# Potential Hydrologic Effects of Ground-Water Withdrawals from the Dakota Aquifer, Southwestern Kansas

United States Geological Survey Water-Supply Paper 2304

Prepared in cooperation with the Southwest Kansas Groundwater Management District No. 3

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By KENNETH R. WATTS

Prepared in cooperation with the
Southwest Kansas Groundwater
Management District No. 3

UNITED STATES GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2304

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## CONVERSION TABLE

Inch-pound units used in this report may be converted to the International System of Units (SI) by the following factors:

| Multiply inch-pound unit | By | To obtain SI unit |
|---|---|---|
| | *Length* | |
| inch (in.) | 2.54 | centimeter (cm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | *Area* | |
| acre | 4,047 | square meter ($m^2$) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | *Slope* | |
| foot per mile (ft/mi) | 0.1894 | meter per kilometer (m/km) |
| | *Volume* | |
| gallon (gal) | 3.785 | liter (L) |
| acre-foot (acre-ft) | 1,233 | cubic meter ($m^3$) |
| | *Flow* | |
| acre-foot per year (acre-ft/yr) | 1,233 | cubic meter per year ($m^3$/yr) |
| cubic foot per day ($ft^3$/d) | 28.31605 | liter per day (L/d) |
| cubic foot per second ($ft^3$/s) | 28.31605 | liter per second (L/s) |
| gallon per minute (gal/min) | 0.06308 | liter per second (L/s) |
| inch per year (in./yr) | 2.540 | centimeter per year (cm/yr) |
| | *Specific capacity* | |
| gallon per minute per foot [(gal/min)/ft] | 0.2070 | liter per second per meter [(L/s)/m] |
| | *Specific conductance* | |
| micromho per centimeter at 25 °Celsius (μmhos/cm at 25 °C) | 1.000 | microsiemens per centimeter at 25 °Celsius (μS/cm at 25 °C) |
| | *Hydraulic conductivity* | |
| foot per second (ft/s) | 0.3048 | meter per second (m/s) |
| foot per day (ft/d)[1] | .3048 | meter per day (m/d) |
| | *Transmissivity* | |
| foot squared per day[2] ($ft^2$/d) | 0.09290 | meter squared per day ($m^2$/d) |
| | *Temperature* | |
| degree Fahrenheit (°F) | (3) | degree Celsius (°C) |

[1]For convenience, hydraulic conductivity is given in units of feet per day. However, by definition, hydraulic conductivity should be given in units of cubic feet per day per square foot [($ft^3$/d)/$ft^2$], which is mathematically equivalent to units of feet per day (ft/d).

[2]Transmissivity by definition should be given in units of cubic feet per day per foot [($ft^3$/d)/ft], which is mathematically equivalent to feet squared per day ($ft^2$/d).

[3]To convert temperature in degrees Fahrenheit (°F) to degrees Celsius (°C) use the following equation:

$$°C = 5/9(°F - 32).$$

## GLOSSARY

**Aquifer.** A formation, group of formations, or part of a formation that contains sufficient saturated, permeable material to yield significant quantities of water to wells and springs.

**Confined aquifer.** An aquifer bounded above and below by beds of distinctly lower permeability than that of the aquifer itself, in which ground water is under pressure significantly greater than that of the atmosphere.

**Confining unit.** A body of impermeable material stratigraphically adjacent to one or more aquifers. The hydraulic conductivity of the confining unit may range from nearly zero to some value distinctly lower than that of the aquifer.

**Formation.** A mappable or traceable body of rock generally characterized by some degree of internal lithologic homogeneity or distinctive lithologic features.

**Hydraulic conductivity.** Volume of water at the existing kinematic viscosity that will move through a porous medium in unit time, under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

**Hydraulic gradient.** Rate of change in hydraulic head per unit of distance of flow in a given direction, generally assumed to be in the direction of maximum decrease.

**Hydraulic head.** Height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point; synonymous with static head.

**Hydrogen ion concentration (pH).** Concentration of hydrogen ions in solution expressed as the negative logarithm of the gram-ionic weight per liter.

**Hydrograph.** A graph showing stage, flow, velocity, or some other characteristic of water with respect to time.

**Outcrop.** That part of a geologic formation or structure that appears at the surface of the Earth.

**Potentiometric surface.** An imaginary surface representing the static head of ground water, defined by the levels to which water will rise in tightly cased wells.

