic units. Regional ground-water flow is generally southeast to southwest toward the Cimarron River, except where the flow direction is affected by perennial tributaries.

Estimated average recharge to the aquifer is 207 cubic feet per second. Estimated average discharge from the aquifer by seepage and evapotranspiration is 173 cubic feet per second. Estimated 1985 discharge by withdrawals from wells was 24.43 cubic feet per second.

Most water in the terrace deposits varied from a calcium bicarbonate to mixed bicarbonate type, with median dissolved-solids concentration of 538 milligrams per liter. Cimarron River water is a sodium chloride type with up to 16,600 milligrams per liter dissolved solids.

A finite-difference ground-water flow model was developed and calibrated to test the conceptual model of the aquifer under steady-state conditions. The model was calibrated to match 1985–86 aquifer heads and discharge to the Cimarron River between Waynoka and Dover.

INTRODUCTION

Ground water in the alluvium and terrace deposits along the Cimarron River in northwestern Oklahoma is used extensively for irrigation, municipal, stock, and domestic supplies. It is the major source of water for the City of Enid, the largest single user of ground water in Oklahoma. Due to the increasing demands for water within the State, the U.S. Geological Survey, in cooperation with the Oklahoma Geological Survey, conducted an investigation from 1985 to 1988 designed to provide State water managers with the quantitative knowledge necessary to manage the ground-water resources of this area effectively.

Purpose and Scope

The objectives of this report are to: (1) Describe the geologic setting of the alluvium and terrace deposits along the Cimarron River from Freedom to Guthrie, Oklahoma (fig. 1); (2) estimate the quantity of water in storage, the annual recharge, and the annual discharge from the alluvium and terrace deposits to the Cimarron River; (3) describe the water quality of the alluvium and terrace deposits; and (4) develop a mathematical model to test the conceptual model of the ground-water hydrology of the alluvium and terrace deposits.

Previous Investigations

Reed and others (1952) investigated the ground-water resources of the Cimarron terrace for a distance of about 40 miles (mi) along the north side of the Cimarron River between Cleo Springs and Dover (fig. 1). Their study described the geology of the alluvium and terrace deposits and underlying Permian rocks, presented available well information, discussed water use, feasibility of further development and ground-water yields, gave estimates of the aquifer properties, and described the surface- and ground-water-quality characteristics in the area.

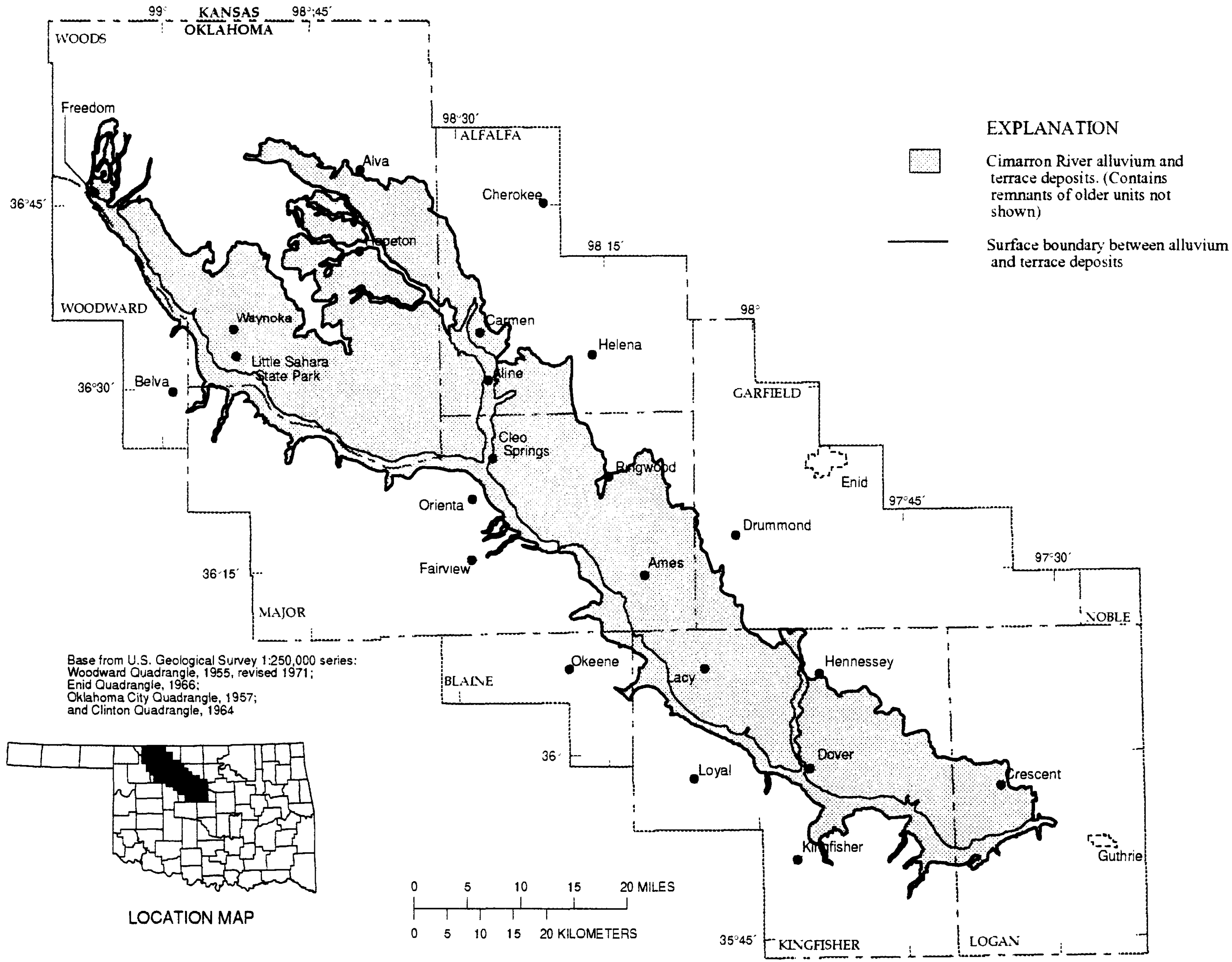


Figure 1. Location of study area.

A study done by the Oklahoma Water Resources Board (1975) demonstrated the application of surface-resistivity techniques to delineate salt-water contamination in the aquifer north of the Cimarron River from the Kansas-Oklahoma border to Guthrie, Oklahoma. The study addressed sodium chloride contamination, both from naturally occurring salt beds and from oil- and gas-production activities. The surface-resistivity technique was useful in delineating salt water in areas where bedrock was near the surface and the terrace was composed of sand.

Engineering Enterprises, Inc. (1977) conducted a study of ground-water flow and chloride contamination of several drainages in the Arkansas River Basin, including the Cimarron River. Their study included test-hole drilling, surface- and ground-water-quality sampling, measurements of streamflow in the Cimarron River and its tributaries, and delineation of areas contributing salt to surface and ground waters.

The Hydrologic Atlas series, a regional reconnaissance investigation of Oklahoma's hydrology and geology, was prepared cooperatively by the Oklahoma Geological Survey and the U.S. Geological Survey. Four atlases cover segments of the study area: The western part is in the Woodward quadrangle (Morton, 1980), the northeastern part is in the Enid quadrangle (Bingham and Bergman, 1980), the southeastern part is in the Oklahoma City quadrangle (Bingham and Moore, 1975), and the south-central part is in the Clinton quadrangle (Carr and Bergman, 1976).

Engineering Enterprises, Inc. (1982) conducted a test-drilling and ground-water-modeling study of the Cleo Springs and Ringwood well field. Field work included drilling 115 observation wells for collection of water-quality samples, instrumenting 7 monitoring wells, conducting aquifer testing at 9 wells, and collecting electric logs at 2 wells and gamma logs at 76 wells. Results of the ground-water-modeling study showed that 30 years of pumping, assuming an annual ground-water recharge of 4 inches (in.), would sustain a yield of 3.8 million gallons per day (Mgal/d) from the Cleo Springs well field, an area of 42.5 square miles (mi^2) northwest of Cleo Springs; and 2.5 Mgal/d from the Ringwood well field, an area of 26 mi^2 northwest of the confluence of the Cimarron River and Indian Creek.

Data for the present project are published in Open-File Report 94–504 "Hydrologic data for the alluvium and terrace deposits of the Cimarron River from Freedom to Guthrie, Oklahoma" (Adams and others, 1994). The report contains well and test-hole records, consisting of ground-water levels, depth of wells, and primary use of water. Water levels include continuous, daily, monthly, and periodic measurements for selected wells. Concentrations of common chemical constituents, selected trace elements, organic constituents, and tritium in water samples from wells completed in the Cimarron River alluvium and terrace deposits and Permian geologic units are reported. Winter and summer base-flow discharge measurements of the Cimarron River and tributaries to the Cimarron River are presented together with water-quality data from the measuring sites. Continuous precipitation-gage and continuous water-level data are presented graphically.

Additional reports describing the geology, hydrology and water quality of the study area are listed in the selected references.

Acknowledgments

The authors thank the personnel of the Oklahoma Water Resources Board for their cooperation in all phases of the study and for supplying data vital to the study. Special thanks are extended to the residents of the study area for their cooperation in providing access to wells and streams on their lands and for furnishing information to the U.S. Geological Survey.

DESCRIPTION OF THE STUDY AREA

The study area consists of 1,305 mi^2 underlain by Quaternary alluvium and terrace deposits associated with 115 mi of the Cimarron River from Freedom to Guthrie, Oklahoma (fig. 1). The Oklahoma Water Resources Board defines the Cimarron River "ground-water basin" to be the 1,223.0 mi^2 where the alluvium and terrace deposits contain 5 feet or more of saturated thickness. In this report the alluvium and terrace deposits associated with the Cimarron River that encompass the "ground water basin" are considered a single aquifer unit, and for convenience will be referred to as the aquifer.

Physiography and Drainage

The study area is included in the Osage Plains section of the Central Lowland physiographic province (Fenneman and Johnson, 1946). Much of the land surface is sand dunes that are stabilized by vegetation. About one-fourth of the terrace is characterized by a gently undulating to flat prairie-like surface sloping toward the river. Upland and valley slopes are vegetated by prairie grasses, small oaks, and brush. Larger trees are scattered along the flood plain of the Cimarron River and its tributaries.

The altitude of the study area ranges from 1,700 feet (ft) in the northwest to about 920 ft in the southeast. In general, local relief varies from 5 ft in the prairie-like areas to 10 to 30 ft in dune areas, with a few higher dunes in the upland. The greatest local relief occurs along the north side of the Cimarron River where some dunes reach heights of 50 to 70 ft.

The study area lies within the Cimarron River drainage basin. The Cimarron River headwaters are in Union County, New Mexico, near the New Mexico-Colorado and New Mexico-Oklahoma State lines. The river flows easterly and southeasterly through Colorado, Kansas, and Oklahoma, and terminates in Keystone Reservoir on the Arkansas River. The Cimarron River drainage basin is bounded to the south by the North Canadian River drainage basin and to the north by the Arkansas River drainage basin. The total drainage basin of the Cimarron River is about 18,927 mi^2, of which 4,927 mi^2 are non-contributing area (Oklahoma Water Resources Board, 1991). The drainage area of the study area between Freedom and Guthrie, Oklahoma, is 4,186 mi^2. This drainage area was determined from Water Resources Data for Oklahoma, Water Year 1992 (Blazs and others, 1993).

The Cimarron River is a mature, well-developed river with a defined channel and flood plain. The streambed generally is flat and sandy. South- and southeast-trending tributaries drain the alluvium and terrace deposits of the study area. In general, most tributaries have well-defined dendritic drainage. However, large areas of poorly defined surface drainage are present along the upper reaches of minor tributaries and along some drainage divides. Some of these areas do not contribute direct surface runoff to streams during storms. Flooding and inundation of the upland areas between Hoyle Creek and Preacher Creek (fig. 2) have caused major economic loss from poor drainage in the dune areas during periods of heavy precipitation, high ground-water tables, or both (U.S. Department of Agriculture, 1975b).

Perennial tributaries to the Cimarron River in the study area are Eagle Chief Creek, Indian Creek, and Turkey Creek (fig. 2). These streams originate outside the study area in Permian-age geologic units and become perennial from ground water draining the terrace deposits. In addition, Whitehorse Creek, Little Eagle Chief Creek, Dog Creek, Sand Creek, a tributary of Eagle Chief Creek, Hoyle Creek, Preacher Creek, Little Turkey Creek, West Fork Sooner Creek, and East Fork Sooner Creek (fig. 2) have sustained flow during multi-year periods of above-normal rainfall, when ground-water levels are high.

Land Use

Generalized land-cover and land-use of the study area are shown in table 1 (Mark Gregory, Oklahoma State University, written commun., 1988). Agriculture and ranching, with related service companies, are the principal land users of the region. Oil and gas production and related petroleum service companies are the principal industrial users in the area.

The number of individual farming operations declined between 1930 and the present; the remaining operations are larger in size. Increasing overhead costs, coupled with variable rainfall, were the primary reasons for this decline (Burton and Fryberger, 1974). Since the development of modern irrigation methods, the total cropland acreage has increased because irrigated, sandier lands have become profitable for cultivation. Wheat is the principal crop grown in the study area. Barley, sorghum, oats, and hay are other major crops. Beef production from farms, ranches, and feedlot operations are very important to the region. Dairy farms, sheep, and pig production are other major livestock activities (Burton and Fryberger, 1974). Little industrialization in the area has taken place, other than activities related to the petroleum industry. Oil and gas production is a major revenue producer within the area, and in many cases, it has provided the financial base for establishment of irrigation systems for individual landowners (Burton and Fryberger, 1974). The study area contains several small communities, but has no large urban areas.

Climate

The climate of the study area in the northwest is dry and in the southeast is subhumid. Most precipitation occurs as rainfall, with some light snow or sleet during the winter. Most precipitation falls during the

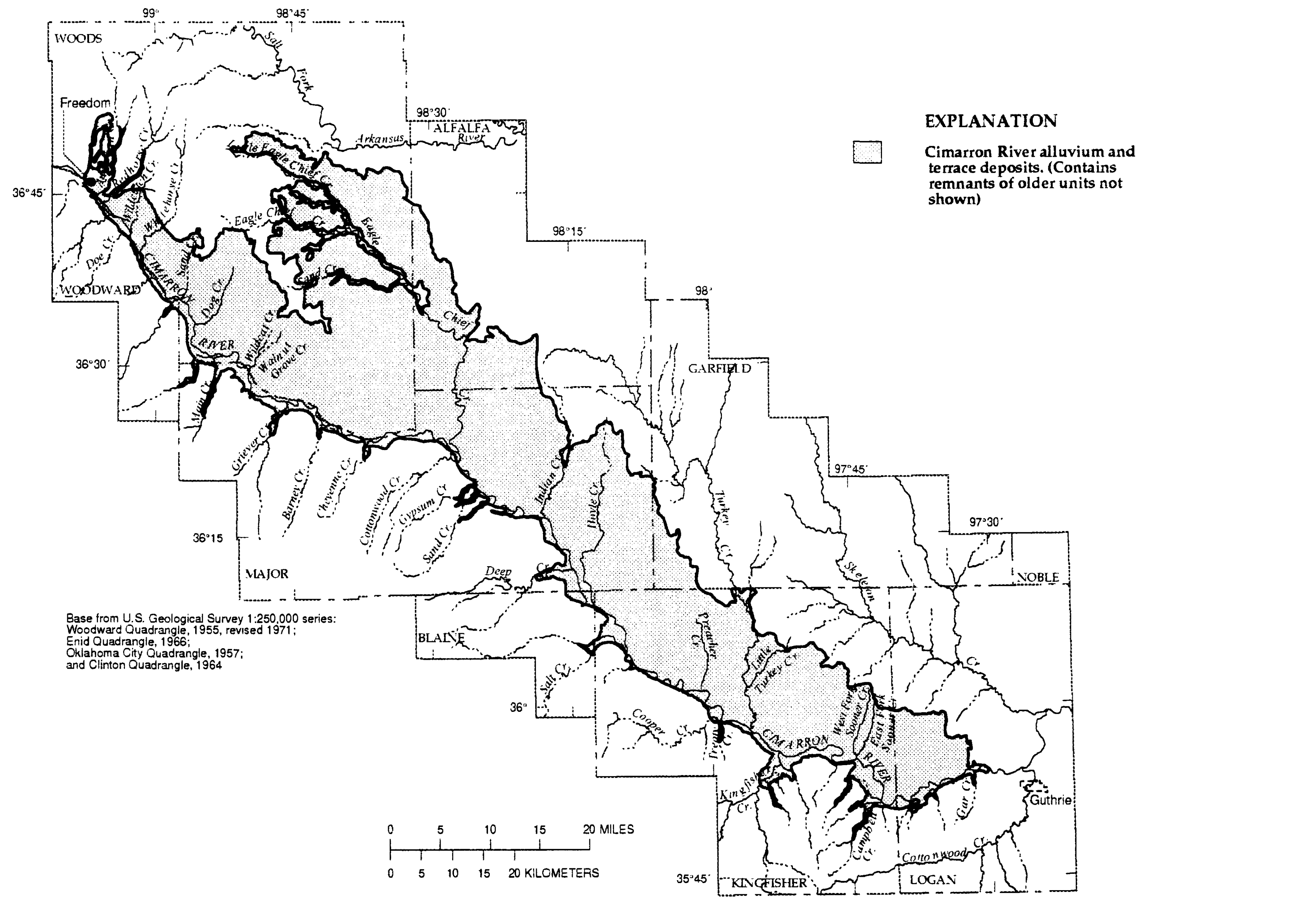


Figure 2. Rivers in study area.

Table 1. Generalized land-cover and land-use of the study area
[Source of data: Mark Gregory, Oklahoma State University, written commun., 1988]

Generalized Class[1]	Land-cover and land-use categories[1]	Percent
Non-irrigated cropland	Cropland and urban cropland	53.7
Native rangeland	Open grasslands, sand sagebrush, shinnery oak (low density), mesquite (low density), juniper or eastern red cedar (low density), blackjack-postoak brush (low density), cottonwood-elm-hackberry-willow (low density), salt cedar (low density), persimmon-winged elm-sumac-osage orange (low density), upland shrubs (blackberry, rough leaf dogwood, skunkbush, buckbrush, hawthorn, sumac, and plum-low density), and yucca or cactus	30.4
Pasture	Old world bluestems, lovegrass, bermudagrass, tall wheatgrass	5.3
Brush – upland	Shinnery oak, juniper or easter red cedar, blackjack-postoak brush, persimmon, winged elm, sumac, osage orange, blackberry, rough leaf dogwood, skunkbush, buckbrush, hawthorn, and plum	4.4
Irrigated cropland	Cropland-irrigated (alfalfa, barley, corn, peanuts, sorghum, soybeans, wheat, and other crops)[2]	1.8
Brush – bottomland	Mesquite, cottonwood, elm, hackberry, willow, and salt cedar	1.7
Urban	Urban and built-up land, urban ranchettes, farmsteads, industrial sites, confined feeding operations, quarries and gravel pits, highways, recreation land, and land fill	1.1
Sand dunes (unvegetated)	Active sand dunes	0.7
Forest – upland	Orchards, groves, horticultural crops, commercial nursery, shortleaf pine, oak, hickory, post oak, blackjack oak, and eastern red cedar	0.3
Irrigated pasture	Old world bluestems, lovegrass, bermudagrass	0.3
Forest – bottomland	Bottomland hardwoods, bottom woodlands, forested (wetlands), and pecan groves	0.1
Wetlands	Wetland-non-forested (grass and or shrubs)	0.1
Water	Water, water and bare sand channel, and sewage lagoon	0.1
		Total 100.0

[1] Generalized class and land-cover and land-use categories are based on Soil Conservation Service classification system.
[2] Oklahoma Water Resources Board, written commun., 1989.

spring and summer months during moderate to intense storms. May, June, and September are normally the wettest months (fig. 3). National Climatic Data Center precipitation records show that the 1950–90 average annual precipitation ranged from approximately 24 in. in the northwest to approximately 32 in. in the southeast (fig. 4). The mean of these average annual precipitation amounts at Freedom, Kingfisher, Waynoka, and Guthrie is approximately 27 in. The area is subject to prolonged periods of deficient rainfall with annual precipitation as little as 55 percent of the long-term average. During the period of study (1985 through 1988) precipitation was slightly above the long-term average except for 1988, which was slightly below average. Seasonal variations of precipitation across the study area for 1950–90 are illustrated in figure 3.

The prevailing wind direction is southerly, although northerly winds prevail from November through March. Average monthly wind velocity varies

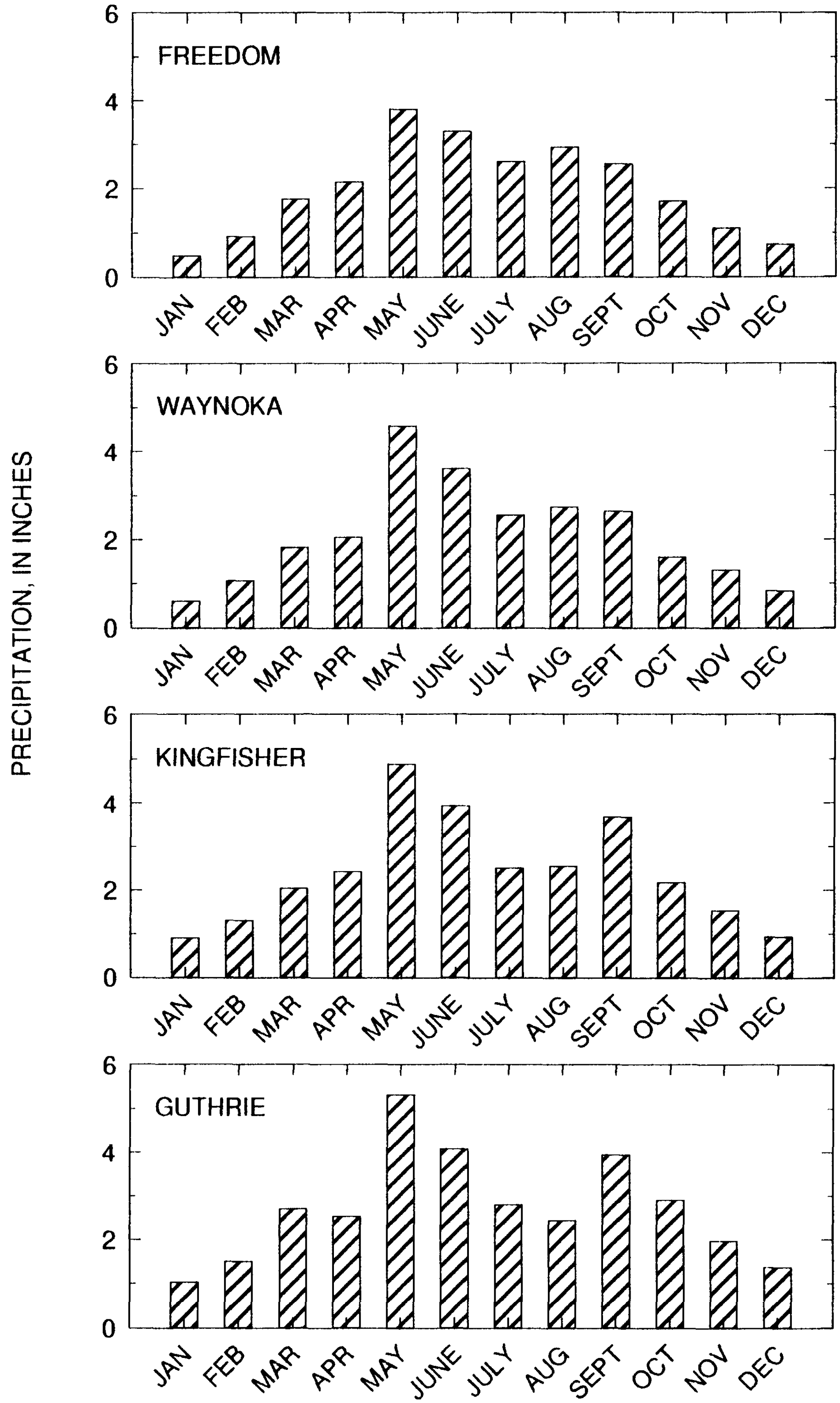


Figure 3. Average monthly precipitation at Freedom, Kingfisher, Waynoka, and Guthrie, Oklahoma, calendar years 1950-90. (National Climatic Data Center, Asheville, N.C.)