**Sodium-adsorption-ratio (SAR).** Definition modified from U.S. Salinity Laboratory Staff (1954). Related to the adsorption of sodium from water to the soil to which the water has been added. SAR is determined by the following relation where sodium ($Na^{+}$), calcium ($Ca^{+2}$), and magnesium ($Mg^{+2}$) ion concentrations are expressed in milliequivalents per liter:

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

**Specific capacity.** Rate of discharge of water from a well divided by the drawdown of water level within the well.

**Specific conductance.** The ability of a substance to conduct an electric current. Specific conductance is the conductance of a body of unit length and unit cross section at a specified temperature and is related to the concentration of dissolved solids in a water sample.

**Specific storage.** Volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

**Specific yield.** Ratio of the volume of water that the saturated porous medium will yield by gravity to the volume of the porous medium.

**Static water level.** The depth to water in a well that represents the unstressed water surface.

**Steady state.** Equilibrium conditions that exist when hydraulic heads and the volume of water in storage do not change significantly with time.

**Storage coefficient.** Volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head.

**Subcrop.** A geologic formation that occurs directly beneath a substantial break in stratigraphic sequence.

**Transient state.** Nonequilibrium conditions that exist when hydraulic heads and the volume of water in storage do change significantly with time.

**Transmissivity.** Rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

**Water table.** The potentiometric surface of an unconfined aquifer at which the water pressure is atmospheric. The surface is defined by the levels at which water stands in wells that penetrate the aquifer enough to hold standing water.

# Potential Hydrologic Effects of Ground-Water Withdrawals from the Dakota Aquifer, Southwestern Kansas

*By* Kenneth R. Watts

## Abstract

A study was conducted to evaluate the effects of potential development of the Dakota aquifer on the layered-aquifer system above Permian rocks in a 5,000-square-mile area of southwestern Kansas. This aquifer system, which consists of five layers, includes the Cheyenne aquifer, the Kiowa confining unit, the Dakota aquifer, the Niobrara-Graneros confining unit, and the High Plains aquifer. Water supplies from the sandstone aquifers thus far have been developed mainly in parts of Hodgeman and Ford Counties. Management restrictions placed on further development of the High Plains aquifer could lead to additional development of the sandstone aquifers in the study area.

The upper sandstone aquifer, the Dakota aquifer, consists of sandstone and shale of the Lower Cretaceous Dakota Sandstone and is as much as 400 feet thick. Transmissivity of the Dakota aquifer, determined from analyses of of pumping tests, ranges from 100–7,100 feet squared per day. The Dakota aquifer is confined where it is overlain by the shales and limestones of the Upper Cretaceous Niobrara-Graneros confining unit, but locally it is unconfined.

The lower sandstone aquifer, the Cheyenne aquifer, consists of the sandstone and shales of the Lower Cretaceous Cheyenne Sandstone in the eastern half of the study area plus undifferentiated Middle and Upper Jurassic rocks (sandstone, siltstone, shale, and limestone) in the western half of the study area. Maximum thickness of the Cheyenne aquifer is more than 300 feet, and maximum transmissivity is estimated at 3,000 feet squared per day.

Estimated water use in the study area was about 8,800,000 acre-feet from the High Plains aquifer and about 160,000 acre-feet from the Dakota aquifer during 1975–82. The Cheyenne aquifer is not developed in the study area, and no water use from it is reported.

The chemical characteristics of water in the sandstone aquifers are highly variable in the study area. Water in the Dakota aquifer is a calcium bicarbonate type water, similar to water in the High Plains aquifer, in the subcrop area. However, in areas distant from the subcrop, water in the Dakota aquifer is a sodium bicarbonate type water with dissolved-solids concentrations in excess of 500 milligrams per liter. In some parts of the study area, water from the Dakota presents high to very high salinity and sodium hazards to crops and soil when it is used for irrigation. The Cheyenne aquifer locally contains mineralized water, as indicated by the response of resistivity curves on geophysical logs.

Hydrographs of wells completed in the Dakota aquifer indicate that the Dakota and High Plains aquifers are hydraulically connected in and near subcrop areas. Locally, the Dakota aquifer has converted from confined to unconfined conditions as a result of declining water levels due to pumpage from the Dakota aquifer and as the result of depletion of the High Plains aquifer in subcrop areas. Gradual declines in the potentiometric surface of the Dakota aquifer have occurred since the onset of pumpage in the 1960's; however, water levels in some wells have risen during the late 1970's.