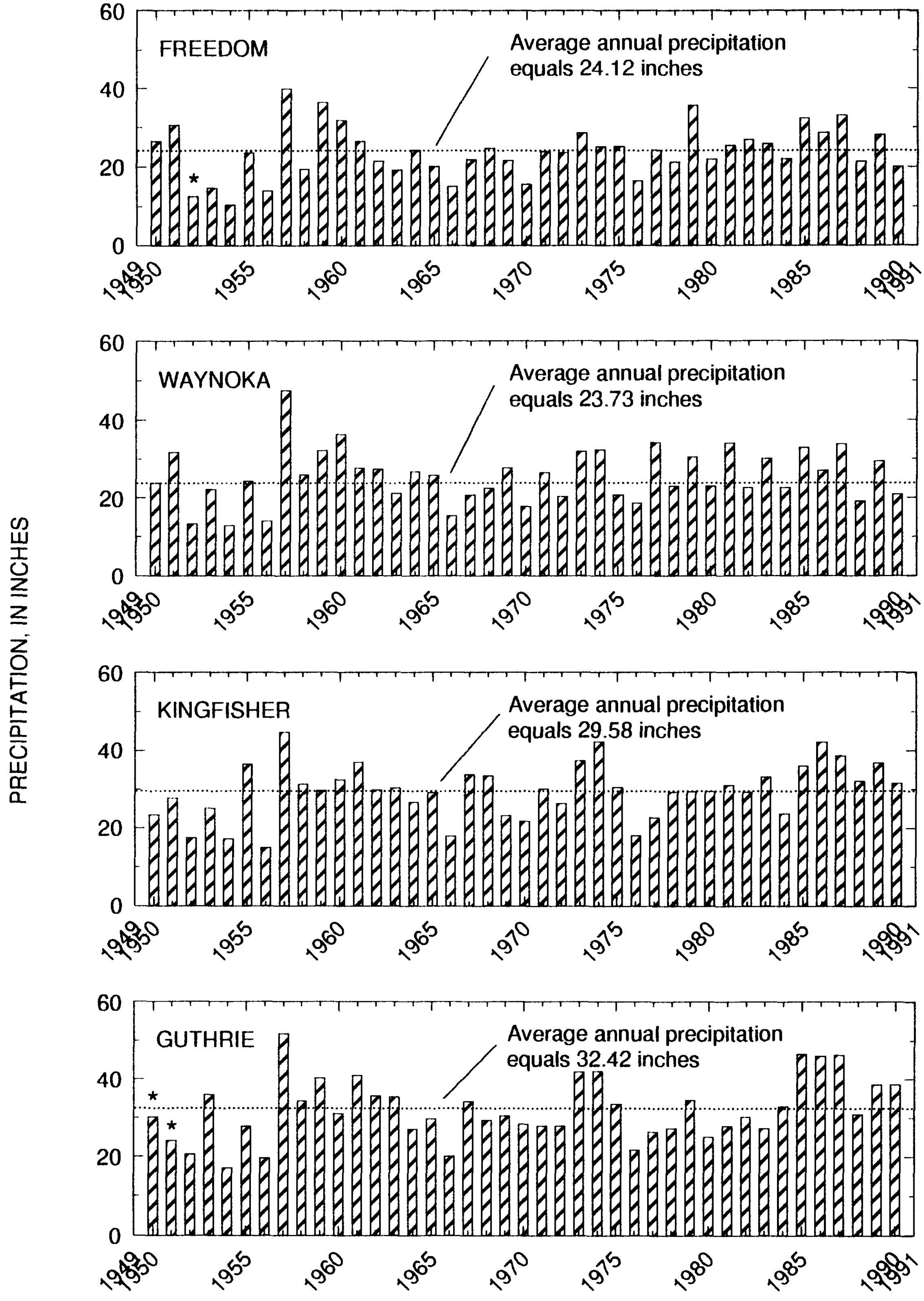


Figure 4. Annual precipitation at Freedom, Kingfisher, Waynoka, and Guthrie, Oklahoma, calendar years 1950-90. (National Climatic Data Center, Asheville, N.C.) [*-incomplete record]

from 15 mi per hour in March and April to 11 mi per hour in July and August (Burton and Fryberger, 1974).

Geologic Framework

The rocks exposed within the study area are sedimentary and range in age from Permian to Quaternary (fig. 5). The rocks of Permian age are a clastic and evaporite sequence that strikes generally to the northwest and have regional south to southwest dips ranging from 4 to 30 ft/mi (Morton, 1980). Within the study area, Permian geologic units crop out in isolated areas where streams have eroded the alluvium and terrace deposits. Permian geologic units consist primarily of a thick sequence of red shales, fine-grained sandstones, siltstones, dolomite, gypsum, and salt beds (Morton, 1980; Bingham and Bergman, 1980; Bingham and Moore, 1975; and Carr and Bergman, 1976). The strata are generally red to reddish-brown and locally are referred to as red beds. The Permian geologic units crop out in northwesterly trending bands with the oldest formation found at the southeast end of the study area (fig. 5). These units, in ascending order, are the Wellington Formation, Garber Sandstone, Hennessey Group, Cedar Hills Sandstone basal unit of El Reno Group, El Reno Group (except Cedar Hills Sandstone), Whitehorse Group, and Cloud Chief Formation.

The Quaternary deposits consist of alluvium, terrace deposits, and dune sand. These deposits unconformably overlie the Permian geologic units. Terrace deposits were laid down by the ancestral Cimarron River as it migrated southwesterly down the regional dip of the underlying Permian geologic units. The terrace deposits are composed of interfingering lenses of clay, sandy clay, and cross-bedded poorly sorted sand and gravel. The color is predominantly reddish brown, but it ranges to brown, gray, and black. Scattered pebbles and cobbles are found in much of the clay. Quartz is the predominant constituent of the gravels, and other constituents are feldspar, ferruginous shale, and quartzitic sandstone (Reed and others, 1952). Thickness of the terrace deposits varies from zero to 120 ft. Variation in thickness over the study area is attributed to erosional features existing in the underlying Permian and variations in deposition and erosion of terrace deposits. Discussion of different types of depositional and facies deposits and their locations was considered outside the scope of this study.

Alluvium associated with the Cimarron River and its main tributaries represents the present cycle of river erosion and redeposition of detrital sediments. Cimarron River alluvium thickness averages more than 20 ft, but varies from zero to about 50 ft. Alluvium is lithologically similar to the adjoining terrace deposits. The alluvium is separated from higher terrace deposits by a well-defined topographic break (Reed and others, 1952).

The dune-sand deposits are wind-laid river-channel sediments that form a strip ranging from 7 to 10 mi in width north of the Cimarron River floodplain (Reed and others, 1952). Their placement is believed to be caused by the prevailing southerly winds (Reed and others, 1952). Dune material consists of brown to reddish-brown, fine to coarse sand, containing small amounts of argillaceous material and calcareous cement (Reed and others, 1952). Dune heights are as much as 70 ft. A few large dunes are unvegetated in the area, the most notable of which are in Little Sahara State Park south of Waynoka (fig. 1).

HYDROLOGY

Surface Water

Streamflow in the study area is sustained by ground-water discharge from the Cimarron River alluvium and terrace deposits. The major perennial streams of the study area are the Cimarron River, Eagle Chief Creek, Indian Creek, and Turkey Creek.

U.S. Geological Survey streamflow gaging stations on the Cimarron River have been located in the study area (fig. 6) south of Freedom at the old State Highway 50 bridge (station number 07157980), at the western edge of the study area, from October 1973 to September 1980; south of Waynoka at the U.S. Highway 281 bridge (station number 07158000), from September 1903 through December 1905 and from October 1937 to the present (1994); south of Dover at the U.S. Highway 81 bridge (station number 07159100), near the eastern edge of the study area, from October 1973 to the present; and north of Guthrie (station number 07160000) downstream from the study area, from October 1937 through September 1976, and from October 1983 to the present.

Streamflow gaging-station data are unavailable for tributaries to the Cimarron River that drain Cimar-

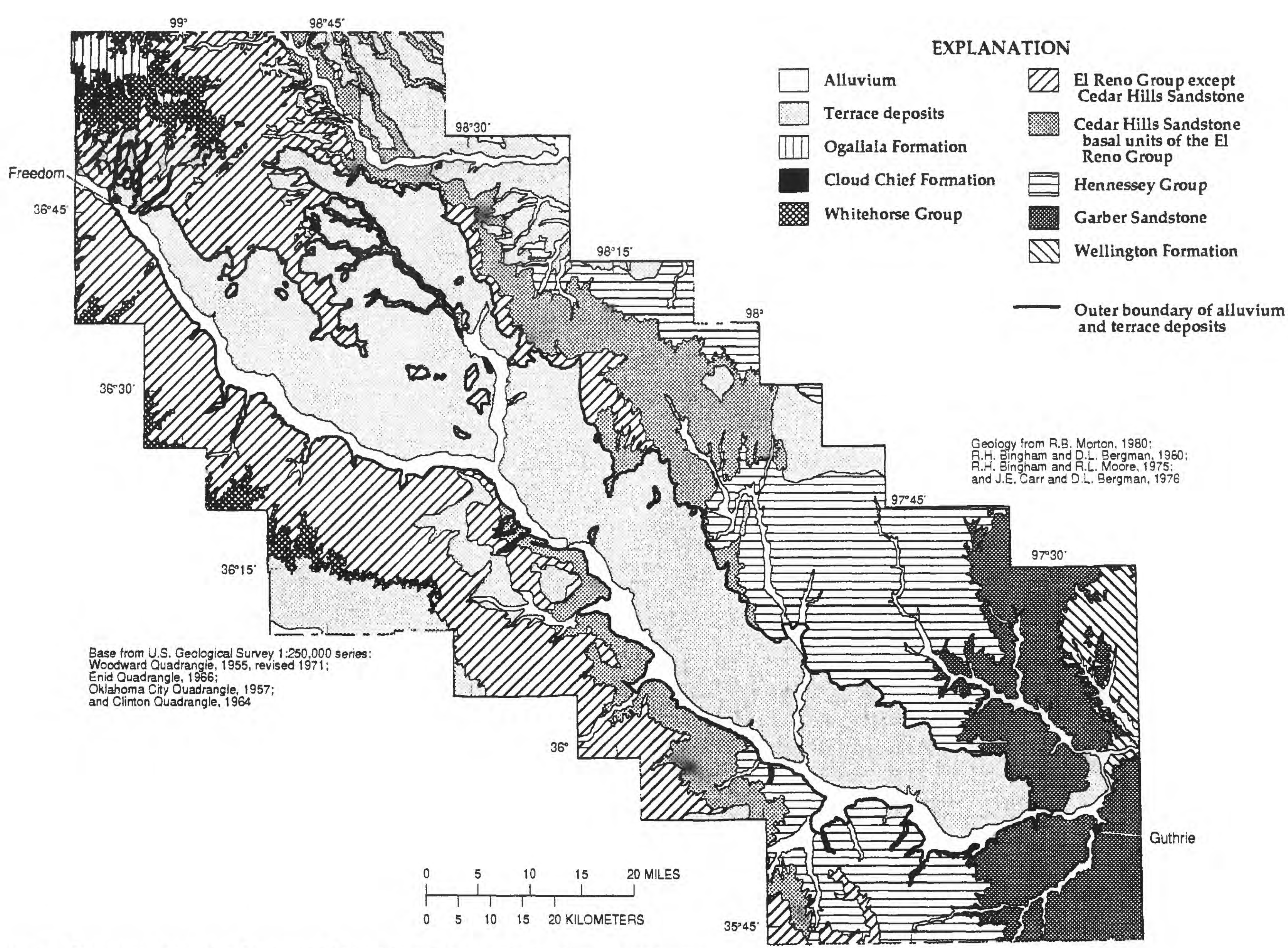


Figure 5. Geology along the Cimarron River from Freedom to Guthrie, Oklahoma.

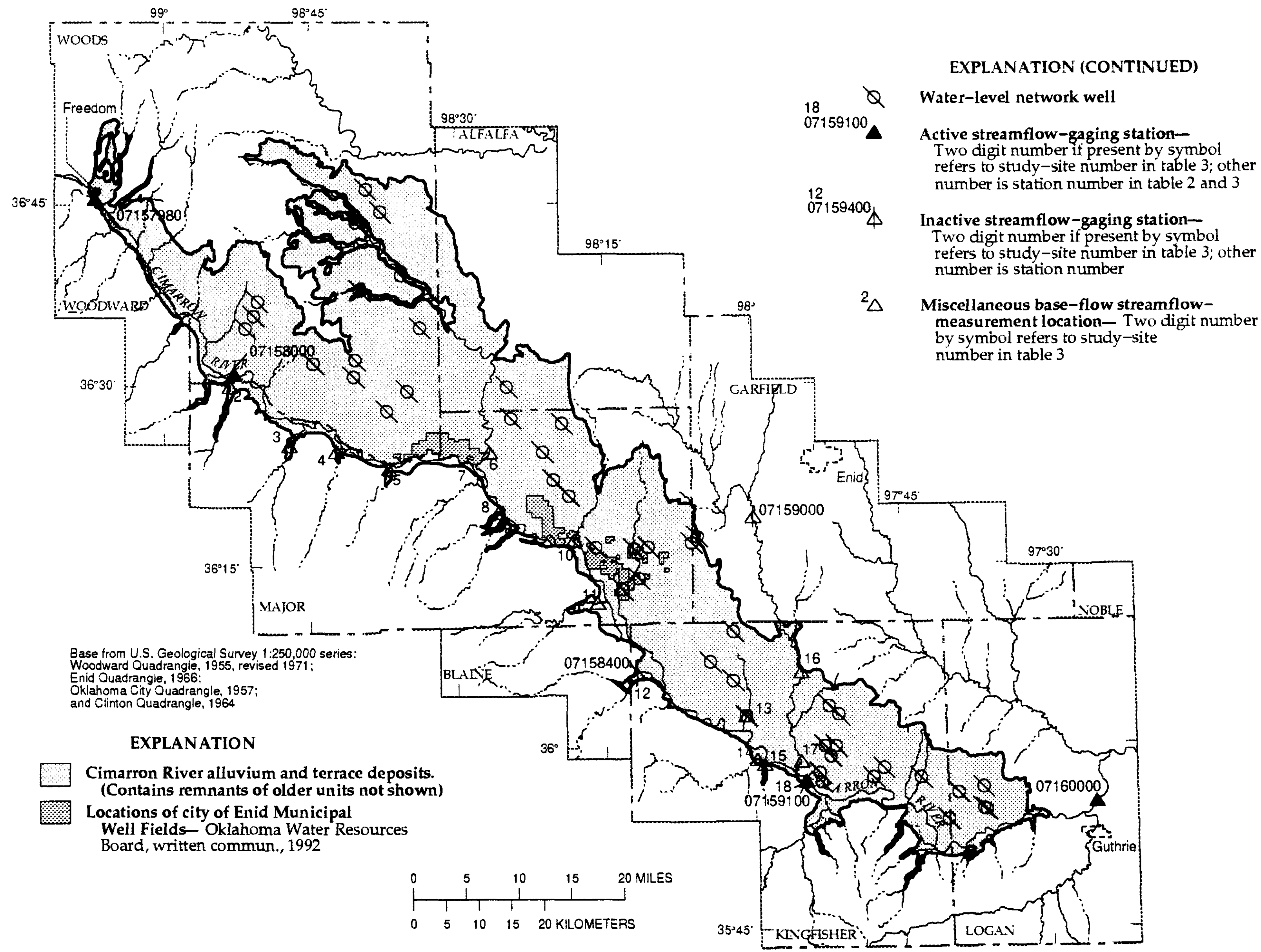


Figure 6. Location of network wells, streamflow-gaging stations, and base-flow stream-measuring sites along the Cimarron River from Freedom to Guthrie, Oklahoma.

ron River alluvium and terrace deposits. However, gaging-station data are available for two tributaries to the Cimarron River that drain the Permian geologic units north and south of the river outside of the study area (fig. 6): Salt Creek near Okeene (station number 07158400), 1973-80, 1986, 1988; and Turkey Creek near Drummond (station number 07159000), 1947-48, 1952-53, 1955-56, and 1976. Low flows of Salt Creek are sustained by mineralized outflow from springs in the Flowerpot Shale, part of the El Reno Group (Engineering Enterprises, Inc., 1977).

The drainage areas between streamflow gaging stations at Freedom, Waynoka, Dover, and Guthrie along the Cimarron River are given in table 2. Also included in the table are the total area, ground-water-basin, and contributing areas of the Cimarron River alluvium and terrace deposits.

Base flow to the Cimarron River between Dover and Guthrie is augmented by sewage outflows from Bethany, Oklahoma City, and Edmond which are located 24 to 16 mi south of the study area (cities are not shown on fig. 1). Sewage outflows are conveyed by Cottonwood Creek to the Cimarron River just upstream from the gaging station at Guthrie (Oklahoma Department of Environmental Quality, oral commun., 1993). Therefore, low flow from the drainage area between Dover and Guthrie does not reflect natural base-flow conditions and was not used in estimating aquifer discharge.

Analyses of Cimarron River streamflow data for the Freedom, Waynoka, Dover, and Guthrie gaging stations from 1973 through 1990 indicate that the intervening stream reaches are gaining reaches. Days of no streamflow occurred at times during most years on the Cimarron River near Freedom and Waynoka, while perennial flow occurred during the same period on the Cimarron River near Dover and Guthrie. A comparison of streamflow for the gaging stations at Waynoka and Dover is illustrated by flow-duration curves in figure 7. These curves illustrate the percent of time that the daily mean discharge has equalled or exceeded any given value during the period 1973–90. For example, 50 percent of the time a flow of 87.9 cubic feet per second (ft^3/s) or more occurred for the Cimarron River near Waynoka; 50 percent of the time a flow of 272 ft^3/s or more was present for the Cimarron River near Dover. Daily values duration hydrographs were calculated from a method described by Wilson (1981) from U.S. Geological Survey data.

The upper segment of the flow-duration curve represents the direct surface-runoff characteristic of the stream, whereas the lower end of the flow-duration curve represents the low-flow characteristic of the stream. The difference in curve slopes at the lower end of the flow-duration curves for the Waynoka and Dover gaging stations illustrates the significant gain in base flow along the Cimarron River reach between Waynoka and Dover.

Three main perennial gaining streams drain the aquifer within the study area: Eagle Chief, Indian, and Turkey Creeks. In addition, parts of Whitehorse, Dog, Little Eagle Chief, Sand, Hoyle, Preacher, Little Turkey, West Fork Sooner, East Fork Sooner Creeks, and several unnamed tributaries not shown on the figures receive ground-water outflow from the alluvium and terrace deposits during periods of high ground-water levels during this study (1985–88). A few low-flow measurements were made at sites along some of these streams during past years: Eagle Chief Creek near Aline (station number 07158100), 1953–55 and 1961–73; Indian Creek near Ringwood (at locations 21N–10W–14 BBB and 21N–10W–20 B), 1950 (Reed and others, 1952); Hoyle Creek near Ames (station number 07158140), 1950–52; Preacher Creek near Dover (station number 07158500), 1950–52; and Turkey Creek near Dover (station number 07159203), 1950.

Eagle Chief Creek provides a substantial contribution of base flow to the Cimarron River. The drainage basin of Eagle Chief Creek at Cleo Springs (station number 07158105) comprises 480 mi^2, of which about 397 mi^2 is underlain by terrace deposits. The stream channel is incised into the underlying Permian geologic units near the town of Carmen. Eagle Chief Creek is an intermittent stream above its contact with the terrace deposits and becomes perennial below the contact. Reaches of Little Eagle Chief Creek, Sand Creek, and several unnamed tributaries not shown on the figures provide small perennial flows to Eagle Chief Creek. Sand Creek is a perennial stream from 3.5 mi. south of the town of Hopeton to Eagle Chief Creek.

Indian Creek near Ringwood (station number 361723098175701) drains 75.4 mi^2, of which 51.1 mi^2 is underlain by terrace deposits. The Indian Creek channel is incised into underlying Permian geologic units from about 2 mi downstream from the town of Ringwood to the terrace deposits contact and again is

Table 2. Drainage areas between streamflow gaging stations at Freedom, Waynoka, Dover, and Guthrie along the Cimarron River

[mi^2, square mile: ≥, greater than or equal to]

Station number (see figure 6)	Station name	Drainage area between stations[1] (mi^2)	Total area of Cimarron River alluvium and terrace deposits[2] (mi^2)	Area of Cimarron River alluvium and terrace deposits[3] with saturated thickness ≥ 5 ft (ground-water basin) (mi^2)	Contributing area of the Cimarron River alluvium and terrace deposits to the Cimarron River[4] (mi^2)
07157980	Cimarron River at Freedom, Okla.	628	138.0	110.8	109.8
07158000	Cimarron River near Waynoka, Okla.				
07158000	Cimarron River near Waynoka, Okla.	2,379	991.6	938.2	899.4
07159100	Cimarron River near Dover, Okla.				
07159100	Cimarron River near Dover, Okla.	1,179	175.7	174.0	158.0
07160000	Cimarron River near Guthrie, Okla.				
	Total	4,186	1,305.3	1,223.0	1,167.2

1. Drainage areas calculated from Blazs and others (1993).

2. Total area of the Cimarron River alluvium and terrace deposits between the two gaging stations was measured from geologic maps (Morton, 1980; Bingham and Bergman, 1980; Bingham and Moore, 1975; and Carr and Bergman, 1976). The remaining drainage area is underlain by Permian geologic units and isolated alluvium and terrace deposits.

3. Area of Cimarron River alluvium and terrace deposits containing 5 ft or more of saturated thickness (ground-water basin) between the two gaging stations was measured on a saturated thickness map (fig. 10).

4. Contributing area of the Cimarron River alluvium and terrace deposits to the Cimarron River and its perennial tributaries between the two gaging stations was measured on a potentiometric surface map (fig. 8); 55.8 mi^2 is non-contributing to the Cimarron River and its perennial tributaries.