A digital computer model of three-dimensional ground-water flow was developed to simulate hydrologic conditions of a five-layer hydrologic system for 1975–82 conditions. The major components of the simulated 1975–82 water budget were well discharge from the High Plains aquifer and loss of ground water from storage in the High Plains aquifer. Although downward leakage from the High Plains aquifer in the study area represented only 18,000 acre-feet of the 1,365,000 acre-feet discharged from the High Plains aquifer during 1982, it was a major source of inflow to the Dakota aquifer. Changes in storage in the Dakota aquifer in the study area during 1982 were about 5,000 acre-feet.

A baseline projection was made using 1982 simulated hydraulic heads from the calibrated model and 1982 rates of pumpage from both the High Plains and the Dakota aquifers for comparison with eight additional projection simulations in which maximum pumpage from the Dakota aquifer at the end of the projections ranged from about 78,000 to 294,000 acre-feet per year. The results from the projections indicate that: (1) pumpage from the Dakota aquifer will have a limited effect on hydraulic heads in the High Plains aquifer, (2) drawdown in the hydraulic heads in the Dakota aquifer will result in conversion of much of the Dakota aquifer to unconfined conditions, (3) change in storage will become the major water-budget component for the Dakota aquifer, and (4) continuation of 1982 rates of withdrawal from the High Plains aquifer will result in dewatering of a substantial part of the aquifer in the study area.

# INTRODUCTION

The availability of an adequate supply of ground water is important to the predominantly agricultural-based economy of southwest Kansas. The water stored in the region's principal aquifer, the High Plains aquifer, is presently being mined. Further development of the High Plains aquifer has been restricted in some areas by ground-water management policies. Alternative water supplies may be obtained from the Dakota and Cheyenne aquifers that underlie parts of this region. A better understanding of the hydrology of the Dakota and Cheyenne aquifers and their interaction with the High Plains aquifer is needed so that management policies may be devised and implemented to guide development of the water resources of southwest Kansas.

## Purpose and Scope

The objectives of this investigation were to evaluate the potential hydrologic effects of ground-water withdrawals from the Dakota aquifer on the overlying High Plains aquifer and to describe the hydrogeology of the Dakota and Cheyenne aquifers in Finney, Ford, Gray, Hodgeman, and Kearny Counties, Kans. This investigation was conducted in cooperation with Southwest Kansas Groundwater Management District No. 3 to provide information with which to evaluate proposed ground-water management guidelines for development of the Dakota and Cheyenne aquifers in southwest Kansas.

This report describes: (1) the geology of a hydrologic system that includes the Dakota and Cheyenne aquifers, shale confining beds in the Cretaceous rocks, and the High Plains aquifer in the unconsolidated Tertiary and Quaternary deposits, (2) the hydraulic properties of the aquifers and confining beds, (3) estimated water use from the principal aquifers, (4) chemical characteristics of water from the Dakota aquifer, (5) the historic hydrologic response of the hydraulic head in the Dakota aquifer, and (6) a numerical model used to evaluate potential hydrologic effects of future ground-water withdrawals.

## Location and Description of Study and Model Areas

The study area, shown in figure 1, includes all of Finney, Ford, Gray, Hodgeman, and Kearny Counties in southwest Kansas. Total surface area is about 5,000 $mi^2$. The model area, used in projecting the potential effects of ground-water withdrawals from the Dakota aquifer, includes about 21,900 $mi^2$ in western Kansas and about 350 $mi^2$ in eastern Colorado.

The study area and most of the model area lie within the High Plains section of the Great Plains physiographic province (Fenneman, 1931). In the study area, altitudes of the land surface range from about 3,500 ft in western Kearny County to about 2,100 ft in the Pawnee River valley in northeast Hodgeman County. The prevailing slope of the topographic surface is about 13 ft/mi in an easterly direction. Where Cretaceous rocks are exposed, local relief of the land surface may exceed 200 ft.

## Methods of Investigation

### Previous Investigations

Many of the reports published by the Kansas Geological Survey and the U.S. Geological Survey contain some geologic and hydrologic information about the Cretaceous and Jurassic rocks (sandstone aquifers) of western Kansas, but they primarily describe the water resources of the High Plains aquifer. Reports by Keene and Bayne (1977), Lobmeyer and Weakly (1979), Kume and Spinazola (1982; 1983), and Kume (1984) described the ground-water resources of the Lower Cretaceous and Jurassic rocks in western Kansas. Hydrogeologic information about the sandstone aquifers in adjacent states was given by McLaughlin (1954) for Baca County, Colo., by Voegeli and Hershey (1965) for Prowers County, Colo., and by Hart and others (1976) for the Oklahoma Panhandle.

The geologic history and stratigraphy of Kansas were described by Merriam (1963) and Zeller (1968). Structural geology and subsurface correlations were given by Lee and Merriam (1954) and Merriam (1957a; 1957b; 1958).

### Data Collection and Analysis

The data-collection activities for this study included: measurements of the depths to water in selected wells, aquifer tests and specific-capacity tests of wells, collection of water samples from selected large-capacity wells completed in Dakota aquifer for chemical analyses, an inventory of large-capacity production wells (discharge of at least 100 gal/min) that were completed in the Dakota aquifer, and compilation of 1975–82 water-use records for these wells.

Maps of the potentiometric surfaces of the Dakota and the High Plains aquifers were prepared from data retrieved from the Ground-Water Site Inventory (GWSI) of WATSTORE (on file with the U.S. Geological Survey, Lawrence, Kans.), published water-level data, unpublished data from drillers' logs (on file with the U.S. Geological Survey in Garden City, Kans.), and unpublished data on

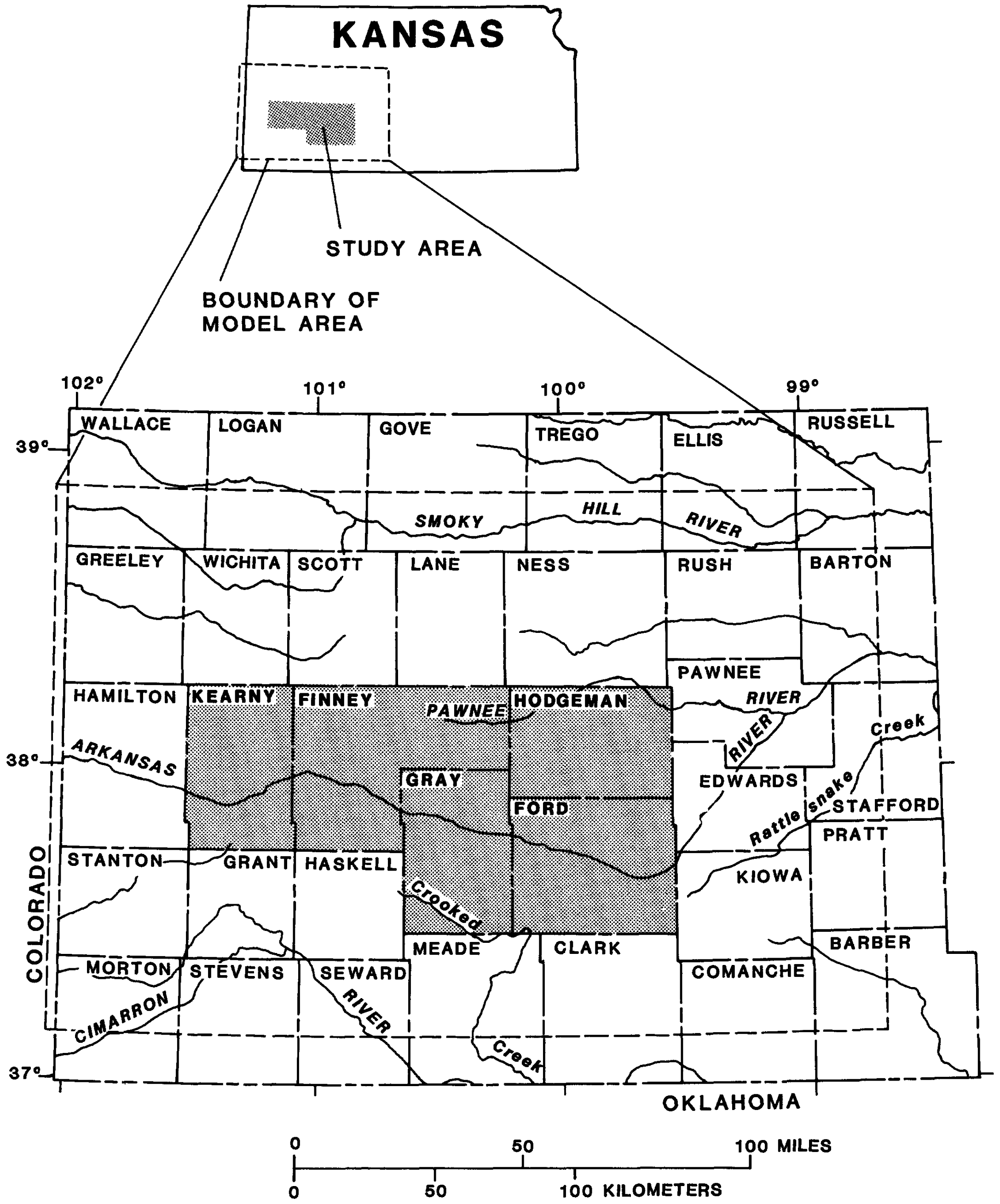



**Figure 1.** Location of study and model areas.

file with the Central Midwest Regional Aquifer-Systems Analysis (U.S. Geological Survey, Lawrence, Kans.). Maps of selected geologic units were prepared from previously published data, supplemented with data from geophysical logs of oil and gas wells and from drillers' logs of water wells and test holes. Estimates of the hydraulic properties of the sandstone aquifers were based on analyses of aquifer tests, specific capacities of wells, and isopach maps and from published data.

Estimates of historical water use from the Dakota aquifer were based on water-use reports filed with the Kansas State Board of Agriculture, Division of Water Resources, and the Southwest Kansas Groundwater Management District No. 3. Estimates of water use from the High Plains aquifer were based on estimates by Barker and others (1983), Lindgren (1982), and Heimes and Luckey (1982) and from data retrieved from the GWSI files of WATSTORE (U.S. Geological Survey, Lawrence, Kans.).