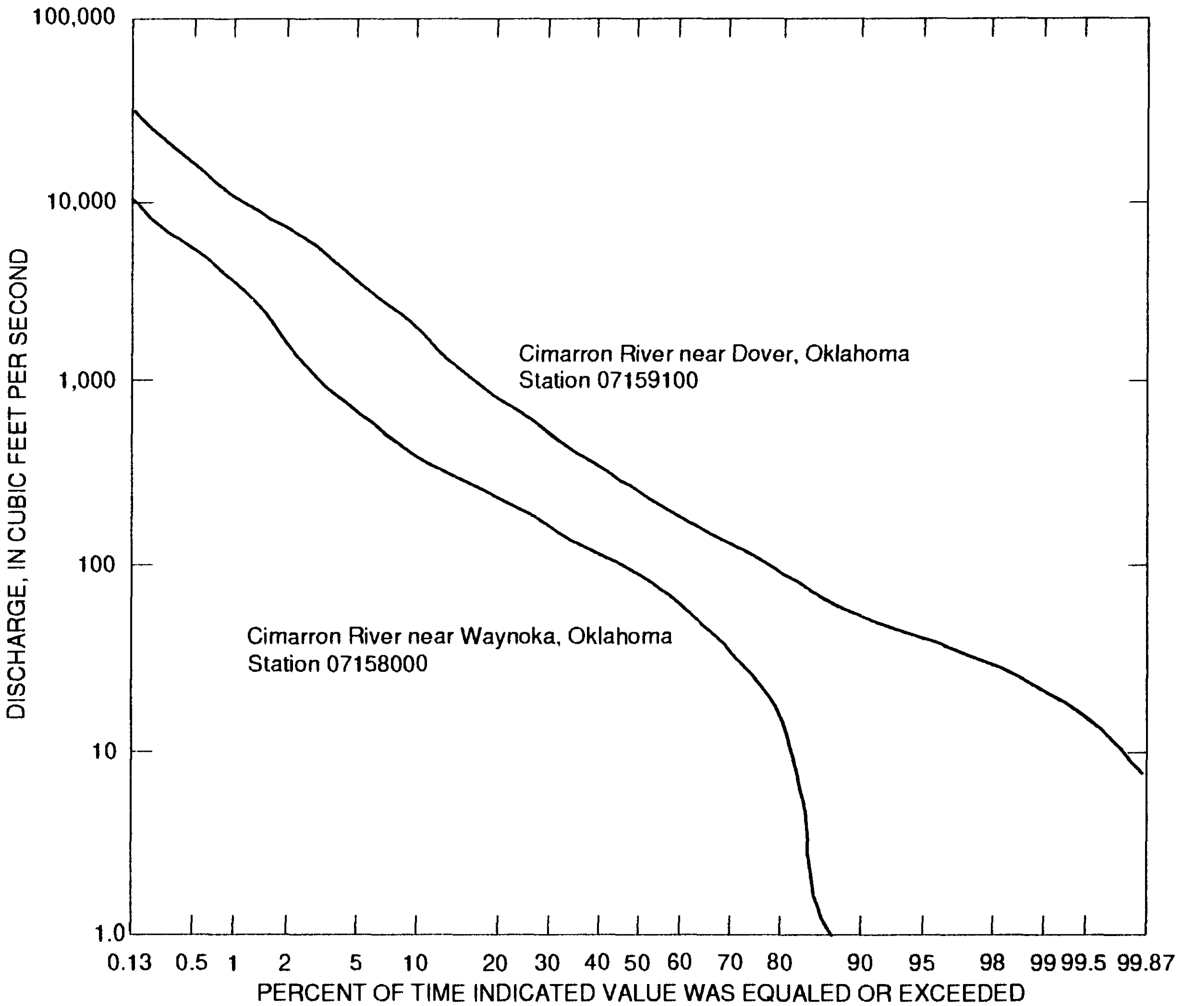


Figure 7. Flow-duration curves of daily mean streamflows for Waynoka and Dover gaging stations, 1973–90.

incised into Permian geologic units from near its confluence with the Cimarron River. Indian Creek is a perennial stream from below Ringwood downstream to the Cimarron River.

Turkey Creek at Dover (station number 355842097551201) drains 428 mi^2, of which about 180 mi^2 is underlain by alluvium and terrace deposits. Turkey Creek becomes a perennial stream near its contact with terrace deposits near the town of Hennessey. Little Turkey Creek provides a small perennial flow to Turkey Creek that originates from thin terrace deposits south of Hennessey.

Six streams originate in the terrace deposits: Whitehorse, Dog, Hoyle, Preacher, West Fork Sooner, and East Fork Sooner Creeks. Whitehorse and Dog Creeks provide small perennial flows to the Cimarron River. Hoyle and Preacher Creeks are classified as intermittent streams in an earlier report (Reed and others, 1952), but reaches of these streams were perennial during the period of this study (1985–88). These creeks probably have sustained flow when ground-water levels in the surrounding terrace are high. Hoyle Creek originates within a 1–mi^2 marsh-like floodplain area and flows to northwest of Ames, where flow decreases downstream. Southwest of Ames, flow in Hoyle Creek increases and the stream enters an extensive, low marshy area with poor drainage. The decrease in flow along the reach north and south of Ames probably is caused by infiltration induced by pumpage of several municipal supply wells along the creek. Flow for Preacher Creek near Dover (station number 07158500), which has a drainage area of 14.5 mi^2, originates within a marshy area. West Fork Sooner and East Fork Sooner Creeks (station numbers 355540097442301 and 355540097440701) are perennial streams and have drainage areas of 9.8 and 11.2 mi^2, respectively. These flows originate within the terrace deposits.

Seven intermittent streams drain the aquifer within the study area: Anderson, Redhorse, Wildcat, Sand, Dog, and Walnut Grove Creeks.The channels of Anderson, Redhorse, and Wildcat Creeks originate in Permian geologic units.

Ground water is the source of base flow in streams, and flow volume is related to ground-water levels, hydraulic gradient, and hydraulic conductivity of the aquifer. Base flow increases with rises in ground-water levels and decreases with declines in ground-water levels. The highest ground-water altitudes are during the winter when evapotranspiration losses and ground-water use are minimal; the lowest ground-water altitudes are in the summer when evapotranspiration losses and water use are at a maximum.

Analysis of base flow can be used to estimate recharge to an aquifer, provided the aquifer is in equilibrium and reliable estimates of ground-water use can be obtained. If there is no change in storage, ground water discharges to streams at approximately the same rate as the aquifer receives recharge, less the ground-water use. A series of measurements and estimates of base flow in the Cimarron River and its tributaries was made in 1986. The measurements were made during a period in which surface-water runoff from storms had dissipated. Therefore, streamflow was considered to be from ground-water contributions only. The base-flow measurements were used to evaluate the difference in areal contribution to the Cimarron River between tributaries draining the Permian geologic units north and south of the river and tributaries draining the aquifer north of the river. This information was used to approximate the average annual recharge and discharge for the aquifer. (see "Recharge" and "Discharge" sections)

Two series of base-flow measurements and estimates were made in 1986 to evaluate the source of base flow in the Cimarron River in the study area (tables 3 and 4). The first series of measurements was obtained in late February when water levels were at yearly highs and evapotranspiration negligible. A second series was obtained in September when water levels were at yearly lows and evapotranspiration was high. Streamflow measurements and estimates were obtained at 16 tributaries to the Cimarron River between the stream gages at Waynoka and Dover (figs. 1 and 6). Twelve sites were on tributaries draining the Permian geologic units north and south of the river (table 3) and four sites on streams draining the aquifer north of the river (table 4).

The measurements made in February 1986 indicate that the total base-flow gain in the Cimarron River between the Waynoka and Dover gaging stations was 171 ft^3/s. The contributing area of the aquifer to the Cimarron River and its perennial tributaries between these two stations was measured on the potentiometric map as 899.4 mi^2 (fig. 8). The contribution of flow from streams draining the Permian geologic units was 38.1 ft^3/s, which was deducted from the total base-flow gain. The total contribution from the aquifer within the 899.4 mi^2 area to the Cimarron River was

Table 3. Measurements and estimates of base flow in the Cimarron River and tributaries draining Permian geologic units within the drainage area between gaging stations located near Waynoka and Dover, Oklahoma

[mi^2, square miles: ft^3/s, cubic feet per second; --, no data]

Study site number (see figure 6)	Station number	Station name	Drainage area (mi^2)	Winter		Summer	
				Date	Discharge (in ft^3/s)	Date	Discharge (in ft^3/s)
1	07158000	Cimarron River near Waynoka, Okla.	13,334 [2](4,830)	02-25-86	[1]133	09-23-86	[1]5.6
18	07159100	Cimarron River near Dover, Okla.	15,713 [2](4,926)	02-25-86	[1]304	09-24-86	[1]77
Total gain in reach:					171		71.4
Inflow to Cimarron River from streams draining Permian geologic units							
2	07158010	Main Creek near Waynoka, Okla.	89.7	02-25-86	7.63	09-24-86	3.67
3	362446098470001	Griever Creek near Waynoka, Okla.	88.8	02-25-86	2.10	09-24-86	.66
4	362414098420201	Barney Creek near Orienta, Okla.	41.1	02-25-86	.28	09-24-86	No flow
5	362137098370501	Cheyenne Creek near Orienta, Okla.	38.8	02-25-86	.29	09-24-86	.05
7	362150098282301	Cottonwood Creek at Orienta, Okla.[3]	54.3	02-25-86	.27	09-24-86	No flow
8	361901098260701	Gypsum Creek near Fairview, Okla.[3]	13.8	02-25-86	.05	09-03-86	No flow
9	361835098252601	Sand Creek near Fairview, Okla.[3]	41.8	02-24-86	1.14	09-23-86	.26
11	07158130	Deep Creek near Okeene, Okla.[3]	110	--	[4]2.49	--	[4].80
12	07158400	Salt Creek near Okeene, Okla.	196	02-24-86	13.7	09-23-86	[5]4.87
14	355902097594501	Cooper Creek near Dover, Okla.	116	02-24-86	3.44	09-22-86	.95
15	355810097590501	Treaty Creek near Loyal, Okla.	6.86	02-24-86	.12	09-22-86	.08
16	07159045	Turkey Creek at Hennessey, Okla.	392	--	[6]6.60	--	[6]2.41
Total inflow from contributing Permian geologic units					38.1		13.8
Total inflow from Cimarron River alluvium and terrace deposits					133		57.6

1. Mean-daily discharge from active gaging-station record.
2. Probable non-contributing drainage area.
3. Permian geologic units contain small areas of isolated terrace deposits
4. Flow estimate from average equivalent annual discharge rate of selected tributaries draining Permian geologic units.
5. Mean-daily flow estimate from median mean-daily 7-day low-flow computation for gaging-station record: 1961-67, 1974-79.
6. Mean-daily flow estimate extrapolated by ratio from mean-daily 7-day low-flow computation for upstream gaging-station number 07159000 for record: 1960-70.

Table 4. Measurements and estimates of base flow from major perennial streams draining the Cimarron River alluvium and terrace deposits within the drainage area between gaging stations located near Waynoka and Dover, Oklahoma

[mi^2: square miles; ft^3/s, cubic feet per second]

Study site number (see figure 6)	Station number	Station name	Drainage area (mi^2)	Winter		Summer	
				Date	Discharge (ft^3/s)	Date	Discharge (ft^3/s)
6	07158105	Eagle Chief Creek at Cleo Springs, Okla.	480	02–25–86	24.7	09–24–86	16.0
10	361723098175701	Indian Creek near Ringwood, Okla.	75.4	02–25–86	6.72	09–23–86	3.56
13	07158500	Preacher Creek near Dover, Okla.	14.5	02–24–86	2.34	09–23–86	.86
17	355842097551201	Turkey Creek at Dover, Okla.	428	02–24–86	[1]21.8	09–23–86	[1]7.51
Total inflow from major perennial streams draining the Cimarron River alluvium and terrace deposits					55.6		27.9

[1] Discharge adjusted for Cimarron River alluvium and terrace drainage contributing area.

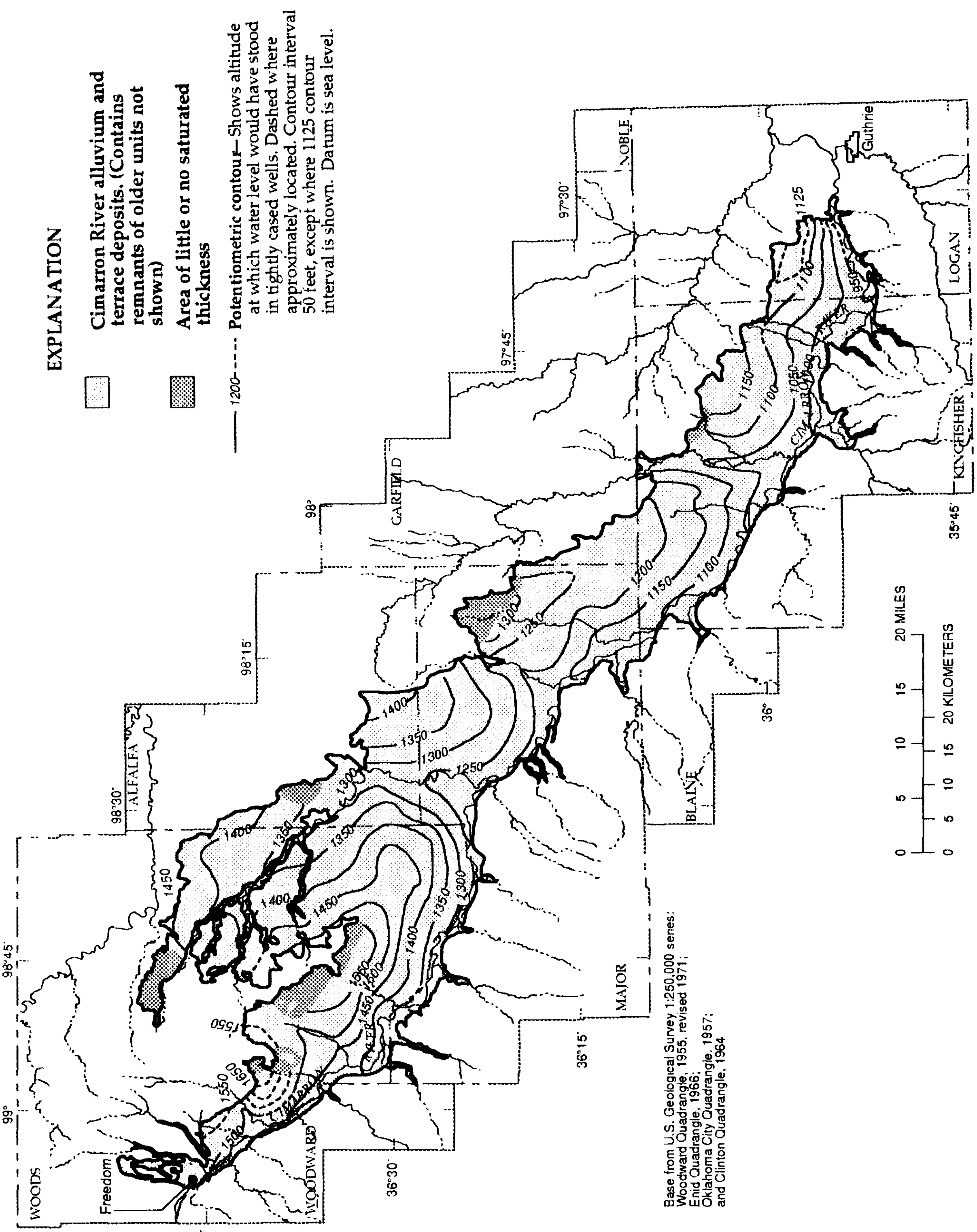


Figure 8. Potentiometric surface of the Cimarron River alluvium and terrace deposits from Freedom to Guthrie, Oklahoma, 1985–86.

133 ft^3/s. Of this 133 ft^3/s, contribution of flow from major perennial streams draining the aquifer is 55.6 ft^3/s (table 4). The remaining 77.4 ft^3/s is considered base flow from the north side of the Cimarron River, an average contribution of 0.90 ft^3/s per river mile. Contribution from the south side, other than the 38.1 ft^3/s, is considered negligible because of the low hydraulic conductivity of the Permian geologic units.

In September 1986, the total base-flow gain within the reach of the Cimarron River between the Waynoka and Dover gaging stations was 71.4 ft^3/s. The contribution of flow from streams draining the Permian geologic units was 13.8 ft^3/s, leaving the total base flow from the aquifer to the Cimarron River of 57.6 ft^3/s. Of this 57.6 ft^3/s, major perennial streams draining the aquifer account for 27.9 ft^3/s (table 4). The remaining 29.7 ft^3/s is considered base flow from the north side of the Cimarron River, an average of 0.35 ft^3/s per river mile.

To determine if the winter and summer base-flow measurements made in 1986 were representative of long-term averages, historic streamflow records were examined for the Waynoka and Dover gaging stations. For this analysis, total gain in the February 7–day low flow between the two stations and total gain in the September 7–day low-flow based on a 2–year recurrence interval for 1974–90 were compared, as shown below:

February		September	
Measured base flow	7–day, 2–year recurrence interval low flow	Measured base flow	7–day, 2–year recurrence interval low flow
171 ft^3/s	149 ft^3/s	71.4 ft^3/s	59 ft^3/s

In any given year the probability is 50 percent that the average difference in minimum flow between Waynoka and Dover for 7 consecutive days will be less than 149 ft^3/s in February and less than 59 ft^3/s in September. The measured base flows of 171 ft^3/s in February and 71.4 ft^3/s in September are considered to be representative of total base-flow gain for the reach of Cimarron River between Waynoka and Dover gaging stations, because the statistical 7-day, 2–year recurrence interval low-flow values of total gain are in reasonable agreement with the measured base-flow values.

To determine if the measured February base-flow total gain of 171 ft^3/s is representative of an average annual base-flow for 1985–86, a streamflow hydrograph separation technique described by Olmsted and Hely (1962) was used. A total average annual base-flow value of 170 ft^3/s was determined by stream-flow hydrograph separation method using 1985–86 streamflow hydrographs from the Cimarron River at Waynoka and Dover gaging stations. Thus the measured February base flow is considered representative of average annual base flow within the reach of Cimarron River between Waynoka and Dover gaging stations.

Ground Water

The principal aquifer in this study area consists of Quaternary alluvium and terrace deposits associated with the Cimarron River. The aquifer boundaries were determined from geologic maps from Morton (1980), Bingham and Bergman (1980), Bingham and Moore (1975), and Carr and Bergman (1976), and from field checks during the investigation.

Ground water in the zone of saturation is contained in the voids of the unconsolidated alluvium and terrace deposits. Unconfined conditions exist in an aquifer when the upper surface of the water is not confined by an overlying relatively impermeable unit and the water surface is free to fluctuate at atmospheric pressure. Regionally, the aquifer is an unconfined aquifer, although it may be confined locally by silt and clay layers. Yields from wells generally range from about 5 gal/min for stock and domestic wells to 500 gal/min for industrial, irrigation, and municipal supply wells.

The underlying Permian geologic units, other than the Cedar Hills Sandstone and the Garber Sandstone, are relatively impermeable. These underlying units consist of clastic and evaporite sequences with low hydraulic conductivity that allow limited flow of water from and to the aquifer.

Wells drilled into the Cedar Hills Sandstone generally have small yields, not always sufficient for stock supplies, because of low transmissivity in sandstone. Locally, wells penetrating lenticular sandstones in the Cedar Hills Sandstone yield sufficient water for stock supply or municipal needs when completed in both the Cedar Hills Sandstone and terrace deposits. The areal and vertical extent of these lenticular sandstones is not known. No large-capacity wells are present in the Garber Sandstone north of the Cimarron River because the transmissivity is small (Parkhurst and others, 1993). Because of the relatively small transmissivities of the Cedar Hills Sandstone and Garber Sandstone, as compared to the alluvium and terrace deposits, the volume of water flowing between these Permian geologic units and the aquifer is considered to be negligible for purposes of this study.

The configuration of the base of the aquifer is shown on figure 9. The data used to prepare this map were compiled from Permian bedrock-altitude data from previous investigations (Reed and others, 1952; Oklahoma Water Resources Board, 1975), drillers' well-log data, and altitude of well depth from the U.S. Geological Survey's National Water Information System (NWIS) data base. Most wells in the study area are drilled to the top of the Permian geologic units.

A potentiometric surface is a surface that represents the static hydraulic heads. As related to an aquifer, the potentiometric surface is defined by the levels to which water will rise in tightly cased wells (Lohman and others, 1972). A potentiometric-surface map of the aquifer was constructed by contouring measurements of head in wells and the altitude of perennial streams (fig. 8). The potentiometric data were obtained from water-level measurements made from 1985 through 1986 (Adams and others, 1994). Horizontal ground-water movement is perpendicular to potentiometric contours and in the direction of lower head. Higher head occurs at topographically high areas farthest from the Cimarron River and its major perennial tributaries; areas of low head occur near the Cimarron River and its major perennial tributaries. Regional ground-water flow is generally southeast to southwest towards the Cimarron River, except where the flow direction is affected by perennial tributaries to the Cimarron River. The potentiometric contours form a "V" pointing upstream and intersecting the Cimarron River and its perennial tributaries, indicating that ground water is discharging to these perennial streams, which is corroborated by streamflow measurements. The potentiometric contours also show no areas where the "V's" are pointing downstream, which would indicate that surface water is discharging to the aquifer. Although streamflow losses were observed near Ames caused by pumpage, additional control would better define the areas of streamflow loss on the potentiometric map.

In several areas along the northeastern boundary of the aquifer the potentiometric surface (fig. 8) indicates that ground water is flowing away from the Cimarron River and its perennial tributaries to the northeast out of the aquifer. Ground water is thought to flow through Permian geologic units and discharge into Eagle Chief Creek, Indian Creek, Turkey Creek, and Skeleton Creek. In several areas as shown on figure 8, the terrace deposits have little or no saturated thickness, which precludes significant ground-water flow between these areas and adjacent terrace deposits. None of these areas were used in measurements of aquifer contributions to base flow of the Cimarron River and its tributaries.

The altitudes of wells used to prepare the base-of-aquifer and the potentiometric-surface maps were derived from the U.S. Geological Survey 7.5–minute topographic maps. The accuracy of these determinations is considered to be plus or minus 10 ft. Thus, the base-of-aquifer and potentiometric-surface maps are considered accurate to within plus or minus 10 ft.

The difference between the altitude of the 1985–86 potentiometric surface and altitude of the base of the aquifer is the saturated thickness of the aquifer (fig. 10). A contour map of the saturated thickness was developed by subtracting the interpolated values discretized on the center of 1–mi^2 grids of the altitude of the base of the aquifer (fig. 10) from the interpolated values discretized on the center of 1–mi^2 grids of the altitude of the potentiometric surface (fig. 8) using a management and statistical program called the Modular Model Statistical Processor (MMSP) for analysis (Scott, 1989). The saturated thickness ranges from zero at the boundary of the aquifer to more than 110 ft. The saturated thickness decreases along the Cimarron River and major tributaries. The average saturated thickness of the aquifer calculated by MMSP was 28 ft in 1985–86. Calculated volumes of water in storage in the "ground water basin" (1,223 mi^2) in 1985–86, assuming specific yields of 0.15, 0.17, and 0.20, are 3.35 million acre-feet, 3.80 million acre-feet, and 4.47 million acre-feet, respectively.

Hydraulic Properties

The hydraulic properties of an aquifer describe its ability to transmit and store water. Transmissivity,

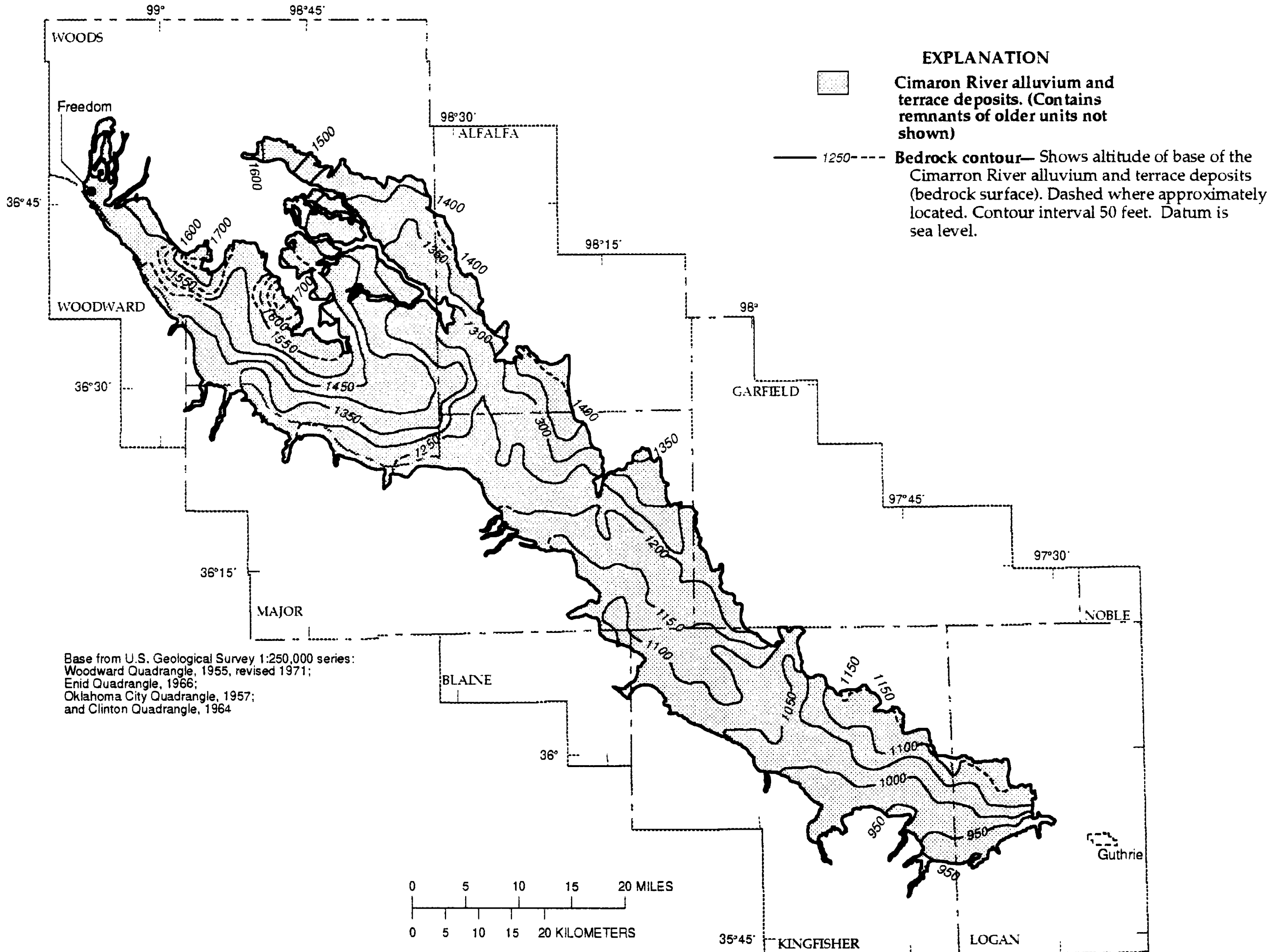


Figure 9. Configuration of the base of the Cimarron River alluvium and terrace deposits from Freedom to Guthrie, Oklahoma.