### Numerical Model

A numerical model of three-dimensional ground-water flow, slightly modified from McDonald and Harbaugh (1984), was used to examine the potential effects in the study area of hypothetical withdrawals from the Dakota aquifer on the hydrologic system. The model simulated a layered-aquifer system with three aquifers and two intervening confining layers. The model incorporated discharge to wells, springs, seeps, and rivers, and areal recharge.

## Location Numbering System

Locations of water wells, test holes, and other data-collection sites referred to in this report are numbered according to a modification of the U.S. Bureau of Land Management's system of land subdisivision. In this system, the first set of digits of a location number indicates the township south of the Kansas-Nebraska State line; the second set, the range east or west of the Sixth Principal Meridian; the third set, the section in which the site is located. The first letter following the third set denotes the quarter section or 160-acre tract; the second, the quarter-quarter section or 40-acre tract; the third, the quarter-quarter-quarter section or 10-acre tract; and the fourth, the quarter-quarter-quarter-quarter section or 2.5-acre tract within the section. The letters are designated A, B, C, and D in a counterclockwise direction beginning in the northeast quadrant. The last two digits in the numbering system are the sequential order, beginning with "01," in which sites within the same tract were numbered. In figure 2, site 23 34W 14CCCC 01 in

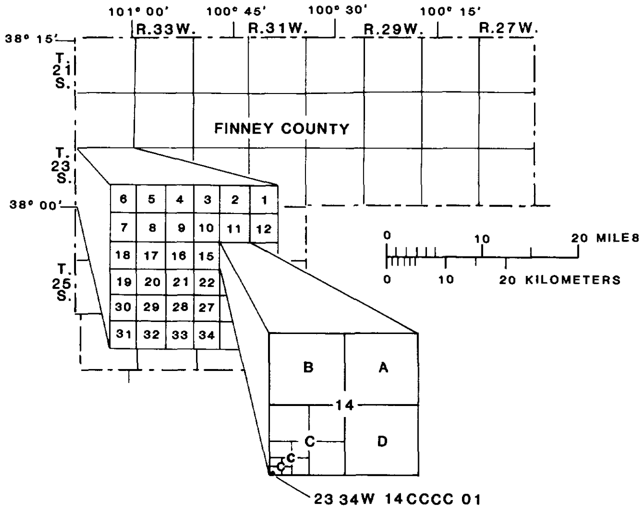



**Figure 2.** Location numbering system.

Finney County is the location of the first well numbered in the SW1/4 SW1/4 SW1/4 SW1/4 sec. 14, T. 23 S., R. 34 W.

## Acknowledgments

The author wishes to thank the landowners, corporations, and public officials who provided information and allowed access to their wells and property. Acknowledgment is given to the staff of Southwest Kansas Groundwater Management District No. 3 (Garden City, Kans.) for assistance in collection and interpretation of data and to the Division of Water Resources, Kansas State Board of Agriculture, for access to water-use reports.

# HYDROGEOLOGY

The occurrence and movement of ground water within the study area is primarily influenced by topography, lithology, and geographic distribution of the rocks and by the stratigraphic and hydraulic relationships between the layers of rock. Stratigraphy describes the sequential relationships between the layers of rock. Structure describes the geometric relationships of the rocks, such as faults and folds.

## Stratigraphy

The stratigraphic section considered during this study includes rocks of the Permian, Jurassic, Cretaceous, Tertiary, and Quaternary Systems (table 1). The lithology of these rocks is highly variable and includes evaporites (halite, gypsum, and anhydrite), clastics (clay, silt, shale, siltstone, sandstone, sand, and gravel), and carbonates (limestone, chalk, and dolomite). Detailed descriptions of the stratigraphy and lithology of these rocks may be found in Zeller (1968).

The rocks at land surface (fig. 3) consist principally of Quaternary unconsolidated deposits of silt (loess) and dune sand of eolian origin and sand, gravel, clay, and silt of alluvial origin. Outcrops of the Tertiary Ogallala Formation are found in Hodgeman, Kearny, northeastern Finney, and north-central Ford Counties. Lower and Upper Cretaceous rocks are exposed in parts of Hodgeman, northeastern Finney, and western Kearny Counties, with limited exposures in Ford and Gray Counties. Permian rocks do not crop out in the study area but are exposed south and southeast of the study area in Clark, Comanche, and Kiowa Counties.

Consolidated Cretaceous and Jurassic rocks underlie the Quaternary and Tertiary unconsolidated deposits. The pre-Tertiary rocks consist of limestone and shales of the Upper Cretaceous Series, sandstone and shales of the Lower Cretaceous Series, and a small area of Jurassic rocks in extreme southwestern Gray County (fig. 4). The pre-Tertiary surface is an erosional surface that has been modified by regional structural movement and local nontectonic movement (subsidence). Average slope of the surface of pre-Tertiary rocks is about 10–11 ft/mi to the east and southeast. Local relief of as much as 275 ft on this surface is the result of several erosional periods and local subsidence.

### Permian Rocks

Lower and Upper Permian rocks that subcrop beneath the Lower Cretaceous and Jurassic rocks in the study area include the Lower Permian Dog Creek Shale, Whitehorse Sandstone, and Day Creek Dolomite and the Upper Permian Big Basin Formation (table 1). Older rocks of the Lower Permian Series do not subcrop beneath the Lower Cretaceous and Jurassic rocks but were included in this study because they contain two formations, the Blaine and the Stone Corral Formations, that are useful in correlation of geophysical logs. These older Lower Permian rocks include the Stone Corral Formation, the Harper Sandstone, the Salt Plains Formation, the Cedar Hills Sandstone, the Flowerpot Shale, and the Blaine Formation (table 1). Lower Permian rocks contain bedded evaporites that affect both the chemistry of ground water and the structure of overlying strata. Detailed descriptions of these rocks are given by Swineford (1955) for the Upper Permian Series and by Holdoway (1978) for the Nippewalla Group (the Lower Permian rocks above the Stone Corral Formation). Descriptions of Permian stratigraphy are given also by Zeller (1968).

### Jurassic Rocks

Undifferentiated Middle and Upper Jurassic rocks occur in the subsurface in parts of the study area (Kume, 1984). These rocks are similar to the Morrison Formation and the Entrada Sandstone of southeastern Colorado (Gutentag and others, 1981) but have been identified, in Kansas only, from drillers' and geophysical logs. A basal, white, very fine grained sandstone (Entrada (?) equivalent) is present in Kearny County. In most of the study area, the Jurassic rocks consist of varicolored shale and siltstone, with some sandstone and limestone (Morrison (?) equivalent). Jurassic rocks range in thickness from zero at their eastern limit to more than 150 ft in Finney and Kearny Counties (Kume, 1984).

### Cretaceous Rocks

The Cretaceous rocks in the study area are divided into two series— the Lower Cretaceous Series, which consists of sandstone and shale, and the Upper Cretaceous Series, which consists of limestone, chalk, and shale. Hattin (1962; 1965a; 1965b; 1975; 1982) provides detailed descriptions of the stratigraphy of the Upper Cretaceous rocks. The Lower Cretaceous section in Kansas consists of the Cheyenne Sandstone, the Kiowa Shale, and the Dakota Sandstone.