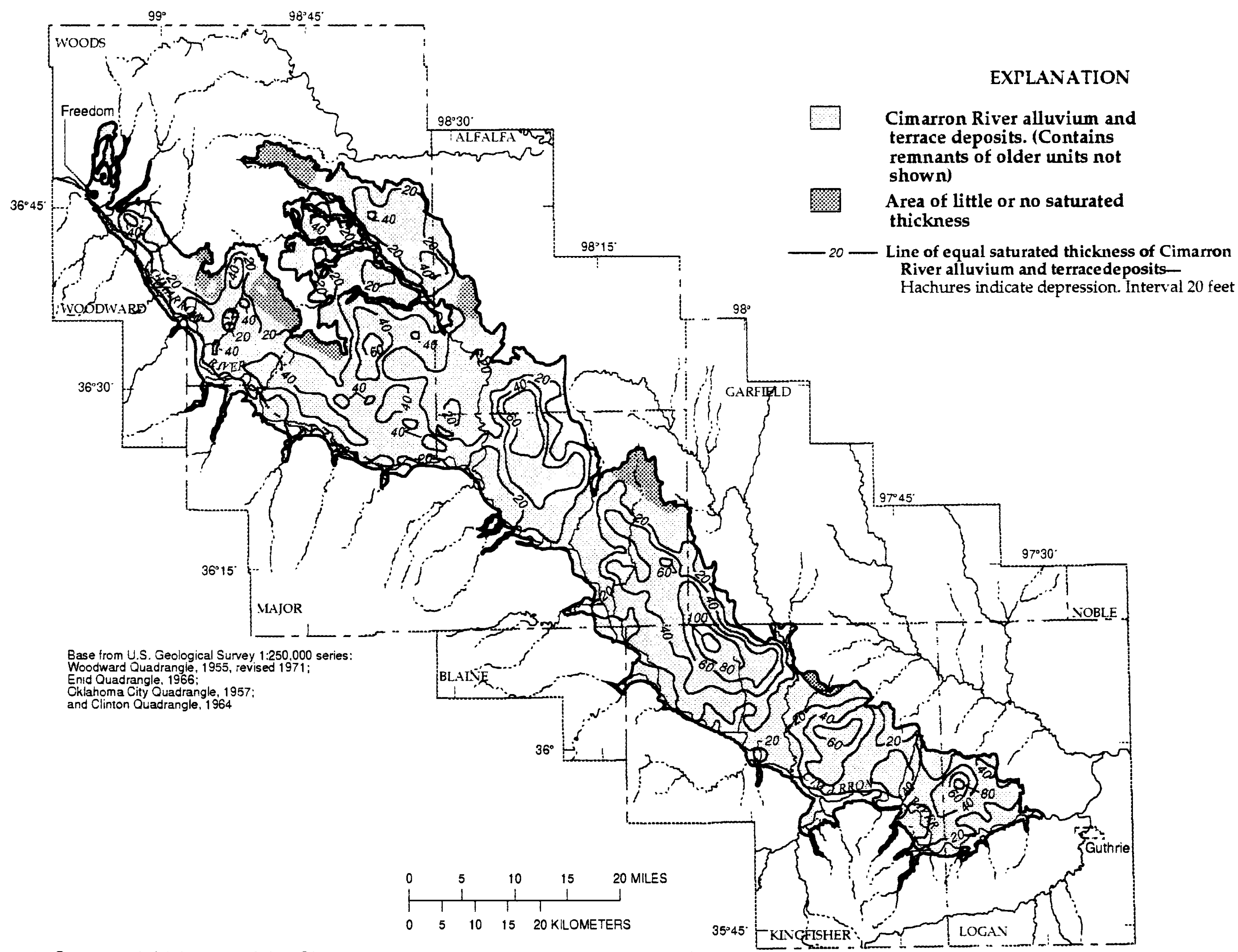


Figure 10. Saturated thickness of the Cimarron River alluvium and terrace deposits from Freedom to Guthrie, Oklahoma, 1985–86.

hydraulic conductivity, and specific yield have been determined or estimated from 23 selected aquifer tests of the alluvium and terrace deposits conducted by previous investigators (Reed and others, 1952; Engineering Enterprises, 1977, 1983).

The transmissivities estimated from aquifer tests range from 603 to 10,184 square feet per day (ft^2/d). The hydraulic conductivity values range from 15 to 542 feet per day (ft/d). The median hydraulic-conductivity value for the alluvium is 221 ft/d and for terrace deposits 98 ft/d. The ratio of median hydraulic conductivity of alluvium to terrace deposits is 2.3:1.

Specific yields as determined from aquifer tests range from 0.0016 to 0.39, with a median value of 0.067. The lower specific yields in this range are low for an alluvium and terrace aquifer; these values typically range from 0.1 to 0.25. The lower values probably are due to the short duration of some of the aquifer tests, which may result in incomplete drainage of the initially saturated sediments within the cone of depression.

Recharge

Recharge to the aquifer includes deep percolation of precipitation, irrigation return flow, leakage through stream channels, and subsurface inflow through alluvium.

Deep percolation of precipitation

Infiltration of precipitation is the major source of recharge to the aquifer. Only a small amount of the total precipitation recharges the aquifer. Most precipitation is lost by evapotranspiration or surface runoff. When precipitation exceeds the infiltration capacity of the soil zone, most of the excess runs over the land surface to streams. Part of the surface runoff is evaporated. Some precipitation infiltrates the ground and the infiltration rate depends upon soil type, land cover, and land use. Precipitation that enters the ground is partially retained in the shallow soil zone (unsaturated zone) by capillary action. Much of this water is returned to the atmosphere by transpiration from vegetation and evaporation from the land surface. The remaining water percolates downward to the water table by gravity, and is considered recharge to the aquifer.

Locally, recharge from precipitation depends partly on the infiltration rate of soils. The soils overlying the aquifer have a moderate to rapid infiltration rate. The soil types are predominantly sandy, well-drained soils that do not vary greatly over the study area (U.S. Department of Agriculture, 1950, 1960, 1962, 1967, 1968, 1975a).

Average base flows of streams are indicators of recharge to aquifers within their drainage basins, provided that the aquifers are in or near equilibrium and that a good estimate of ground-water withdrawals can be obtained. Under equilibrium conditions water should discharge to streams at about the same rate as the aquifer receives recharge. An estimate of the average annual recharge rate to the aquifers may be obtained by dividing the average annual base flow plus the average annual pumpage by the area of the drainage basin.

As discussed in the "Base Flow" subsection of this report, base flow from the aquifer to the Cimarron River and perennial tributaries between the Waynoka and Dover gaging stations, measured during February 1986, was 133 ft^3/s (table 3). This measurement is representative of long-term average conditions. Only 899.4 mi^2 of the aquifer are contributing the measured base flow in this reach of the Cimarron River, because of the location of the measurement reach between Waynoka and Dover. Of the 1,223.0 mi^2 included in the Oklahoma Water Resources Board "ground-water basin," only 1,167.2 mi^2 of the ground-water basin are contributing to the Cimarron River. By linear extrapolation, the ground-water flow from 1,167.2 mi^2 of contributing area of the aquifer to perennial tributaries and to the Cimarron River is estimated to be 173 ft^3/s. The recharge rate then was estimated by dividing the extrapolated base-flow estimate (173 ft^3/s) plus the reported average annual pumpage (24.43 ft^3/s, see section on "Withdrawals") by contributing drainage area (1,167.2 mi^2), to give a recharge rate of 2.3 inches per year (in/yr). This recharge amount is approximately 8 percent of the 27 in/yr mean average annual precipitation for the study area. Assuming an average rate of 2.3 in/yr, the average recharge to the 1,167.2 mi^2 of contributing area and 55.8 mi^2 of non-contributing area (discharge out of aquifer) of the aquifer is 207 ft^3/s.

Irrigation return flow

In addition to recharge from precipitation, return flow from irrigation water derived from the aquifer is estimated to be the second largest recharge source for the aquifer. Applied irrigation water is returned to the aquifer through deep percolation. No measurements of irrigation return flow to the aquifer were made; however, an estimated value of 20 percent of total irrigation water withdrawn was used. This value was used in two studies of the North Canadian River alluvium and terrace deposits in Oklahoma (Davis and Christenson, 1981; Christenson, 1983), which have hydrologic conditions similar to those in the Cimarron River alluvium and terrace deposits. If the return flow from irrigation is estimated at 20 percent of the applied water, 13.63 ft^3/s for 1985 (9,868 acre-feet, see "Water Use" section) return flow would be 2.73 ft^3/s. This applied irrigation water is not included as recharge but is subtracted from the irrigation withdrawal. Return flow of irrigation water obtained from surface-water sources was not included in this investigation because it is a minor part of the water use (Oklahoma Water Resources Board, written commun., 1989).

Leakage through stream channels

Recharge by leakage of surface water through stream channels may occur along some perennial streams as noted from field observations near Ames. (see "Surface Water" subsection) The amount of stream water recharging the aquifer is considered small because base flow measurements indicates that ground water is discharging to perennial streams and that no large reaches are losing surface water to the aquifer. This is corroborated by the potentiometric-surface map (fig. 8) that shows no large areas where the Cimarron River or perennial streams are losing water to the aquifer.

Subsurface inflow

Recharge by subsurface inflow occurs at the upstream boundaries of the study area along the Cimarron River and Turkey Creek. The alluvium extends beyond the geographic limits of the study area at these upstream locations. The amount of ground water moving into the study area at these upstream locations is dependent on the cross-sectional area through which the flow is occurring, the hydraulic gradient, and the hydraulic conductivity of the alluvium. The amount of water recharging the aquifer by subsurface inflow is small because of the small cross-sectional area of the alluvium.

Discharge

Discharge from the aquifer includes discharge to streams, evapotranspiration, withdrawals, leakage to Permian geologic units, and subsurface outflow through alluvium.

Discharge to streams

Ground-water discharge by seepage into the Cimarron River and its perennial tributaries is the principal means of discharge from the aquifer. As discussed in the "Recharge" section of this report, ground-water discharge from the 1,167.2 mi^2 of contributing area of the aquifer to the Cimarron River and its perennial tributaries is estimated to be 173 ft^3/s; this rate is considered to include the effect of evapotranspiration along streams, in following section.

Evapotranspiration

Evapotranspiration generally is defined as the evaporation or transpiration of water from open bodies of water, the unsaturated soil zone, and the shallow saturated zone. Evapotranspiration, for purposes of analysis, is limited to ground water that is discharged from the saturated zone of the aquifer to the atmosphere by evaporation from soil and transpiration by plants. Discharge of water by transpiration from shallow-rooted vegetation in the unsaturated zone and by evaporation from open bodies of water that are several feet above the water table are not considered discharge from the aquifer. Because the water table in the aquifer is generally greater than 12 feet below land surface, transpiration from the aquifer by shallow-rooted crops and grasses is not considered significant. Phreatophytes growing along major streams discharge water through transpiration. Discharge by evapotranspiration along streams is considered part of discharge from the aquifer and is considered leakage to streams for this investigation.

Withdrawals

Withdrawals of ground water for municipal, irrigation, industrial, and mining use are the second largest source of discharge from the aquifer. In 1985 withdrawals from the aquifer were 24.43 ft^3/s, which consisted of reported withdrawals, (see "Water Use" section) (table 5) for the following categories: munici-

Table 5. Permitted allocations, reported withdrawals, and classification of ground-water use from the Cimarron River alluvium and terrace deposits, 1950-88

[Sources of data: Oklahoma Water Resources Board, written commun., 1989 and City of Enid, written commun., 1993]

Calendar year	Permitted allocation, in acre-feet					Reported withdrawals, in acre-feet				
	Total	Irrigation	Municipal supply	Mining	Industrial	Total	Irrigation	Municipal supply	Mining	Industrial
1950	6,480	3,046	3,434	0	0	2,512	964	1,548	0	0
1951	7,095	3,566	3,434	95	0	2,957	1,349	1,591	17	0
1952	10,542	6,623	3,824	95	0	3,392	1,688	1,609	95	0
1953	16,696	10,257	6,344	95	0	6,303	4,527	1,684	92	0
1954	18,464	12,025	6,344	95	0	7,608	5,726	1,790	92	0
1955	19,460	12,933	6,432	95	0	9,656	6,505	3,059	92	0
1956	21,279	13,463	7,721	95	0	8,876	6,916	1,868	92	0
1957	22,043	13,663	8,205	175	0	9,330	6,965	2,193	172	0
1958	22,599	13,736	8,688	175	0	9,340	6,991	2,178	171	0
1959	22,599	13,736	8,688	175	0	9,326	7,016	2,140	170	0
1960	22,599	13,736	8,688	175	0	9,298	6,921	2,207	170	0
1961	22,773	13,910	8,688	175	0	9,179	7,079	1,931	169	0
1962	22,773	13,910	8,688	175	0	9,575	7,221	2,185	169	0
1963	23,869	13,910	9,090	869	0	9,007	6,631	2,270	106	0
1964	27,693	16,396	10,428	869	0	8,851	6,287	2,406	158	0
1965	29,281	17,984	10,428	869	0	10,400	7,067	3,092	241	0
1966	33,659	22,362	10,428	869	0	11,317	7,863	3,118	336	0
1967	42,565	29,207	11,780	1,578	0	12,257	7,953	3,700	604	0
1968	44,693	31,040	12,075	1,578	0	13,077	9,474	3,283	320	0
1969	52,181	32,020	18,319	1,598	244	11,906	8,260	3,002	506	138
1970	68,186	41,622	24,722	1,598	244	15,607	11,167	3,618	822	0
1971	76,495	48,491	26,162	1,598	244	19,561	14,190	4,294	1,077	0
1972	84,684	56,139	26,403	1,898	244	24,137	18,314	4,289	1,290	244

Table 5. Permitted allocations, reported withdrawals, and classification of ground-water use from the Cimarron River alluvium and terrace deposits, 1950-88—Continued

Calendar year	Permitted allocation, in acre-feet					Reported withdrawals, in acre-feet				
	Total	Irrigation	Municipal supply	Mining	Industrial	Total	Irrigation	Municipal supply	Mining	Industrial
1973	93,803	63,539	28,122	1,898	244	19,517	14,411	4,029	1,077	0
1974	103,167	71,623	29,402	1,898	244	19,536	14,392	4,073	1,071	0
1975	105,621	74,077	29,402	1,898	244	19,682	14,976	3,270	1,436	0
1976	108,875	77,331	29,402	1,898	244	27,806	22,060	4,967	779	0
1977	112,423	80,879	29,402	1,898	244	26,272	19,515	5,447	1,309	0
1978	113,583	82,039	29,402	1,898	244	30,801	22,151	7,564	1,086	0
1979	116,897	85,010	29,745	1,898	244	26,216	20,963	4,524	729	0
1980	119,217	86,850	30,225	1,898	244	20,862	14,507	5,610	745	0
1981	131,270	98,623	30,505	1,898	244	19,468	15,782	3,367	319	0
1982	140,625	99,903	38,252	2,218	252	23,040	18,560	3,988	491	1
1983	142,479	100,063	39,946	2,218	252	17,228	12,966	3,719	543	0
1984	142,924	100,345	40,106	2,218	255	22,161	16,703	5,082	376	0
1985	142,925	100,345	40,106	2,218	256	19,660	9,868	9,209	434	149
1986	143,085	100,345	40,266	2,218	256	18,056	9,924	7,828	303	1
1987	143,238	100,395	40,266	2,218	359	16,150	9,434	6,412	303	1
1988	143,238	100,395	40,266	2,218	359	17,427	10,041	7,082	303	1

pal, 12.72 ft^3/s (9,209 acre-feet); irrigation, 13.63 ft^3/s (9,868 acre-feet); industrial, 0.21 ft^3/s (149 acre-feet); and mining, 0.60 ft^3/s (434 acre-feet). Withdrawals were tabulated from Oklahoma Water Resources Board water-use system and ground-water rights files (James Summers, Oklahoma Water Resources Board, written commun, 1989), and from the City of Enid pumpage records (Robert Hill, City of Enid, written commun., 1993). An irrigation withdrawal rate of 10.90 ft^3/s, 80 percent of the reported value was used in the water-budget, because 20 percent was considered return flow.

Leakage to Permian geologic units

Leakage to Permian geologic units is the discharge of ground water from the aquifer to Permian geologic units. Evidence of leakage occurs in limited areas. As discussed in the "Ground Water" section, in several areas along the northern boundary of the study area, ground water flows northeast out of the aquifer, seeps through Permian geologic units, and discharges into Eagle Chief, Indian, Turkey, and Skeleton Creeks. The amount of leakage to the Permian units depends on the cross-sectional area of flow, the hydraulic gradient, and the hydraulic conductivity of the Permian units. The volume of flow from the aquifer to the Permian units is small, because of the relatively small hydraulic conductivity of the Permian as compared to the alluvium and terrace deposits. No base-flow measurements were available for this combined contributing area of 55.8 mi^2.

Subsurface outflow

Discharge by subsurface outflow occurs at the downstream boundary of the study area along the Cimarron River where the alluvial deposits are narrow, approximately 1 mile wide. The alluvium extends beyond the geographic limits of the study area at this downstream location. The amount of ground water moving out of the study area depends on the cross-sectional area through which the flow is occurring, the hydraulic gradient, and hydraulic conductivity. The amount of water discharging from the aquifer by subsurface outflow is small because of the small cross-sectional area of the alluvium at the downstream boundary.

Changes in Water Levels

Seasonal ground-water fluctuations and annual long-term trends were evaluated from monthly water-level measurements of 45 network wells, periodic measurement of 6 wells, and continuous water-level measurements of 4 wells (Adams and others, 1994). The locations of the 45 monthly network wells are shown on figure 6.

Records of monthly water-level measurements (Adams and others,1994) in 45 network wells (fig. 6) indicate that the average fluctuation for water year 1988 (October 1 to September 30) is about 3 ft, and fluctuations range from 0.96 to 11.49 ft for individual wells (U.S. Geological Survey records). Water-level fluctuations are seasonal; in general the highest water levels occur during late winter to late spring, and the lowest water levels occur during the summer. Seasonal water-level changes typical of the study area are shown in figure 11. Inspection of hydrographs from these 45 wells indicates that the water-level fluctuations are greatest in areas of shallow water table and in recharge areas, and are less in areas of deep water table and in discharge areas.

Water levels trend upward during years of above-normal precipitation and downward during years of below-normal precipitation. Water levels generally rose during the years 1957–62, 1973–75, and 1985–87 (fig. 12), when precipitation was near or above normal (fig. 4). Significant water-level declines occurred during the years 1951–56 and 1963–72, when precipitation was below normal (fig. 4). Hydrographs from selected long-term ground-water recorders illustrate the water-table response to the variable annual precipitation pattern, with a general trend of rising water levels (fig. 12) from about 1957 through 1987.

WATER USE

Ground water is withdrawn for municipal, domestic, industrial, mining, irrigation, and stock-watering uses inside the study area, and for some municipal, domestic, and industrial uses outside the study area. Domestic water supplies also are provided by rural water districts, serving areas within and outside the study area, that obtain water from within the study area. Surface water is used for industrial, min-

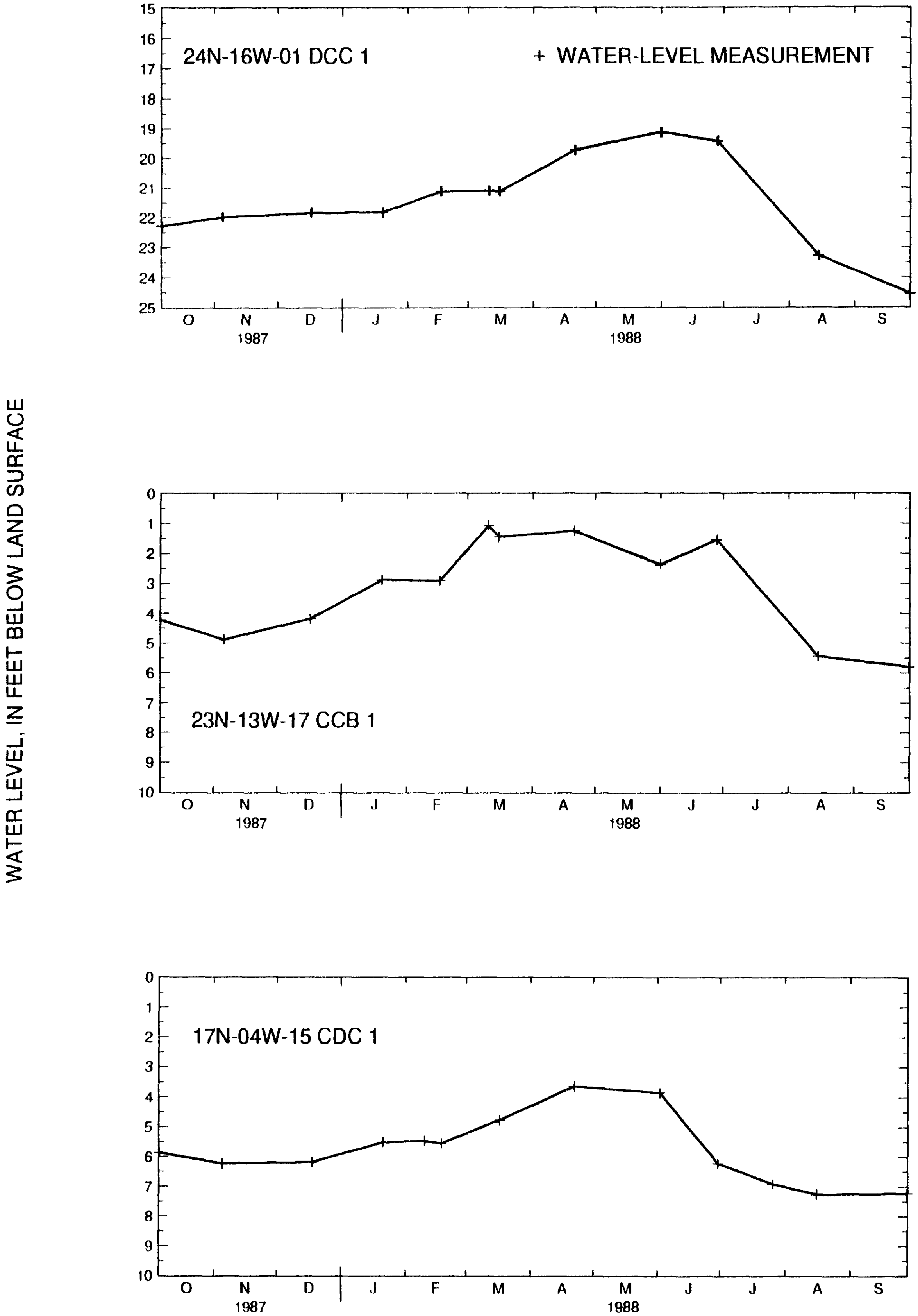


Figure 11. Water-level hydrographs of selected wells completed in the Cimarron River alluvium and terrace deposits for 1988 water year.