The Cheyenne Sandstone is a fine- to medium-grained, white, brown, or gray sandstone that may be interbedded with dark-gray marine shale. Thickness of the Cheyenne Sandstone in the study area is reported to range from zero, in the extreme southwestern corner of Gray County, to 200 ft in parts of Ford and Hodgeman Counties. The Cheyenne Sandstone in the study area generally ranges between 50–100 feet in thickness. The Cheyenne Sandstone unconformably overlies Permian rocks in the eastern one-half and Jurassic rocks in the western one-half of the study area. The Cheyenne Sandstone crops out to the south and east of the study area in Barber, Clark, and Comanche Counties, Kans.

The Kiowa Shale is a light-gray to black marine shale, with some interbedded siltstone, fine-grained sandstone, and limestone. Kiowa rocks underlie all of the study area, except the extreme southwest corner of Gray County. Thickness of the Kiowa Shale in the study area ranges from zero, in southwestern Gray County, up to 300 ft in parts of Ford County. The contact of the Kiowa with the Cheyenne is often gradational; therefore, interpretation of this contact's position from geophysical or drillers' logs is subjective.

The Dakota Sandstone consists of fine- to medium-grained, white, gray, or brown sandstone, interbedded with varicolored shale and siltstone. The formation contains both marine and nonmarine (fluvial-deltaic) deposits. Character, thickness, and trends in the formation

**Table 1.** Generalized stratigraphic section of geologic and hydrologic units and their physical and hydrologic characteristics

| System | Series (group) | Geologic unit | Thickness (feet) | Physical characteristics | Hydrologic unit | Hydrologic characteristics |
|---|---|---|---|---|---|---|
| Quaternary | Holocene | Alluvium | 0–80 | Stream-laid deposits ranging from clay and silt to sand and gravel that occur in the principal stream valleys. | High Plains aquifer | Well yields range from 50–1,000 gallons per minute. Hydraulic and storage properties vary within short distances. |
| | Pleistocene | Dune sand | 0–75 | Fine to medium quartzose sand with small amounts of silt, clay, and coarse sand deposited into dunes by the wind. | | Lies above the water table and does not yield water to wells. In areas where dune sand occurs, infiltration is rapid, and areas of appreciable ground-water recharge are delineated. |
| | | Loess | 0–45 | Silt with minor amounts of very fine sand and clay deposited as windblown dust. | | Lies above the water table and does not yield water to wells. In areas where loess occurs, specific retention is appreciable, and areas of minimal ground-water discharge are delineated. |
| Quaternary and Tertiary | Pleistocene-Miocene | Undifferentiated deposits | 0–550 | Composite of Quaternary-age sand, gravel, silt, clay, and caliche that overlie the Ogallala Formation, where present; composite of stream-laid and windblown deposits | | The sand and gravel of the undifferentiated deposits and the Ogallala Formation are the principal water-bearing deposits in the area. Well yields range from 100–3,100 gallons per minute, and water in the aquifer is unconfined to semiconfined. |
| Tertiary | Miocene | Ogallala Formation | 0–500 | Poorly sorted clay, silt, sand, and gravel generally calcareous; when cemented by calcium carbonate, forms caliche or mortar beds. | | |
| Cretaceous | Upper Cretaceous (Colorado Group) | Niobrara Chalk | 0–250 | Upper part, Smoky Hilk Chalk Member is yellow to orange-yellow chalk and light- to dark-gray chalky shale; basal part, Fort Hays Limestone Member is white to yellow, massive, chalky limestone that contains thin beds of dark-gray, chalky shale. | Niobrara-Graneros confining unit | Areas of secondary porosity may yield water to wells. Where secondary porosity values are small, areas may yield small quantities of water to stock and domestic wells. |
| | | Carlile Shale | 0–330 | Upper part consists of a dark-gray to blue-black, noncalcareous to slightly calcareous shale that is locally interbedded with calcareous, silty, very fine grained sandstone. Lower part consists of very calcareous, dark-gray shale and thin, gray interbedded limestone layers. | | Sandstone in upper part may yield small quantities of water, 5–10 gallons per minute, to wells. |
| | | Greenhorn Limestone | 0–200 | Chalky, light yellow-brown shale with thin-bedded limestone. Dark-gray, calcareous shale and light-gray, thin-bedded limestone; contains layers of bentonitic shale. | | Not known to yield water to wells in southwest Kansas. |
| | | Graneros Shale | 0–130 | Dark-gray, calcareous shale interbedded with black, calcareous shale; contains thin beds of bentonitic shale. Also contains thin-bedded, gray limestone and fine-grained silty sandstone. | | Not known to yield water to wells. |
| | | Dakota Sandstone | 0–400 | Brown, yellow, white, and gray fine- to medium-grained sandstones; interbedded with gray sandy shale, and varicolored clays; contains lignite, pyrite, and siderite. Generally has an upper shaley sandstone, middle sandy shale, and lower sandstone. Marine and fluvial-deltaic deposits | Dakota aquifer | In some areas, the sandstones may yield more than 1,000 gallons per minute to wells. Water in the aquifer generally is confined where the Niobrara-Graneros confining unit is present. The principal aquifer in parts of Hodgeman and northern Ford Counties. |