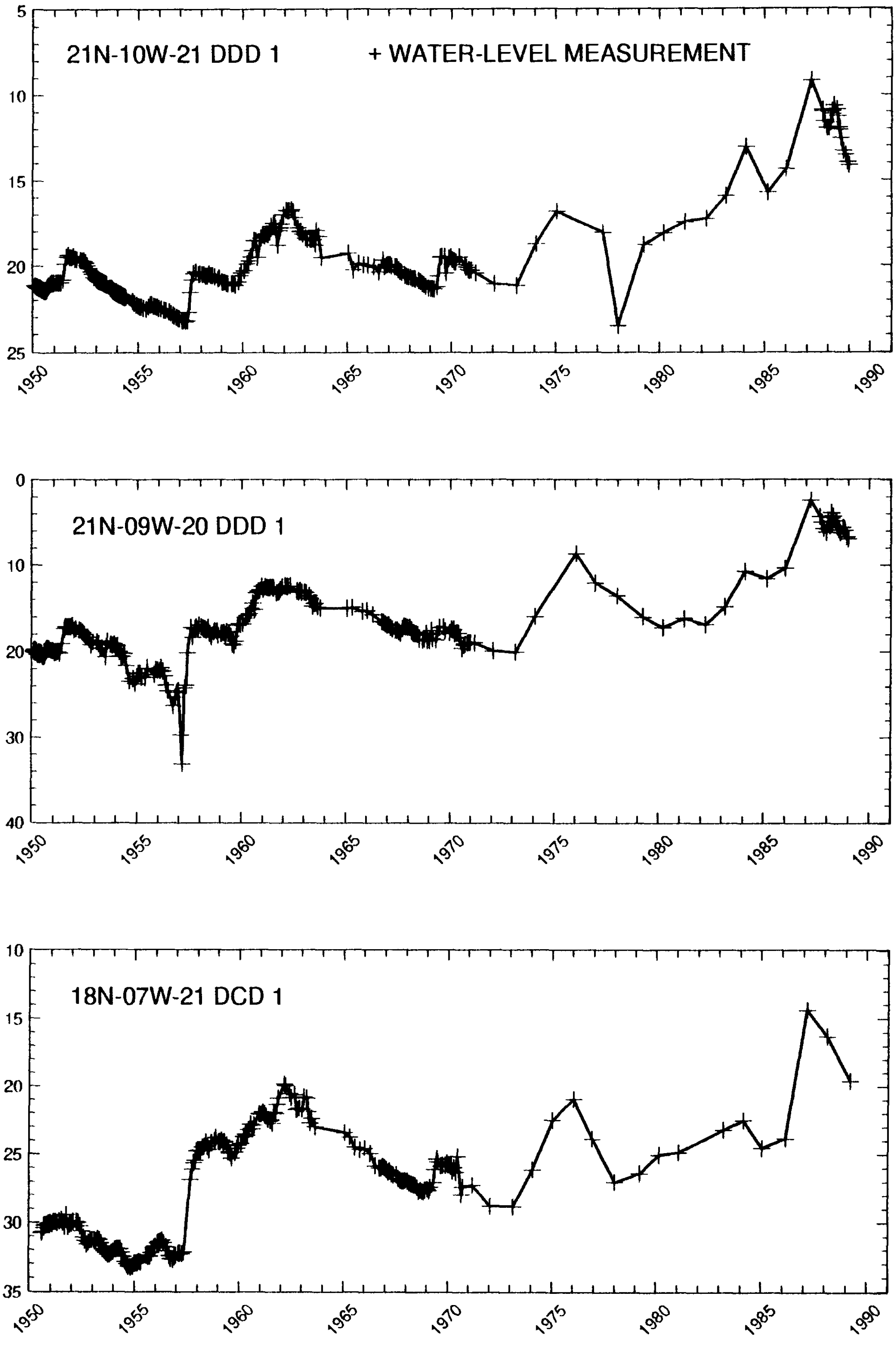


Figure 12. Water-level hydrographs of selected wells completed in the Cimarron River alluvium and terrace deposits, calendar years 1950-89, showing long-term trends. (Some water-level measurements are highest for the day from analog recorder.)

ing, irrigation, and stock-watering supplies, and for recreation, fish, and wildlife supplies.

Estimates of ground-water and surface-water withdrawals from the aquifer for uses other than private domestic and stock were obtained from the Oklahoma Water Resources Board water-use system and ground-water and surface-water rights files (James Summers, Oklahoma Water Resources Board, written commun., 1989), and from City of Enid pumpage records (Robert Hill, City of Enid, written commun., 1993). The Oklahoma Water Resources Board allocates ground water, appropriates surface water, and collects annual reported water-use data in Oklahoma. Some reported water-use withdrawals are only estimates because, under Oklahoma law, metering of water use is not required (although many municipal and industrial users are metered).

Permitted allocations, reported withdrawals, and classification of use for ground water (1950–88 calendar years) from the aquifer are shown in table 5, and appropriations of surface water (1985 calendar year) from the Cimarron River, its tributaries, and lakes within the study area are shown in table 6. Permitted allocations for ground-water withdrawal increased from 6,480 acre-feet in 1950 to 143,238 acre-feet in 1988. Total water use reported to the Oklahoma Water Resources Board from 1950 through 1988 increased from 2,512 acre-feet in 1950 to a maximum of 30,801 acre-feet in 1978, then generally declined to 17,228 acre-feet in 1983. Permitted appropriations and reported withdrawals for surface water in 1985 were 2,853 and 258 acre-feet, respectively (table 6). The largest permitted withdrawal was 1,190 acre-feet for Eagle Chief Creek, and the smallest permitted withdrawal was 40 acre-feet for West Fork Sooner Creek.

Municipal water supplies for the communities of Aline, Alva, Ames, Cleo Springs, Crescent, Dover, Enid, Fairvalley (not shown on fig. 1), Fairview, Freedom, Hennessey, Kingfisher, Okeene, Orienta, Ringwood, and Waynoka are withdrawn from the aquifer (James Summers, Oklahoma Water Resources Board, written commun., 1989). All of these communities are within the Cimarron River drainage basin except for Alva and Enid, which are in the Salt Fork of the Arkansas River drainage basin. The City of Enid is not only the largest single user of ground water from the aquifer but is the largest single user of ground water in Oklahoma. The City of Enid has developed well fields for municipal water in three areas. These well fields and the number of wells producing from the terrace aquifer are: Cleo Springs, 31 wells; Ringwood, 28 wells; and Ames, 30 wells. Well-field-pumpage policy during the time of field investigation for this study was to pump one field at a time for 1 to 3 months (Lester Long, Water Production Superintendent, City of Enid, oral commun., 1993). Water-table declines in the well fields would recover typically in 30 to 60 days (Lester Long, Water Production Superintendent, City of Enid, oral commun., 1993). Reported annual municipal use of ground-water increased from 1,548 acre-feet in 1950 to 9,209 acre-feet in 1985, then decreased to 6,412 acre-feet in 1987. The decline in withdrawals is due to a decrease in population related to a depressed economy associated with changes in the oil, natural gas, and agricultural industries (Reely, 1992). No surface-water withdrawal permits have been issued for municipal use.

Irrigation wells were first developed in the 1950's in the area between Eagle Chief Creek and Turkey Creek (James Summers, Oklahoma Water Resources Board, written commun., 1989), where most of the wells are concentrated. Later well development expanded westward to the area around Waynoka and eastward to the area around Crescent (James Summers, Oklahoma Water Resources Board, written communication, 1989). At the time of this investigation (1985–88), irrigation wells were scattered throughout the aquifer, but large areas in Woods and Alfalfa Counties had relatively small saturated thicknesses and only a few irrigation wells were present. Approximately 50,000 acres (80 mi^2), or 6 percent of the land surface overlying the aquifer in 1985, were irrigated from permitted wells.

Reported annual use of water for irrigation increased from 964 acre-feet in 1950 to 22,151 acre-feet in 1978, then decreased to 9,434 acre-feet in 1987. The smaller reported irrigation use from 1987 through 1988 was largely because of near-normal to above-normal precipitation over most of the area. Other possible reasons irrigation use declined include increased fuel costs, more efficient application, a switch to crops requiring less water, and a decrease in the number of farms. Reported annual surface-water withdrawal for irrigation use in 1985 was 206 acre-feet. Withdrawals were from Indian Creek, West Fork Sooner Creek, East Fork Sooner Creek, and unnamed tributaries.

Industrial use of water from the aquifer was relatively small from 1950 through 1988. Maximum

Table 6. Permitted appropriations, reported withdrawals, and classification of surface-water use from the Cimarron River, tributaries, and lakes within the study area for the 1985 calendar year

[Source of data: Oklahoma Water Resources Board written communication, 1989; --, no data]

Source of surface water	Permitted appropriation, in acre-feet					Reported withdrawals, in acre-feet				
	Total	Irrigation	Mining	Industrial	Recreation, fish, and wildlife	Total	Irrigation	Mining	Industrial	Recreation, fish, and wildlife
Eagle Chief Creek	1,190	1,190	--	--	--	--	--	--	--	--
Unnamed tributaries	436	406	30	--	--	60	60	--	--	--
Indian Creek	418	418	--	--	--	68	68	--	--	--
East Fork Sooner Creek	240	240	--	--	--	70	70	--	--	--
Turkey Creek	216	216	--	--	--	--	--	--	--	--
Cimarron River	103	31	--	11	61	52	--	--	10	42
Lakes	90	90	--	--	--	--	--	--	--	--
Little Turkey Creek	60	--	--	60	--	--	--	--	--	--
Little Eagle Chief Creek	60	60	--	--	--	--	--	--	--	--
West Fork Sooner Creek	40	40	--	--	--	8	8	--	--	--
Total	2,853	2,691	30	71	61	258	206	--	10	42

reported use was 244 acre-feet in 1972 and has since ranged from zero to 149 acre-feet per year. Reported industrial water use has been related mainly to the requirements of the petroleum industry, and does not include industrial use serviced by municipal systems. Reported surface-water withdrawal for industrial use was 10 acre-feet in 1985, all from the Cimarron River (table 6).

Water use reported for the purpose of mining in this region generally is that amount of water used for sand-and-gravel washing operations. The first reported ground-water use for this purpose was 17 acre-feet in 1951. This annual use increased to about 1,436 acre-feet in 1975 and decreased to about 300 acre-feet since 1986. No surface-water withdrawals were reported for mining in 1985. Recreation, fish, and wildlife use of surface water was reported to be 42 acre-feet in 1985 from the Cimarron River.

WATER QUALITY

Available Ground- and Surface-Water-Quality Data

Field water-quality measurements and chemical analyses of water samples from 50 wells located within the terrace deposits were collected during 1985-86. Specific conductance, pH, and temperature were determined at the well sites. Water samples were analyzed by the Oklahoma Geological Survey (OGS) for alkalinity (1986 samples only), dissolved common cations and anions, and trace metals. A second ground-water sampling was conducted, during 1988, when 17 samples were collected at different locations. Specific conductance, pH, and temperature were measured at the well sites. These samples were analyzed by the Oklahoma Department of Environmental Quality (DEQ), formerly the Oklahoma State Department of Health (OSDH), for alkalinity, total and dissolved common cations and anions, dissolved and total trace metals, and organic compounds (five samples). Nine samples were analyzed for tritium by the National Water Quality Laboratory of the U.S. Geological Survey in Denver.

Surface-water-quality samples and discharge measurements were obtained at 29 tributaries to the Cimarron River and at 3 gaging stations on the Cimarron River (Adams and others, 1994) during a period of base flow in February 1986. Six measurement locations were on tributary streams draining terrace deposits, and 23 measurement locations were on tributary streams draining Permian geologic units. Specific conductance, temperature, and pH were obtained at the measurement sites. Water-quality samples were analyzed by the OGS for alkalinity, dissolved common cations, anions, and trace metals. All chemical analyses of ground- and surface-water samples collected for this investigation, along with historic analyses, are presented in Adams and others (1994).

Statistical Summary of Selected Ground-Water-Quality Data and Water-Quality Standards

Summary statistics are presented in Appendix 1 for selected water-quality samples collected during the present study from wells located within the terrace deposits. The table lists methods used to calculate the percentiles for each constituent, the constituent, number of samples, highest value, lowest value, largest minimum reporting level, and selected percentiles for the constituents. Percentiles for constituents that have censored data, or data reported as less than the reporting level, were calculated by the method of Helsel and Cohn (1988). No percentiles were calculated if fewer than 10 analyses were available for a constituent. Water-quality data from four wells drilled through the terrace deposits into Permian geologic units were excluded from the data set because water from the Permian geologic units may have contributed to the water samples. The summary statistics are limited in completely representing the water-quality in the terrace aquifer because of the following biases: (1) Samples were obtained during different years, (2) there was an uneven areal distribution of the sampled wells, and (3) different laboratories and analytical methods were used in analyzing water samples. Because of the difficulty of determining appropriate corrections to these biases, no corrections were made to the statistical summary.

In addition to the statistics, selected U.S. Environmental Protection Agency (1988a, 1988b) national primary and secondary drinking-water standards are listed in Appendix 1 for constituents in the table. The primary regulations specify the maximum contaminant levels (MCL), which are the maximum permissible levels of a contaminant in water in public supplies and are health related. The secondary drinking-water regulations specify the secondary maximum contaminant levels (SMCL) for contaminants in drinking water that primarily affect the aesthetic qualities related to public acceptance of drinking water.

Data from Appendix 1 show that nitrate, total nitrite-plus-nitrate, and cadmium concentrations exceeded the MCL's in some ground-water samples from the terrace deposits. More than 50 percent of the 46 ground-water samples for nitrate analysis exceeded the MCL (10 mg/L as nitrogen). Two different analytical methods were used by the OGS and the OSDH to determine the nitrogen species, dissolved nitrate, and total nitrite plus nitrate. Figure 13 shows the locations where samples were collected for analysis of nitrate (dissolved or total) and where nitrate concentrations exceeded the MCL. Becker (1994) shows additional locations where the concentration of nitrate exceeded the MCL, for water-quality samples taken before this investigation (1985–88) in parts of Woods, Woodward, Alfalfa, and Major Counties.

The three ground-water samples that exceeded the MCL for cadmium (5 μg/L) contained high dissolved-solids concentrations and would not be used for public supplies. Concentrations of sulfate, iron, manganese, and dissolved solids exceeded the SMCL's in some of the water-quality samples. The three values for aluminum that exceeded the SMCL (50–200 μg/L) were from samples containing high dissolved solids. One field analysis for pH was less than the SMCL (6.5-8.5).

Ground-water-quality samples for the analysis of pesticides were collected from 5 wells located in the terrace deposits: 17N–04W–31 CCC 1, 17N–06W–11 DDD 1, 23N–11W–19 DAA 1, 24N–14W–23 CCC 1, and 26N–13W–07 BBB 1. The samples were analyzed for selected insecticides, herbicides, and polychlorinated biphenyls (PCB's) (Appendix 1). All concentrations for organic compounds were below the detection limits of the analyses, except for aldrin, which was detected at a concentration of 0.08 micrograms per liter (μg/L) at well 24N–14W–23 CCC 1; there is no MCL for aldrin.

Major-Element Chemistry

The major-element chemistry is shown on figures 14a, 14b, and 14c by modified Stiff (1951) water-quality diagrams and associated dissolved-solids concentrations. The water-quality diagrams show variations in major-element concentrations for ground-water samples from wells within the terrace deposits and for surface-water samples obtained during periods of base flow from streams draining the aquifer, streams draining Permian geologic units, and three gaging stations on the Cimarron River. The Stiff water-quality diagrams show ionic concentrations in milliequivalents per liter and are plotted for sodium plus potassium (Na + K), magnesium (Mg), calcium (Ca), chloride plus fluoride (Cl + F), sulfate (SO_4), and bicarbonate plus carbonate ($HCO_3 + CO_3$). Anions are plotted to the right of the vertical axis and cations to the left. The area of the diagram is an indication of the dissolved-solids concentration. Variations in shape of the diagram reflect variations in the chemical character of the water sampled.

Water-type classifications used in this report are based on ratio of milliequivalent contributions of various chemical species to total number of milliequivalents of cations and anions. The water types are determined by the predominant cation and anion. If the concentration of the cation or anion in milliequivalents per liter is greater than 50 percent of the total cations or anions, then that cation or anion is considered dominant. If no cation or anion is dominant, the water type is described as mixed.

Most water of the terrace deposits varied from a calcium bicarbonate to a mixed bicarbonate type. Ground-water samples from the terrace deposits had a median value of 538 mg/L for dissolved-solids concentration (Adams and others, 1994). Water from several wells located in the northwestern part of the terrace deposits was either a calcium sulfate or sodium chloride type. These samples contained more than 1,000 mg/L of dissolved solids. The calcium sulfate water was from Permian geologic units that crop out within or underlie the terrace. The sodium chloride water within the terrace may have been from upward leakage from underlying Permian geologic units, recharge from streams draining Permian geologic units prior to entering the terrace, or possible contamination from oil and gas production sites.

Water types from streams draining the aquifer vary. Eagle Chief Creek contained a mixed water type with sulfate the dominant anion and a dissolved-solids concentration of 1,670 mg/L. Indian, Preacher, West Fork Sooner, and East Fork Sooner Creeks also contained mixed water types with dissolved-solids con-

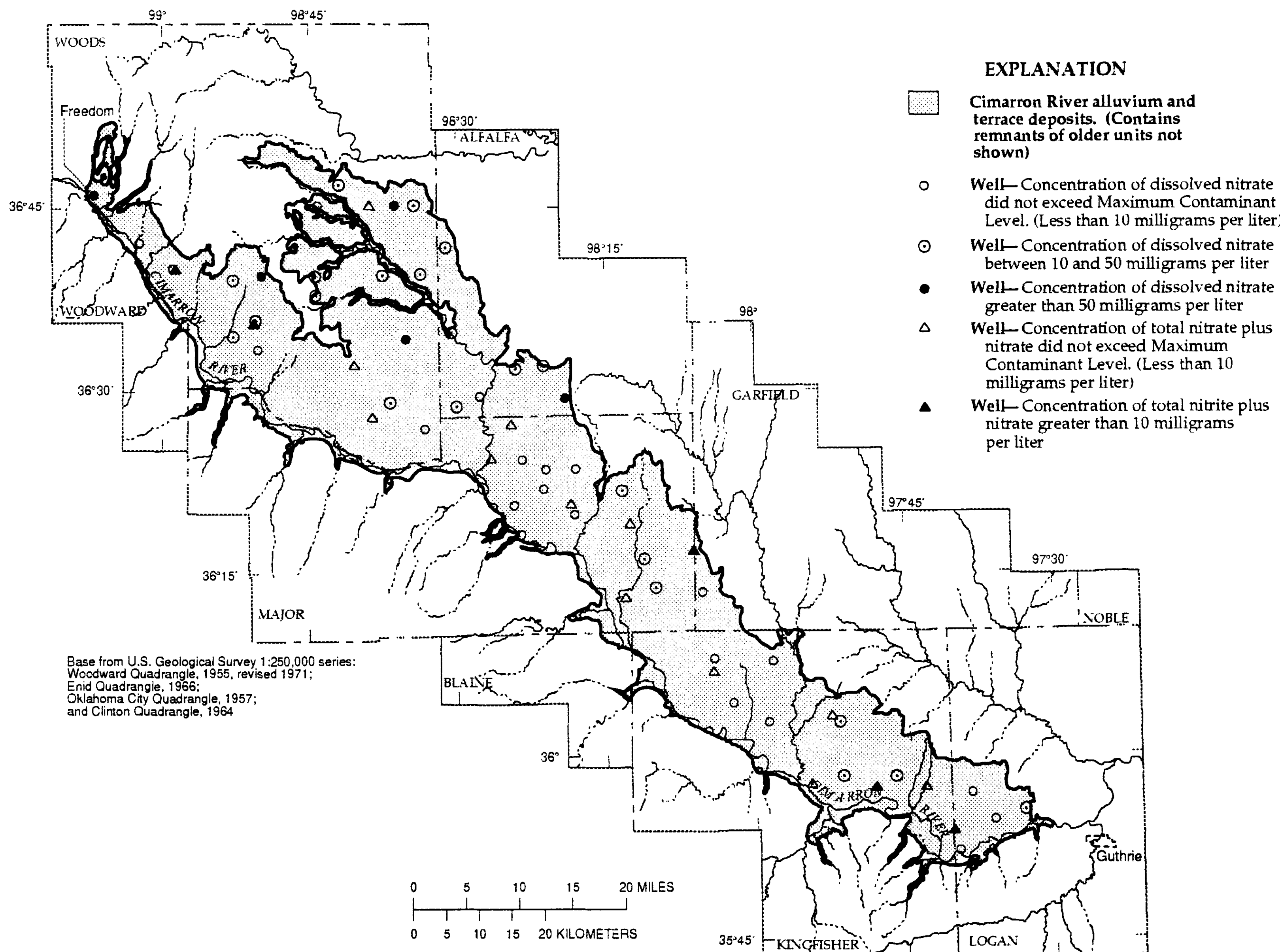


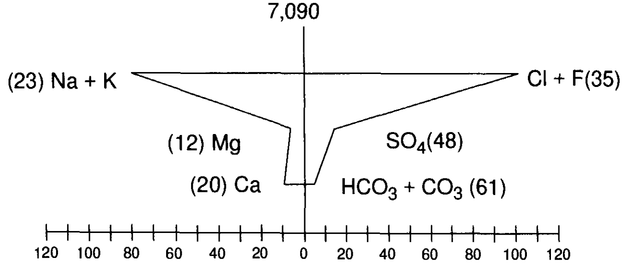
Figure 13. Location of dissolved nitrate and total nitrite plus nitrate analyses in the Cimarron River alluvium and terrace deposits.

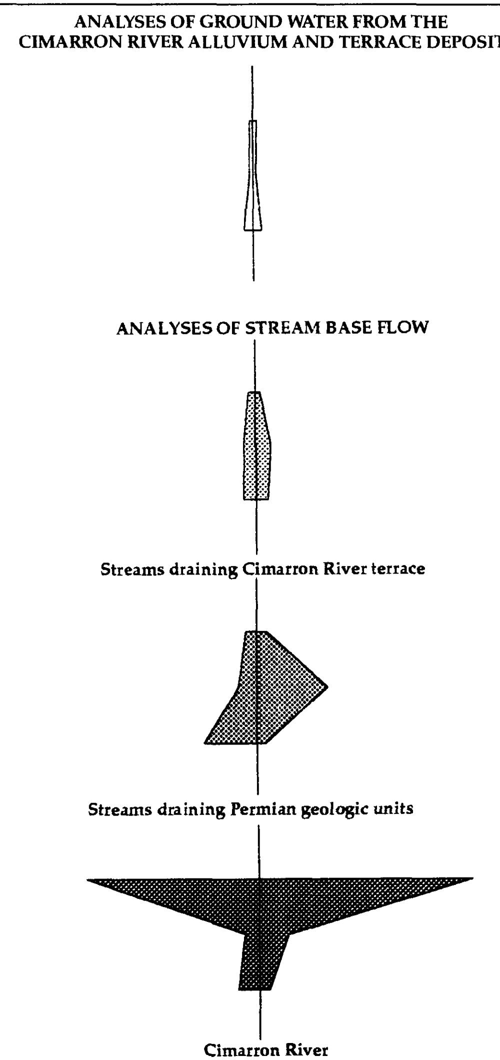
EXPLANATION

Stiff diagrams (Stiff, 1951) that show the general character of water are based on analyses of water samples from wells located in the Cimarron River alluvium and terrace deposits and on analyses of water from streams during a period of base flow at the indicated points. Ionic concentrations in milliequivalents per liter are plotted for sodium plus potassium (Na + K), magnesium (Mg), calcium (Ca), chloride plus fluoride (Cl + F), sulfate (SO_4), and bicarbonate plus carbonate ($HCO_3 + CO_3$). Anions are plotted to the right of the vertical axis and cations to the left. The area of the diagram is an indication of the dissolved-solids content. Variations in shape of the diagram reflect variations in the chemical character of the water sampled. Numbers located above the diagrams are dissolved-solids concentrations in mg/L. These represent the total concentration of dissolved material in water after evaporation of the water sample at 180 °C.

Numbers in parentheses beside ions in the diagram below are factors that can be used to convert ionic concentration from milliequivalents per liter to milligrams per liter. For example, use the scale to read the value of milliequivalents per liter of a particular ion, and multiply the value by the number beside the ion. The resulting number for Mg, Ca, or SO_4 ions is the concentration in milligrams per liter, and the resulting number for Na + K is the concentration as Na; Cl + F is concentration as Cl; and $HCO_3 + CO_3$ is the concentration as HCO_3.

DISSOLVED SOLIDS, IN MILLIGRAMS PER LITER





Cimarron River alluvium and terrace deposits. (Contains remnants of older units not shown)

Location of well

Miscellaneous low–flow measurement site and water–quality sampling site

Streamflow–gaging station location and water–quality sampling site

Figure 14a. Chemical quality of water in the Cimarron River alluvium and terrace deposits and Cimarron River and tributaries, 1985-88.

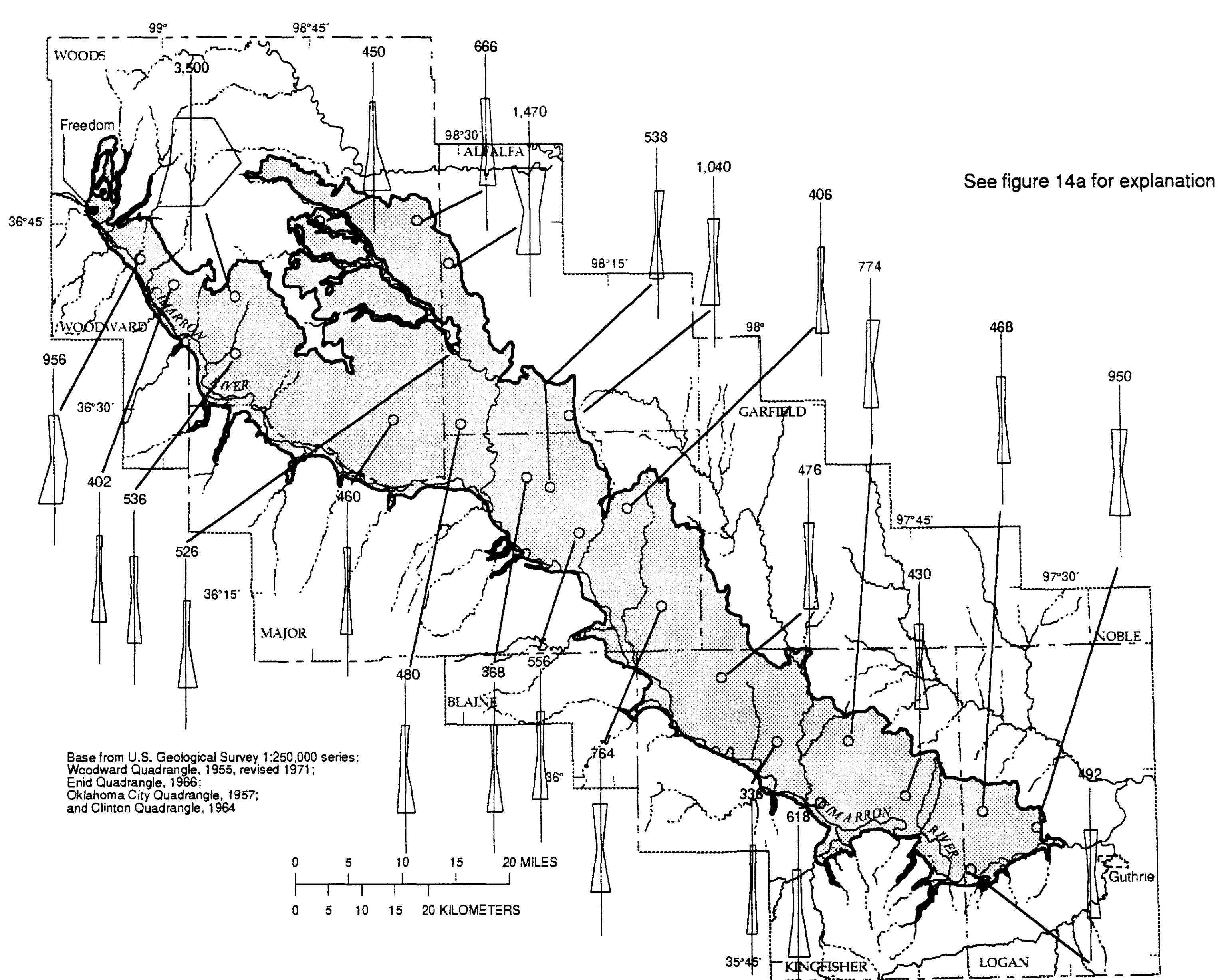
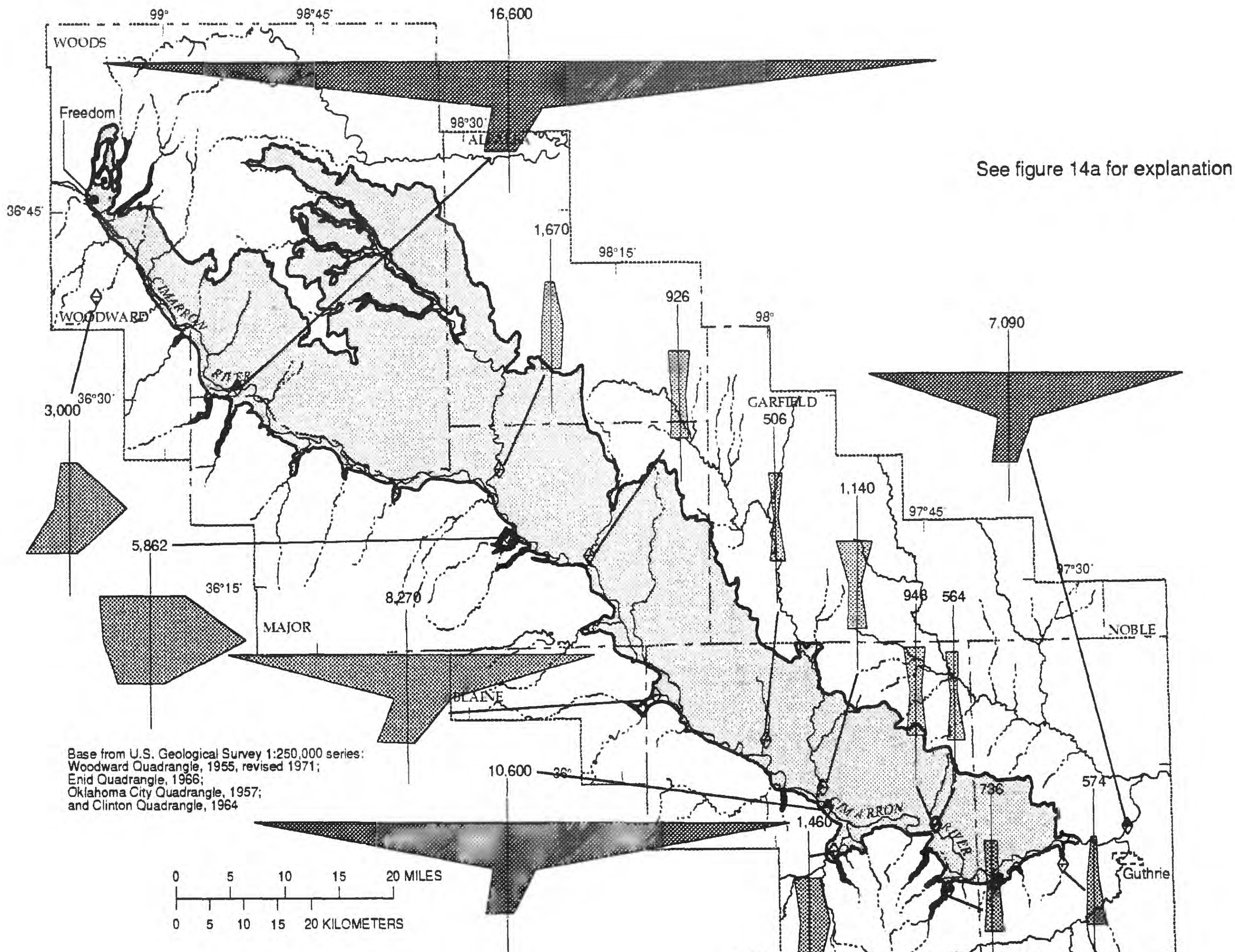


Figure 14b. Chemical quality of water in the Cimarron River alluvium and terrace deposits, 1985–88.



See figure 14a for explanation

Figure 14c. Chemical quality of water in the Cimarron River and tributaries, 1985–88.

centrations of 926, 506, 948, and 564 mg/L, respectively.

Generally, the water types for creeks draining the Permian geologic units gradually changed from west to east from a calcium sulfate type to a mixed type, to a sodium chloride type water at Salt Creek, about halfway down the reach of the Cimarron River. The dissolved-solids concentrations for tributaries in this reach ranged from 2,890 at the upper end to 8,270 mg/L at Salt Creek. Tributaries in the lower one-half of the Cimarron, between Cooper and Gar Creeks, showed a mix of different water types with fewer dissolved solids.

The water type for samples taken from the Cimarron River near the three gaging stations at Waynoka, Dover, and Guthrie was sodium chloride with dissolved-solids concentrations of 16,660, 10,600, and 7,090 mg/L, respectively. Water from the Cimarron River contained concentrations of sulfate and chloride that exceed 900 and 5,000 mg/L, respectively, which makes the water unsuitable for many uses. Sulfate and chloride are derived from evaporite beds within the Permian geologic units that crop out over most of the Cimarron River basin from the Oklahoma-Kansas State line downstream to south of Dover, Oklahoma.

Water-quality analyses of Cimarron River water obtained during base-flow periods show a 36-percent reduction of dissolved solids between the Waynoka and Dover gaging stations. This is an indication of significant dilution by ground-water contributions from the alluvium and terrace deposits along this reach of the river. Analyses also show a 33-percent reduction of dissolved solids between the Dover and Guthrie gaging stations. Dilution along this reach of channel probably is due in part to ground-water contributions from adjacent terrace deposits and the Garber Sandstone. There is also substantial inflow from municipal treatment facilities from Cottonwood Creek just upstream from the Guthrie gaging station.

GROUND-WATER MODEL

The geohydrologic information presented in previous sections of this report is a conceptual model of the ground-water flow system in the alluvium and terrace deposit aquifer. The conceptual model can be considered to be a theoretical description of the ground-water flow system in the aquifer. A digital ground-water flow model was used to test the validity of the conceptual model of the aquifer. A digital model combines a mathematical model of ground-water flow with a conceptual model of the aquifer and computes simulated heads and volumetric fluxes. These simulated heads and volumetric fluxes then are compared to field measurements of the same variables. When the computed simulated heads and volumetric fluxes from the digital model approximate the measured simulated heads and volumetric fluxes, the digital model is considered to be a reasonable approximation of the modeled aspects of the ground-water flow system and, by extension, the conceptual model of the aquifer is considered reasonable.

Mathematical-Numerical Model

A finite-difference ground-water flow model was developed and calibrated to verify the conceptual geohydrologic model for the aquifer under steady-state conditions. Steady-state flow conditions require that net inflow (recharge) equal the net outflow (discharge) and that fluxes or stress are constant with time. Thus, hydraulic head is constant and there is no change in storage. A steady-state condition may be defined mathematically, although it cannot accurately represent a real aquifer with large variations in recharge and stress.

Steady-state conditions may be approximated by the assumption that the aquifer is in a state of dynamic equilibrium, for which a steady-state simulation based on 1985-86 conditions is a reasonable approximation. Water-level fluctuations are seasonally small (fig. 11) and indicate small net changes in storage over the long term (fig. 12). Ground-water withdrawals have not changed substantially during a period of many years (table 5). Furthermore, 1986 base flow was concluded to be representative of long-term base flow, as discussed previously in the "Surface Water" section. Therefore, conditions during 1985-86 are assumed to represent long-term average steady-state conditions.

The computer code used to simulate flow in the aquifer was the modular three-dimensional finite-difference ground-water flow model by McDonald and Harbaugh (1988). Although the model is designed to simulate three-dimensional flow, it can be used to simulate two-dimensional flow, as in this study. The program employs a block-centered finite-difference solution approach to simulate ground-water flow. The model solves a large system of simultaneous linear equations representing ground-water flow using the slice-successive overrelaxation method (McDonald and Harbaugh, 1988, p. 13–1). No revisions to the simulation code were necessary.

A two-dimensional rectangular grid was superimposed on the aquifer. Hydraulic and physical values of the aquifer, such as water-table elevation, base of aquifer, and hydraulic conductivity, were discretized to the center of each cell (node). The discretization requires that assumptions be made about the hydraulic properties. Hydraulic properties are represented by a single interpolated value for each cell, which eliminates local variations. Thus, hydraulic properties computed at the node may not correspond to observations made at the edges of the cell. The horizontal dimensions of the finite-difference grid used in this model are 27 mi wide from southwest to northeast and 104 mi long from northwest to southeast (fig. 15). The area is divided into 2,808 cells, each cell being 1 mi on a side. This cell spacing provides appropriate resolution for the entire study area, but does not give sufficient resolution for individual wells or well fields.

To simulate the areal extent of the aquifer 1,240 active cells were used. The remaining cells were inactive cells. Inactive cells have zero transmissivity and, thus, no flow into or out of the cell. The head may vary at active cells throughout the simulation, although control may be placed on the cells to specify head or flux. Various types of hydrologic conditions and combinations may be simulated within an active cell by a variety of available options.

The choice of simulating average steady-state conditions simplifies the construction of the model by eliminating consideration of storage terms and initial conditions in the equations of flow. It is assumed that the simulated potentiometric surface produced from the model will represent the average distribution of head in the aquifer resulting from an average of boundary values and stresses.

The limitations and misuses of mathematical numerical models are presented in Mercer and Faust (1981). Modeling assumptions unique to this study are: (1) The Permian geologic units underlying and adjacent to the aquifer are impermeable in most areas, (2) minimal saturated thickness is assumed along the upper reaches of Eagle Chief, Little Eagle Chief, and Sand Creeks, and (3) the hydrologic conditions observed for 1985-86 represent long-term average conditions.

Description of Model Boundary Conditions

For the simulation of steady-state flow in the aquifer, three boundary conditions (fig. 15) were modeled to represent as closely as possible the conceptual model: (1) no-flow boundaries, (2) head-dependent flux boundaries, and (3) constant-flux boundaries.

No-flow boundaries

All effectively impermeable boundaries of the conceptual model were represented by no-flow boundaries, as noted by the inactive cells shown on figure 15. A no-flow boundary was used to simulate the northeast and west extent of terrace deposits of the aquifer that pinch out against relatively impermeable Permian geologic units. The no-flow boundary on the southwest perimeter represents where alluvium has been deposited against relatively impermeable Permian geologic units. The contact between the base of the aquifer and the Permian geologic units is assumed to be a no-flow boundary because the underlying rocks are much less transmissive than the aquifer.

Head-dependent flux boundaries

Four separate head-dependent flux-boundary conditions of the conceptual model were simulated: (1) Leakage to or from the Cimarron River to the aquifer, (2) leakage to or from tributaries to the aquifer, (3) leakage to Permian geologic units from the aquifer system in some areas, and (4) leakage to and from the aquifer by subsurface inflow and outflow from alluvium along the Cimarron River and Turkey Creek. The head-dependent flux boundary may be used to simulate recharge to or discharge from the aquifer; that is, influence by sources of water that are inside or outside the modeled area. Head-dependent flux boundaries supply water to a cell in the modeled area at a rate proportional to the head difference between the source and the cell (McDonald and Harbaugh, 1988).

The leakage of water between the Cimarron River and the aquifer was simulated as head-dependent flux by using stream nodes of the model river package (fig. 15). The Cimarron River was treated as a partially penetrating river with a leaky riverbed. The leakage between aquifer and river is approximated as

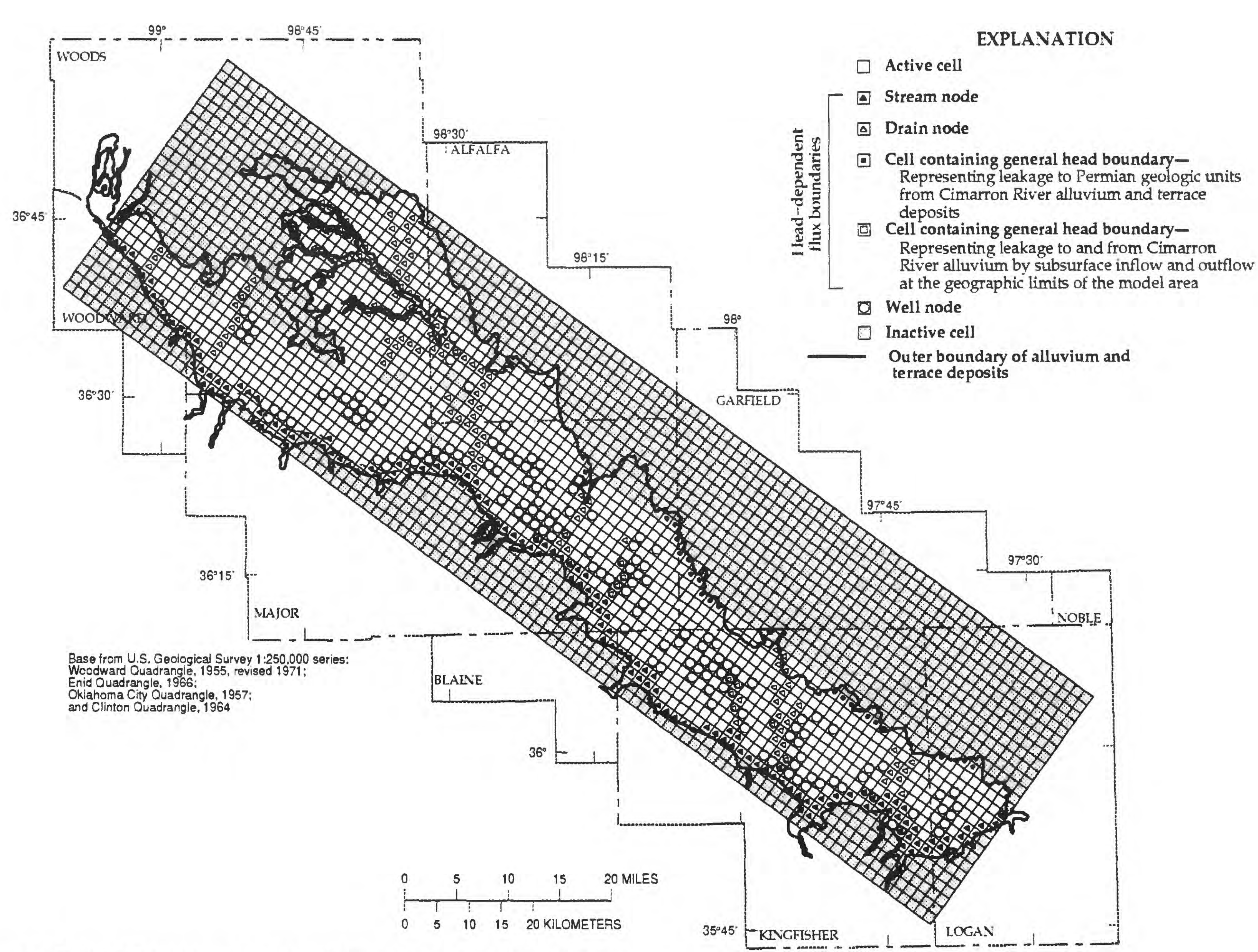


Figure 15. Finite-difference grid of the model area, north-central Oklahoma.

the product of the difference between the river stage and aquifer head times the riverbed hydraulic conductance. The hydraulic conductance represents the hydrogeologic parameter controlling leakage to the aquifer (McDonald and Harbaugh, 1988, p. 6–5) and is the product of the vertical hydraulic conductivity (*Kr*) of the riverbed material and the length (L_1) and width (W_1) of river reach in each cell, divided by thickness of the riverbed (M), as shown in figure 16. The lengths of the river reaches for each cell were determined from U.S. Geological Survey 1:250,000–scale maps with the model grid superimposed. Average Cimarron River widths and stages were determined from stage-discharge rating tables using records from U.S. Geological Survey gaging stations along the Cimarron River near Buffalo, Waynoka, Dover, Crescent, and Guthrie. U.S. Geological Survey 7.5–minute topographic maps were used to interpolate the stage data between gaging stations. The riverbed was assigned a thickness of 5 ft. No riverbed vertical hydraulic-conductivity values could be found for the Cimarron River. The vertical hydraulic conductivity for the riverbed material was chosen as 2.0 ft/d [2.3×10^{-5} feet per second (ft/s)]. The bed material and the alluvium are considered to be the same material, so the vertical hydraulic conductivity value of 2.0 ft/d was estimated as 1/100 of the median horizontal hydraulic conductivity calculated by aquifer tests for the Cimarron River alluvium (221 ft/d). This value is comparable to a value of 1.34 ft/d that was used for similar streambed material in Kansas (Dunlap and others, 1985).

The leakage of water between tributaries and the aquifer was simulated as a head-dependent flux by using drain nodes of the drain package from the model (fig. 15). The tributaries were treated as open drains with a leaky channel-bed material. The leakage between the aquifer and the tributaries is approximated as the difference between the fixed head (elevation of the bottom of the channel) and the head in the aquifer times the channel-bed conductance. Unlike a river node, if the head in the aquifer falls below the fixed head during simulation, no leakage from the channel to the aquifer will be simulated. The tributary channel-bed hydraulic conductance represents the hydrogeologic property controlling leakage to the aquifer and is the product of the vertical hydraulic conductivity of the channel-bed material (*Kd*), and length (L_1) and width (W_1) of channel reaches in each cell, divided by the thickness of the channel-bed material (*M*) (fig. 16). Lengths of individual channel reaches were measured from a U.S. Geological Survey 1:250,000-scale map with the model grid superimposed. Fixed heads (elevation of the bottom of the channel bed) were estimated from U.S. Geological Survey 7.5–minute topographic maps. Widths of stream channel and thickness of channel-bed material were estimated from field observations. Stream channel widths ranged from 5 to 30 ft, and the thickness of channel-bed material ranged from 1 to 5 ft. The hydraulic conductivity for the channel bed was chosen to be the same as for the Cimarron River bed material, 2.0 ft/d.

Leakage to Permian geologic units from the aquifer in limited areas along the northeastern boundary of the aquifer (as discussed in the "Ground Water" section) was simulated as a head-dependent flux boundary using the general head-boundary package for the model (fig. 15). Permian geologic units have small hydraulic conductivity and generally are treated as a no-flow boundary except for these limited areas. The discharge by leakage from the aquifer to the Permian geologic units was approximated as the difference between the fixed head in the Permian geologic unit and the head in the aquifer times the hydraulic conductance. The leakage from the head-dependent boundary representing the geologic unit adjacent to the model area is controlled by the hydraulic conductance (McDonald and Harbaugh, 1988, p. 11–2). Hydraulic conductance of the Permian geologic units is the horizontal hydraulic conductivity (*Kha*) of adjacent unit, times the width of cell (W_2), times aquifer thickness (*B*), divided by the length of the flow path (L_2) as shown in figure 16. The hydraulic conductivity values for the Permian geologic units were determined by trial and error during model calibration. These values were in the typical range for this type of geologic unit (Freeze and Cherry 1979).

Leakage to and from the aquifer by subsurface inflow and outflow from alluvium along the Cimarron River and Turkey Creek also were simulated as a head-dependent flux boundaries using the general head-boundary package for the model. Alluvium extends beyond the upstream and downstream geographic limits of the study area. General head boundaries were used to represent subsurface inflow at the upstream ends of the Cimarron River and Turkey Creek, and subsurface outflow at the downstream end of the Cimarron River. Recharge by subsurface inflow and discharge by subsurface outflow may be approxi-

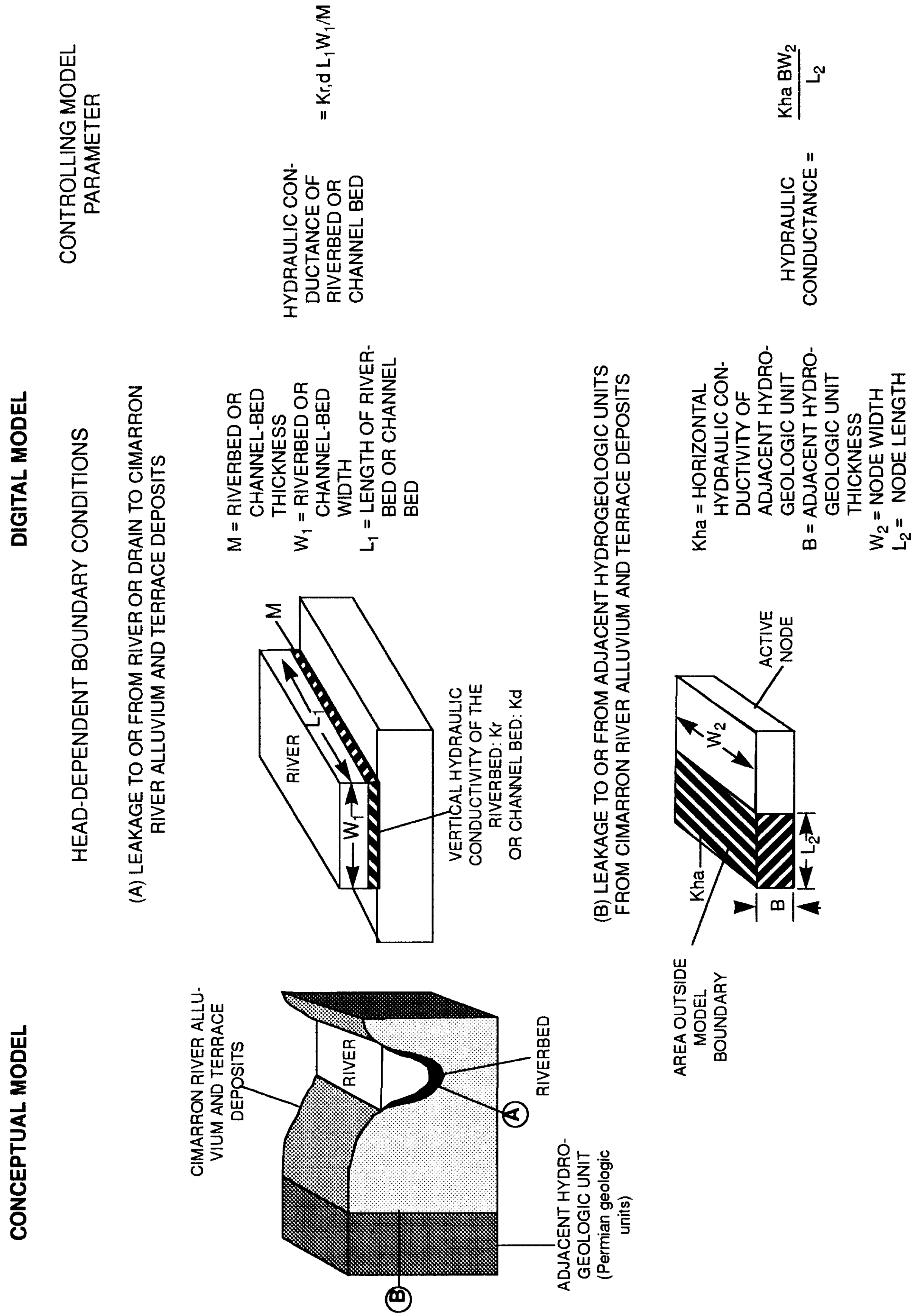


Figure 16. Conceptual and digital model of head-dependent boundaries (Modified from Ackerman, 1989, p. 35).

mated as the difference between the assigned fixed head in the river outside the study area and the head of the river node at the study boundary times the hydraulic conductance. The hydraulic conductance is the horizontal hydraulic conductivity of the alluvium, times the width of cell, times the aquifer thickness, divided by the length of the flow path. The hydraulic conductivity for the alluvium was chosen to be 104.5 ft/d, the same as the model-calibrated hydraulic conductivity.

Constant-flux boundaries

Two separate constant-flux boundaries are represented in the model. A constant-flux boundary is a boundary condition that has a fixed value of volumetric flow rate per unit area (discharge) across the boundary. Uniform areal recharge across the upper water-table surface was simulated as a constant-flux boundary using the recharge package of the model. A recharge rate of 2.3 in/yr was used in the model. This rate was based on (see "Recharge" section) the extrapolated base-flow estimate (173 ft^3/s), the reported average annual pumpage (24.43 ft^3/s), and the drainage area (1,167.2 mi^2). Stresses (totaling 24.43 ft^3/s) resulting from reported annual withdrawals for municipal, irrigation, industrial, and mining were simulated in the model by specifying a constant-flux rate at the nodes representing the cells containing the well or wells, using the well package of the model. An irrigation withdrawal rate of 10.90 ft^3/s, 80 percent of the reported value was used in the model, because 20 percent (2.73 ft^3/s) was considered return flow (see "Withdrawals" and "Irrigation return flow" subsections.

The terrace deposits located in several areas as noted on figure 5 were not included as active nodes in the model. These deposits have little or no saturated thickness, thus precluding significant ground-water flow.

Steady-State Simulation and Calibration

The steady-state model was calibrated to simulate the flow system in the aquifer. For the purpose of calibration it was assumed that hydrologic conditions measured for 1985-86 represented long-term steady-state conditions. Calibration of the ground-water model consisted of adjusting model input parameters within objective criteria so that the simulated water levels and flow rates accurately simulated the assumed average water levels and flow rates. The model input parameters included recharge; altitude of aquifer base; hydraulic conductivity of the aquifer; hydraulic conductivities of the riverbeds, drainbeds, and Permian geologic units; pumpage withdrawals; and initial altitude of the potentiometric surface. Some of the parameters were known more accurately than others and, therefore, were adjusted less or not at all during the calibration process.

To demonstrate that the flow model is reasonable, model results must correlate closely with field observations. Field observations used to calibrate the model include measured ground-water levels and discharge measurements for the river between Waynoka and Dover along the Cimarron River. The calibration process consisted of holding the areal recharge constant and adjusting the hydraulic conductivity of the aquifer to produce a reasonable match between simulated results and field observations. The model parameters recharge and hydraulic conductivity are proportional; therefore, either parameter may be held constant and the other adjusted to produce a match between simulated and measured water levels. The parameter recharge was known more accurately and held constant for the following two reasons: (1) Recharge was estimated from measured base-flow which is representative of long-term average conditions (see "Recharge" and "Surface Water" sections) and (2) hydraulic conductivity varies spatially and the wells used in the aquifer tests were deliberately sited in productive areas of the aquifer.

At the end of each model simulation, the simulated values of hydraulic heads and volumetric fluxes were transferred to a management and statistical program called the Modular Model Statistical Processor (MMSP) for analysis (Scott, 1989). The MMSP was used to evaluate the goodness of fit of the simulation results by measuring: (1) The mean of the arithmetic values of head difference between simulated and measured aquifer heads at every active node, (2) The mean of the absolute value of head difference between simulated and measured aquifer heads at every active node, and (3) Root mean squared value of head difference between simulated and measured aquifer heads at every active node. The mean of the arithmetic values of head difference was calculated by summing the differences between measured and simulated head at each active node and dividing by the total number of active nodes. This value should approach zero in the calibration process, showing that, on the average, simulated and measured heads are the same, and that positive differences are balanced by negative differences. The mean of the absolute values was calculated by summing the absolute values of the difference between measured and simulated heads at each active node and dividing by the number of active nodes. This sum also should be minimized during the calibration process, which indicates that the absolute difference between measured and simulated heads is small. The root mean squared value of head difference was calculated by summing the squares of the difference between measured and simulated heads at each active node and dividing by the number of active nodes.

The model-calibrated hydraulic conductivity of 104.5 ft/d for alluvium and 47.5 ft/d for terrace deposits are about one-half the median values (221 ft/d and 98 ft/d, respectively) obtained from aquifer tests. The reason for this discrepancy is not known, although it may be related to the fact that the wells used in the aquifer tests were deliberately sited in productive areas of the aquifer.

Once the steady-state flow model was adjusted to produce a reasonable agreement between simulated and measured heads, final calibration was achieved by adjusting the recharge estimated from the conceptual model to match the stream-aquifer flux along the river reach between Waynoka and Dover. The base flow between the gaging stations at Waynoka and Dover was 133 ft^3/s in February 1986. The calibrated steady-state model simulated a base flow of 132.86 ft^3/s. The MMSP calculated an arithmetic mean head difference of 0.004, a mean of the absolute values head difference of 5.70, and a root mean squared value of head difference of 7.69 ft per model cell for the final steady-state model simulation. The inspection of the distribution of the differences between the simulated and measured heads for individual cells indicates areas where the model does not accurately fit the conceptual model. The maximum and minimum of difference between simulated and measured heads was 27.60 (simulated head was below observed head) for cell 19,16 (row, column) and –18.58 (simulated head was above measured head) for cell 16,39; cell 20,17 went dry during the simulation. The most notable deviation between simulated and measured heads occurs in the eastern and west-central part of the study area (figs. 8 and 17). In these areas the simulated head is greater than 20 ft below observed head. These differences were considered to be tolerable because the altitude of water levels are considered accurate to within plus or minus 10 ft.

The potentiometric surface simulated by the steady-state model is shown in figure 17 and is a reasonable match to the 1985–86 potentiometric surface shown in figure 8. A closer match between simulated and measured potentiometric surfaces could have been obtained if hydraulic-conductivity values were individually adjusted throughout the model grid. Some heterogeneity undoubtedly exists in the aquifer, although hydraulic-conductivity data are not available to document areal variation. Any further attempt to improve the match between simulated and measured water levels by altering assigned values of hydraulic conductivity was deemed impractical and unjustified.

In addition to simulating water levels the calibrated model provided simulated hydrologic fluxes. The rates at which water leaves and enters the aquifer represent the mass balance. The mass balance for the steady-state simulation is shown in figure 18.

Sensitivity Analyses

The sensitivity of the calibrated ground-water model to selected model parameters was tested. Recharge and hydraulic conductivity each was varied uniformly in the steady-state model as all other model parameters were held constant. The effect of these variations on the simulated heads was measured by the mean of the arithmetic differences between simulated and measured heads. Figure 19 shows the rate of change in the mean of the arithmetic differences between simulated and measured head at every active node when recharge and hydraulic conductivity are varied individually in 5 percent intervals to a total of 20 percent greater than and 20 percent less than their respective calibrated values. The slope of the lines connecting the points indicates the sensitivity of the model to changes in the values. The effect of varying the recharge by plus and minus 20 percent changes the mean of the arithmetic head difference from –3.8 ft to 3.5 ft. The effect of varying the hydraulic conductivity plus and minus 20 percent changes the mean of the arithmetic head difference from 2.7 ft to –3.6 ft. Thus, simulated heads are comparably sensitive to recharge and hydraulic conductivity.

SUMMARY

Ground water in alluvium and terrace deposits of Quaternary age along the Cimarron River from

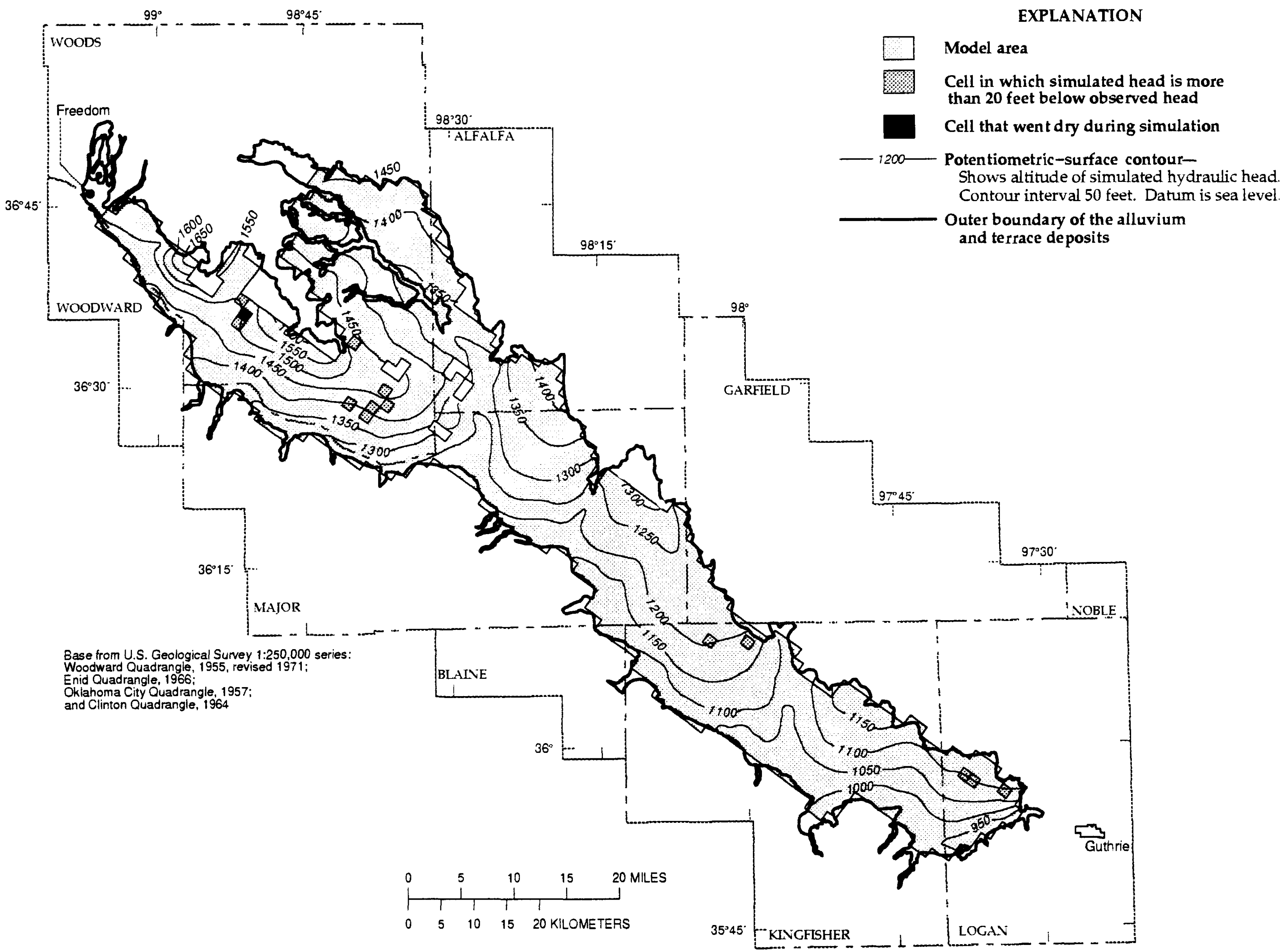


Figure 17. Simulated potentiometric surface for steady-state conditions in the Cimarron River alluvium and terrace deposits from Freedom to Guthrie, Oklahoma.

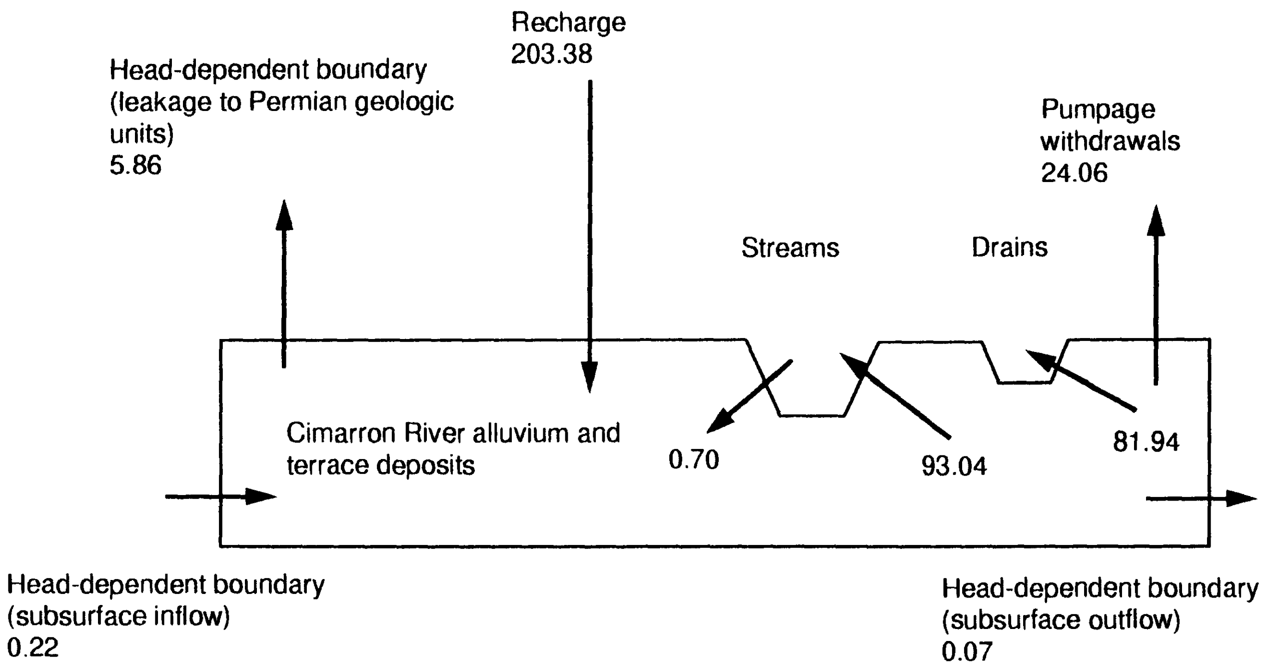


Figure 18. Mass balance for steady-state simulation (rates are in cubic feet per second).

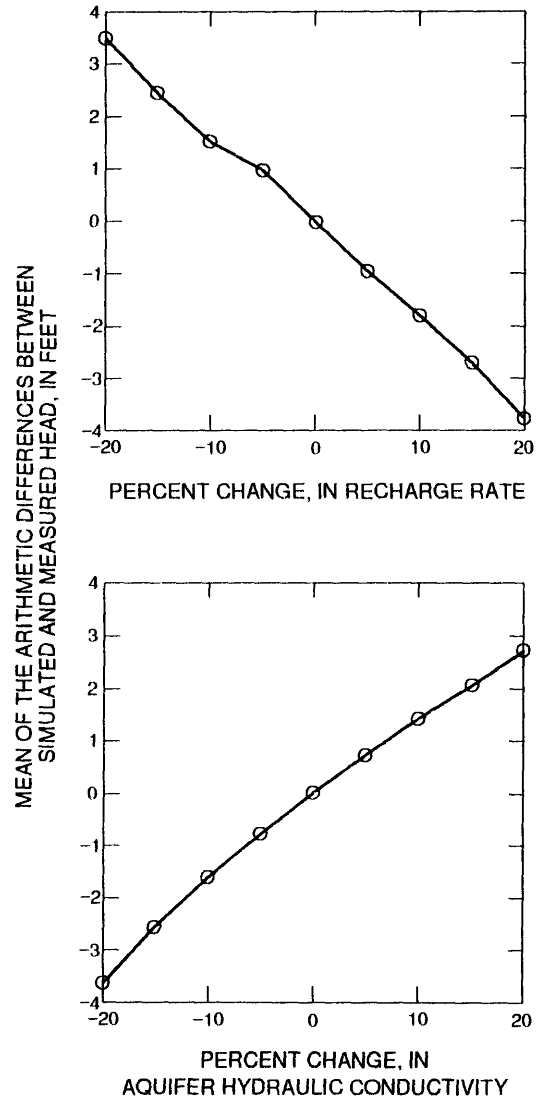


Figure 19. Diagrams showing sensitivity of simulated head in the study area to changes in recharge rate and hydraulic conductivity during steady-state simulation of 1985–86 head distribution.

Freedom to Guthrie, Oklahoma, an area of approximately 1,305 mi^2, is used extensively for irrigation, municipal, stock, and domestic supplies. An investigation was undertaken, in cooperation with the Oklahoma Geological Survey, to provide state water managers with the quantitative knowledge necessary to manage the ground-water resource effectively. The deposits are composed of varying proportions of clay, silt, sand, and gravel and vary in thickness from 0 to as much as 120 ft. Terrace deposits vary in thickness because of erosional features in the underlying Permian geologic units and variation in deposition and erosion of the deposits. The alluvium and terrace deposits associated with the Cimarron River are considered a single aquifer unit. The aquifer is unconfined and has an average saturated thickness of 28 ft. The amount of water in storage, assuming a specific yield of 20 percent, was 4.47 million acre-feet in 1985–86. The boundaries of the aquifer are where the alluvium and terrace deposits of the aquifer abut relatively impermeable Permian geologic units. The base of the aquifer is the contact with underlying Permian geologic units. Ground-water leakage across the contact is assumed to be negligible at most locations.

The 1985-86 potentiometric-surface map indicates that ground-water flow is from topographically high areas farthest from the Cimarron River and its perennial tributaries to areas of low head at the Cimarron River and its perennial tributaries. The potentiometric-surface map also indicates several areas along the northeastern boundary where ground water flows northeast out of the aquifer. Regional ground-water flow is generally to the southeast to southwest towards the Cimarron River, except where the flow direction is affected by perennial tributaries of the Cimarron River. The water table fluctuates in a cyclical manner because of seasonal climatic changes and seasonal irrigation practices.

Estimates of transmissivity from aquifer tests conducted by previous investigators ranged from 603 to 10,184 ft^2/d. Hydraulic-conductivity values ranged from 15 to 542 ft/d, with a median of 221 ft/d for alluvium and 98 ft/d for terrace deposits. Specific yields ranged from 0.0016 to 0.39.

Recharge to the aquifer is from downward percolation of precipitation and from return flow of applied irrigation water. Small quantities of water also recharge the aquifer from leakage of surface water through stream channels of the Cimarron River and perennial tributaries, and from subsurface inflow from alluvium along the Cimarron River and Turkey Creek at the geographic limits of the study area. Estimated average recharge to the system is 207 ft^3/s. This recharge amount is approximately 8 percent of the 27 in/yr mean of the average annual precipitation measured at Freedom, Kingfisher, Waynoka, and Guthrie. Average discharge from the aquifer by seepage to the Cimarron River and perennial tributaries, including the effect of evapotranspiration along streams, is estimated to be 173 ft^3/s. Discharge by withdrawals from wells was estimated to be 24.43 ft^3/s in 1985. Small quantities of water are discharged by leakage to Permian geologic units and by subsurface outflow from alluvium along the Cimarron River at the downstream limits of the study area.

Ground water is withdrawn for municipal, domestic, industrial, mining, irrigation, and stock-watering uses inside the study area, and for municipal, domestic, and industrial uses outside the study area. Domestic water supplies also are provided by rural water districts serving areas within and outside the study area. Surface water is withdrawn for industrial, irrigation, stock-watering uses, and for recreation, fish, and wildlife. Reported average annual ground-water withdrawals by category in 1985 were: Municipal, 9,209 acre-feet; irrigation, 9,868 acre-feet; industrial, 149 acre-feet; and mining, 434 acre-feet. The reported surface-water withdrawal in 1985 is 258 acre-feet.

Field water-quality measurements and ground-water samples from 67 wells completed within the terrace deposits were collected during 1985, 1986, and 1988. The samples were analyzed for alkalinity, total and dissolved common cations and anions, trace metals, tritium, and selected organic compounds. Surface-water samples obtained during a period of base flow from the Cimarron River and 29 tributaries to the Cimarron River were analyzed for alkalinity, dissolved common cations and anions, and trace metals. More than 50 percent of the 46 ground-water samples exceed the Maximum Contaminant Level in concentrations of nitrate. Values of pH, sulfate, aluminum, iron, manganese, and dissolved-solids exceeded the Secondary Maximum Contaminant Level in some of the ground-water-quality samples.

Most water in the terrace deposits varied from a calcium bicarbonate to mixed bicarbonate type, with a median value of 538 mg/L of dissolved solids. The water type from streams draining the aquifer varied. Water in the Cimarron River was a sodium chloride type with dissolved-solids concentrations of 16,600 mg/L at Waynoka and 7,090 mg/L at Guthrie.

A finite-difference ground-water-flow model was developed and calibrated to test the conceptual model of the aquifer under steady-state conditions. It was assumed that hydrologic conditions during 1985-86 represented long-term average steady-state conditions. The calibrated hydraulic conductivity for the alluvium and terrace deposits are 104.5 and 47.5 ft/d, respectively. The model simulated a mean of the arithmetic values of difference between measured 1985–86 heads to simulated heads as 0.004 ft, mean of the absolute values of head difference between measured 1985–86 heads to simulated heads as 5.70 ft, and the root mean squared value of head difference between measured 1985–86 heads to simulated heads as 7.69 ft. The model simulated discharge to the Cimarron River between Waynoka and Dover was 132.86 ft^3/s. The model was considered reasonable because the altitudes of the wells used to measure head were considered accurate to within plus or minus 10 ft, and the measured discharge along the Cimarron River between Waynoka and Dover was 133 ft^3/s in February 1986.

SELECTED REFERENCES

Ackerman, D.L., 1989, Hydrology of the Mississippi River Valley Alluvial aquifer, south-central United States—A preliminary assessment of the regional flow system: U.S. Geological Survey Water-Resources Investigations Report 88–4028, 74 p.

Adams, G.P., Bergman, D.L., Pruitt, D.J., May, J.E., and Kurklin, J.K., 1994, Hydrologic data for the alluvium and terrace deposits of the Cimarron River from Freedom to Guthrie, Oklahoma: U.S. Geological Survey Open-File Report 94–504, 236 p.

Aurin, Fritz, 1917, Geology of the redbeds of Oklahoma: Oklahoma Geological Survey Bulletin 30, 66 p.

Becker, C.J., 1994, Distribution and variability of nitrogen and phosphorus in the alluvial, High Plains, Rush Springs, and Blaine aquifers in western Oklahoma: U.S. Geological Survey Open-File Report 94–41, 30 p.

Bingham, R.H., and Bergman, D.L., 1980, Reconnaissance of the water resources of the Enid quadrangle, north-central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 7, scale 1:250,000, 4 sheets.

Bingham, R.H., and Moore, R.L., 1975, Reconnaissance of the water resources of the Oklahoma City quadrangle, central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 4, scale 1:250,000, 4 sheets.

Blazs, R.L., Walters, D.M., Coffey, T.E., White, D.K., Boyle, D.L., and Kerestes, J.F., 1993, Water resources data, Oklahoma, water year 1992: U.S. Geological Survey Water-Data Report OK–92–1, 524 p.

Burton, L.C, and Fryberger, John, 1974, Demonstration of new and improved methods for locating, categorizing, and quantitating sources of salt water pollution in ground water: Oklahoma Water Resources Board, 93 p.

Carr, J.E., and Bergman, D.L., 1976, Reconnaissance of the water resources of the Clinton quadrangle, west-central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 5, scale 1:250,000, 4 sheets.

Chilton, R.L., 1930, Oil and gas in Oklahoma; Woods, Alfalfa, Harper, Major, Woodward, and Ellis Counties: Oklahoma Geological Survey Bulletin 40, vol. 2, p.1–20.

Christenson, S.C., 1983, Numerical simulation of the alluvium and terrace aquifer along the North Canadian River from Canton Lake to Lake Overholser, central Oklahoma: U.S. Geological Survey Water-Resources Investigations Report 83–4076, 36., 13 plates.

Clark, G.C., and Cooper, C.L., 1930, Oil and gas in Oklahoma; Kay, Grant, Garfield, and Noble Counties: Oklahoma Geological Survey Bulletin 40, v. 2, p. 67–104.

Davis, R.E., and Christenson, S.C., 1981, Geohydrology and numerical simulation of the alluvium and terrace aquifer along the Beaver–North Canadian River from the Panhandle to Canton Lake, northwestern Oklahoma, U.S. Geological Survey Open–File Report 81–483, 42 p.

Dunlap, L.E., Lindgren, R.J., and Saver, C.G., 1985, Geohydrology and model analysis of stream-aquifer system along the Arkansas River Kearny and Finney Counties, southwestern Kansas, U.S. Geological Survey Water-Supply Paper 2253, 52 p.

Engineering Enterprises, Inc., 1977, Ground-water flow evaluation for Cimarron River, Salt Fork River, Arkansas River: Arkansas River Chloride control project Oklahoma, for U.S. Army Corps of Engineers, Tulsa District, Oklahoma: Norman, Oklahoma, Engineering Enterprises, Inc., 95 p.

______1982, Test drilling and computer modeling of Cimarron terrace aquifer near Cleo Springs, Oklahoma: Norman, Oklahoma, Engineering Enterprises, Inc., variable pagination.

______1983, Ground water development plan, City of Guthrie: Norman, Oklahoma, Engineering Enterprises, Inc., 32 p.

Fay, R.O., 1962, Geology and mineral resources of Blaine County, Oklahoma: Oklahoma Geological Survey Bulletin 89, 258 p.

______1965, The geology and mineral resources of Woods County, Oklahoma: Oklahoma Geological Survey Bulletin 106, 184 p.

Fenneman, N.M., and Johnson, D.W., 1946, Physical divisions of the United States: U.S. Geological Survey, 1 sheet, scale 1:7,000,000,1 sheet.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 604 p.

Gould, C.N., 1905, Geology and water resources of Oklahoma: U.S. Geological Survey Water-Supply Paper 148, 178 p.

Haug, J.A.H., 1985, CLIMOCS: A climatological summary of 267 Oklahoma cooperative stations 1954–1983: Norman, Oklahoma, Oklahoma Climatological Survey, Climate Summary 1985–1, no pagination.

Helsel, D.R., and Cohn, T.A., 1988, Estimation of descriptive statistics for multiply censored water quality data: Water Resources Research, v. 24, no. 12, p. 1997–2004.

Johnson, K.S., and others, 1972, Geology and earth resources of Oklahoma: Oklahoma Geological Survey Educational Publication 1, 8 p.

Jordan, Louise, and Vosburg, D.C., 1963, Permian salt and associated evaporites in the Anadarko Basin of the western Oklahoma-Texas Panhandle region: Oklahoma Geological Survey Bulletin 102, 76 p.

Kite, W.C., 1930, Oil and gas in Oklahoma; Kingfisher and Canadian Counties: Oklahoma Geological Survey Bulletin 40, v. 2, p. 193–201.

Lohman, S.W., and others, 1972, Definitions of selected ground-water terms—Revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.

———1979, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

McDonald, M.G., and Harbaugh, A.H., 1988, A modular three-dimensional finite-difference ground-water flow model: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Book 6, Chapter A1, 586 p.

Mercer, J.W., and Faust, C.R., 1981, Ground-water modeling: National Water Well Association, 60 p.

Miser, H.D., 1954, Geologic map of Oklahoma: U.S. Geological Survey, 1 sheet, scale 1:500,000.

Morton, R.B., 1980, Reconnaissance of the water resources of the Woodward quadrangle, northwestern Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 8, scale 1:250,000, 4 sheets.

Oklahoma Water Resources Board, 1972, Appraisal of the water and related land resources of Oklahoma; Region Ten: Oklahoma Water Resources Board, 137 p.

———1975, Salt water detection in the Cimarron terrace, Oklahoma: U.S. Environmental Protection Agency Ecological Research Series EPA–660/3–74–033, 166 p.

———1991, Hydrologic investigation of the Cimarron River: U.S Army Corps of Engineers Technical Report 91–1, 41 p.

Olmsted, F.H., and Hely, A.G., 1962, Relation between ground water and surface in Brandywine Creek basin, Pennsylvania: U.S. Geological Survey Professional Paper 417–A, 21 p.

Parkhurst, D.L., Christenson, Scott, and Breit, G.N., 1993, Ground-water-quality assessment of the Central Oklahoma aquifer, Oklahoma: Geochemical and geohydrologic investigations: U.S. Geological Survey Open-File Report 92–642, 113 p.

Patterson, J.M., 1933, Permian of Logan and Lincoln Counties, Oklahoma: Bulletin of the American Association of Petroleum Geologists, v. 17, no. 3, p. 241–253.

Pettyjohn, W.A., White, Hal, and Dunn, Shari, 1983, Water atlas of Oklahoma: University Center for Water Research, Oklahoma State University, Stillwater, Oklahoma, 71 p.

Reed, E.W., Mogg, J.L., Barclay, J.E., and Peden, G.H., 1952, Ground-water resources of the terrace deposits along the northeast side of the Cimarron River in Alfalfa, Garfield, Kingfisher, and Major Counties, Oklahoma: Oklahoma Planning and Resources Board Division of Water Resources Bulletin 9, 101 p.

Reely, B.T., 1992, A linked optimization-simulation aquifer management model: Stillwater, Okla., Oklahoma State University, Ph.D. dissertation, 234 p.

Renick, B.C., 1925, Additional ground water supplies for the city of Enid, Oklahoma: U.S. Geological Survey Water-Supply Paper 520–B, p. 15–25.

Robertson, W.D., and Cherry, J.A., 1989, Tritium as an indicator of recharge and dispersion in a groundwater system in Central Ontario: Water Resources Research, v. 25, no. 6, p. 1097–1109.

Schoff, S.L., 1949, Ground water in Kingfisher County, Oklahoma: Oklahoma Geological Survey Mineral Report 19, 20 p.

Schoff, S.L., 1950, Ground water in the Cherokee area, Alfalfa County, Oklahoma: Oklahoma Geological Survey Mineral Report 21, 17 p.

Schwenneson, A.T., 1914, Ground water for irrigation in the vicinity of Enid, Oklahoma: U.S. Geological Survey Water-Supply Paper 345–B, p. 11–23.

Scott, J.C., 1989, A statistical processor for analyzing simulations made using the modular finite-difference ground-water flow model: U.S. Geological Survey Water-Resources Investigations Report 89–4159, 218 p.

Stiff, H.A., Jr., 1951, The interpretation of chemical water analysis by means of patterns: Journal of Petroleum Technology, v. 3, no. 10, p. 15-17.

U.S. Department of Agriculture, 1950, Soil Survey of Woods County, Oklahoma: Soil Conservation Service, Series 1939, no. 7, 107 p.

———1960, Soil Survey of Logan County, Oklahoma: Soil Conservation Service, Series 1948, no. 7, 60 p.

———1962, Soil Survey of Kingfisher County, Oklahoma: Soil Conservation Service, Series 1959, no. 12, 63 p.

———1967, Soil Survey of Garfield County, Oklahoma: Soil Conservation Service, 57 p.

———1968, Soil Survey of Major County, Oklahoma: Soil Conservation Service, 84 p.

———1975a, Soil Survey of Alfalfa County, Oklahoma: Soil Conservation Service, 76 p.

———1975b, Cimarron terrace flood study: Soil Conservation Service, 17 p.

U.S. Environmental Protection Agency, 1988a, Maximum contaminant levels (subpart B of part 141, National interim primary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100–149, revised as of July 1, 1988, p. 530–533.

———1988b, Secondary maximum contaminant levels (section 143.3 of part 143, National secondary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100–149, revised as of July 1, 1988, p. 608.

U.S. Geological Survey, 1966, Ground water in the Cimarron River basin: New Mexico, Colorado, Kansas, and Oklahoma: U.S. Geological Survey, Open-File Report 66–159, 51 p.

U.S. Department of Health, Education, and Welfare, 1953, Cimarron River basin: Public Health Service, 55 p.

Ward, P.E., 1961, Shallow halite deposits in northern Woodward and southern Woods Counties, Oklahoma: Oklahoma Geological Survey Oklahoma Geology Notes, v. 21, no.10, p. 275–277.

———Geology and ground-water features of salt springs, seeps, and plains in the Arkansas and Red River basins of western Oklahoma and adjacent parts of Kansas and Texas: U.S. Geological Survey Open-File Report 63–132, 194 p.

Wilson, T.A., 1981, Daily values duration hydrograph tables and plots (Program K956), Chap. IV, section I, of WATSTORE user's guide: U.S. Geological Survey Open-File Report 75–426, v. 1, p. I–1 to I–15.

Wood, P.R. and Stacy, B.L., 1965, Geology and ground-water resources of Woodward County, Oklahoma: Oklahoma Water Resources Board Bulletin 21, 114 p.

APPENDIX

Appendix 1. Statistical summary of selected ground-water-quality data collected from 1985 through 1988

[Method: 1, no censored data, ordinary percentile calculation; 2, censored data present, percentiles calculated using methods of Helsel and Cohn (1988); 3, no calculation, more than 95 percent of the data were censored; 4, no calculation, less than 10 analyses for the constituent. Largest MRL: largest minimum reporting level. MCL, (Maximum Contaminant Level), maximum permissible level of a contaminant in water that is delivered to any user of a public water system (U.S. Environmental Protection Agency, 1988a); SMCL (Secondary Maximum Contaminant Level), suggested maximum level of contaminants that only affect the aesthetic quality of drinking water (U.S. Environmental Protection Agency, 1988b); °C, degrees Celsius; µs/cm, microsiemens per centimeter at 25 degrees C; mg/L, milligrams per liter; µg/L, micrograms per liter; PCB's, polychlorinated biphenyls; Tn, tentative levels; Pr, proposed levels; pCi/L, picocuries per liter; .., no censored data for this constituent; --, no statistic was calculated, more than 95 percent of data were censored]

Constituent and properties	Method	Descriptive statistics: Sample size	Highest value	Lowest value	Largest MRL	Percentiles: 75%	(Median) 50%	25%	MCL	SMCL
Properties and major elements										
Specific conductivity (µs/cm @ 25°C)	1	63	6,500	332	..	1,280	850	581		
pH (standard units)	1	63	7.5	6.3	..	7.3	7.1	6.9		6.5–8.5
Water temperature (degrees C)	1	63	21	15	..	17.5	17	16.5		
Total hardness (mg/L as $CaCO_3$)	1	63	2,800	140	..	510	310	230		
Calcium, dissolved (mg/L)	1	63	610	37	..	120	89	63		
Magnesium, dissolved (mg/L)	1	63	320	6.7	..	40	22	14		
Sodium, dissolved (mg/L)	1	63	370	14	..	89	54	30		
Potassium, dissolved (mg/L)	1	63	18	0.9	..	3.7	2.3	1.8		
Total alkalinity, laboratory (mg/L as $CaCO_3$)	1	59	462	87.0	..	268	213	170		
Sulfate, dissolved (mg/L)	2	63	2,500	< 20	<20	200	44	28	400 Tn	250
Chloride, dissolved (mg/L)	1	63	1,000	7.2	..	130	69	35		250
Fluoride, total (mg/L)	1	17	0.90	0.20	..	0.40	0.40	0.30	4	2
Bromide, dissolved (mg/L)	2	63	2	<0.01	<0.01	0.29	0.12	0.06		
Silica, dissolved (mg/L)	1	46	36	9.9	..	22	20	16		
Dissolved solids, residue @ 180°C (mg/L)	1	47	5,680	230	..	1,040	538	424		500

Appendix 1. Statistical summary of selected ground-water-quality data collected from 1985 through 1988—Continued

Constituent and properties	Method	Descriptive statistics				Percentiles			MCL	SMCL
		Sample size	Highest value	Lowest value	Largest MRL	75%	(Median) 50%	25%		
Dissolved solids, residue, @ 105°C (mg/L)	1	16	1,030	242	..	699	546	340		
Nitrate, nitrogen (mg/L as N)	1	46	89	0.8	..	25	13.5	6.4	10	
Nitrite plus nitrate, total (mg/L as N)	2	17	30.7	<.5	<.5	12.8	6.8	5.25	[1]10	
Phosphorus, orthophosphate, total (mg/L as P)	1	17	0.11	0.01	--	0.05	0.02	0.02		
Trace elements										
Aluminum, dissolved (µg/L)	3	61	<300	<140	<300	--	--	--		50–200
Arsenic, dissolved (µg/L)	3	60	20	< 10	<10	--	--	--	50	
Barium, dissolved (µg/L)	2	32	1,400	<10	<10	360	195	74	2,000	
Boron, dissolved (µg/L)	2	61	670	<500	<500	215	105	60		
Cadmium, dissolved (µg/L)	2	61	12	<.50	<10	3.2	2.0	1.2	5	
Chromium, dissolved (µg/L)	3	61	<100	<10	<100	--	--	--	100	
Cobalt, dissolved (µg/L)	3	17	<100	<100	<100	--	--	--		
Copper, dissolved (µg/L)	2	61	51	<10	<14	4.5	1.6	0.53	1,300 Pr	1,000
Iron, dissolved (µg/L)	2	61	16,000	<10	<100	50	20	3.04		300
Lead, dissolved (µg/L)	3	61	<100	<45	<100	--	--	--	500 Pr	
Manganese, dissolved (µg/L)	2	61	720	<10	<20	8.5	0.77	0.08	50	
Mercury, dissolved (µg/L)	3	17	< 0.5	<0.5	<0.5	--	--	--	2	
Molybdenum, dissolved (µg/L)	3	17	<100	<100	<100	--	--	--		
Nickel, dissolved (µg/L)	3	17	<25	<25	<25	--	--	--	100	
Selenium, dissolved (µg/L)	2	45	14	<5	<10	3.35	1.64	0.86	50	
Silver, dissolved (µg/L)	3	17	<7	<7	<7	--	--	--		100
Zinc, dissolved (µg/L)	2	60	1,200	<5	<5	99.5	35	12.3		5,000

Appendix 1. Statistical summary of selected ground-water-quality data collected from 1985 through 1988—Continued

Constituent and properties	Method	Descriptive statistics: Sample size	Highest value	Lowest value	Largest MRL	Percentiles: 75%	(Median) 50%	25%	MCL	SMCL
Radionuclides										
Tritium, total (pCi/L)	1	12	64	5.1	..	55.5	33	18.5		
Insecticides										
Aldrin, total (µg/L)	4	5	0.08	<0.03	<0.03	--	--	--		
Alpha benzene hexachloride, total (µg/L)	4	5	<0.02	<0.02	<0.02	--	--	--		
Beta benzene hexachloride, total (µg/L)	4	5	<0.02	<0.02	<0.02	--	--	--		
Chlordane, total (µg/L)	4	5	<0.20	<0.20	<0.20	--	--	--	2	
Chlordane, cis isomer, total (µg/L)	4	5	<0.10	<0.10	<0.10	--	--	--		
Chlordane, trans isomer, total (µg/L)	4	5	<0.10	<0.10	<0.10	--	--	--		
Chlordane-nonachlor, trans isomer, total (µg/L)	4	5	<0.10	<0.10	<0.10	--	--	--		
Chloropyrifos, total (µg/L)	4	5	<0.10	<0.10	<0.10	--	--	--		
DDT, total (µg/L)	4	5	<0.70	<0.70	<0.70	--	--	--		
Diazinon, total (µg/L)	4	5	<0.05	<0.05	<0.05	--	--	--		
Dicofol, total (µg/L)	4	5	<2.0	<2.0	<2.0	--	--	--		
Dieldrin, total (µg/L)	4	5	<0.06	<0.06	<0.06	--	--	--		
Heptachlor, total (µg/L)	4	5	<0.03	<0.03	<0.03	--	--	--	.4	
Heptachlor epoxide, total (µg/L)	4	5	<0.03	<0.03	<0.03	--	--	--	.2	
Hexachloride, delta benzene, total (µg/L)	4	5	<0.02	<0.02	<0.02	--	--	--		
Hexachlorobenzene, total (µg/L)	4	5	<0.20	<0.20	<0.02	--	--	--	.1	
Endosulfan sulfate, total (µg/L)	4	5	<0.20	<0.20	<0.02	--	--	--		

Appendix 1. Statistical summary of selected ground-water-quality data collected from 1985 through 1988—Continued

Constituent and properties	Method	Sample size	Descriptive statistics: Highest value	Lowest value	Largest MRL	Percentiles: 75%	(Median) 50%	25%	MCL	SMCL
Endosulfan beta, total (µg/L)	4	5	<0.20	<0.20	<0.02	--	--	--		
Endosulfan alpha, total (µg/L)	4	5	<0.20	<0.20	<0.02	--	--	--		
Endrin aldehyde, total (µg/L)	4	5	<0.06	<0.06	<0.06	--	--	--		
Endrin ketone, total (µg/L)	4	5	<0.06	<0.06	<0.06	--	--	--		
Endrin, total (µg/L)	4	5	<0.03	<0.03	<0.03	--	--	--	2	
Lindane, total (µg/L)	4	5	<0.02	<0.02	<0.02	--	--	--	.2	
Malathion, total (µg/L)	4	5	<0.40	<0.40	<0.40	--	--	--		
Methyl parathion, total (µg/L)	4	5	<0.10	<0.10	<0.10	--	--	--		
Methoxychlor, total (µg/L)	4	5	<0.70	<0.70	<0.70	--	--	--	40	
Parathion, total (µg/L)	4	5	<0.10	<0.10	<0.10	--	--	--		
P,p' DDE, total (µg/L)	4	5	<0.20	<0.20	<0.20	--	--	--		
O,p' DDT, total (µg/L)	4	5	<0.20	<0.20	<0.20	--	--	--		
P,p' DDT, total (µg/L)	4	5	<0.20	<0.20	<0.20	--	--	--		
O,p' DDD, total (µg/L)	4	5	<0.20	<0.20	<0.20	--	--	--		
P,p' DDD, total (µg/L)	4	5	<0.20	<0.20	<0.20	--	--	--		
O,p' DDE, total (µg/L)	4	5	<0.20	<0.20	<0.20	--	--	--		
Toxaphene, total (µg/L)	4	5	<0.30	<0.30	<0.30	--	--	--	.3	
Herbicides										
Dacthal, total (µg/L)	4	5	<0.10	<0.10	<0.10	--	--			
2,4,5-T, total (µg/L)	4	5	<0.20	<0.20	<0.20	--	--	--		
2,4-D, total (µg/L)	4	5	<20.0	<20.0	<20.0	--	--	--	70	
2,4-DP, total (µg/L)	4	5	<0.20	<0.20	<0.20	--	--	--		
PCB's										
Aroclor 1016 PCB, total (µg/L)	4	5	<0.3	<0.3	<0.3	--	--	--		

Appendix 1. Statistical summary of selected ground-water-quality data collected from 1985 through 1988—Continued

Constituent and properties	Method	Descriptive statistics				Percentiles			MCL	SMCL
		Sample size	Highest value	Lowest value	Largest MRL	75%	(Median) 50%	25%		
Aroclor 1221 PCB, total (µg/L)	4	5	<0.3	<0.3	<0.3	--	--	--		
Aroclor 1232 PCB, total (µg/L)	4	5	<0.3	<0.3	<0.3	--	--	--		
Aroclor 1242 PCB, total (µg/L)	4	5	<0.3	<0.3	<0.3	--	--	--		
Aroclor 1248 PCB, total (µg/L)	4	5	<0.3	<0.3	<0.3	--	--	--		
Aroclor 1254	4	5	<0.3	<0.3	<0.3					
Aroclor 1260 PCB, total (µg/L)	4	5	<0.3	<0.3	<0.3	--	--	--		
PCB, total (µg/L)	4	5	<0.3	<0.3	<0.3	--	--	--	5	

[1] The MCL applies to nitrate; the nitrite plus nitrate analysis is used as an estimate of nitrate.

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