| | | | | | | |
|---|---|---|---|---|---|---|
| Cretaceous | Lower Cretaceous | Kiowa Shale | 0–300 | Dark-gray to black shale, interbedded with light-yellow-brown to gray, fine-grained sandstone. | Kiowa confining unit | Does not yield water to wells in southwest Kansas. |
| | | Cheyenne Sandstone | 0–200+ | Gray, brown, and white, very fine to medium-grained sandstone with interbedded dark-gray shale. | Cheyenne aquifer | Upper part (Cheyenne Sandstone) may yield up to 1,000 gallons per minute to wells in southeast Colorado; undeveloped in southwest Kansas. In some areas contains mineralized water. Lower part (undifferentiated Jurassic rocks) may yield water to wells in parts of southwest Kansas, but water is generally mineralized. |
| Jurassic | Upper and Middle Jurassic | Undifferentiated rocks | 0–150+ | Dark-gray shale interbedded with grayish-green and blue-green calcareous shale; contains very fine to medium-grained, silty sandstone and thin limestone beds at the base. | | Water is generally highly mineralized. |
| | Upper Permian | Big Basin Formation | 0–160 | Brick-red to maroon siltstone and shale; contains very fine grained sandstone. | | In Morton County, wells developed in solution cavities yield 300–1,000 gallons per minute of sulfate water. |
| | | Day Creek Dolomite | 0–80 | White to pink anhydrite and gypsum with interbedded dark-red shale. | | |
| | | Whitehorse Sandstone | 160–350 | Red to maroon, fine-grained, silty sandstone, siltstone, and shale. | Permian confining unit | Not known to yield water to wells in southwest Kansas; may contain highly mineralized water. |
| | | Dog Creek Shale | 15–60 | Maroon, silty shale, siltstone, very fine grained sandstone, and thin layers of dolomite and gypsum. | | Not known to yield water to wells. Water is probably highly mineralized. |
| | | Blaine Formation | 20–150 | Generally consists of four gypsum and anhydrite beds separated by red shale. Bedded halite is present in some areas. Locally, a marker bed on geophysical logs. | | Not known to yield water to wells; contains highly mineralized water. |
| Permian | Lower Permian (Nippewalla Group) | Flowerpot Shale | 140–340 | Gypsiferous shale and silty shale with thin beds of sandstone and siltstone; locally contains up to 250 feet of bedded gypsum and halite. | | |
| | | Cedar Hills Sandstone | 77–180 | Saliferous and gypsiferous, amber to pink, fine- to coarse-grained, shaley sandstone. | | Generally contains highly mineralized water in southwest Kansas. In some areas it is used for brine disposal. |
| | | Salt Plains Formation and Harper Sandstone | 300–500 | Upper unit (Salt Plains Formation)—reddish-brown siltstones, thin sandy siltstones, and very fine grained sandstone. Lower unit (Harper Sandstone)—brownish-red siltstones and silty shales with a few silty sandstones. In the subsurface, may contain bedded halite, anhydrite, and gypsum. | | Not known to yield water to wells in southwest Kansas. May contain highly mineralized water.<br><br>Oilfield-brine disposal zone. Contains highly mineralized water. |
| | Lower Permian (Sumner Group) | Stone Corral Formation | 25–100 | Dolomite, anhydrite, gypsum, and halite; gray to mottled with interbedded red shale. Distinctive marker bed on geophysical logs. | | Not known to yield water to wells in southwest Kansas. |

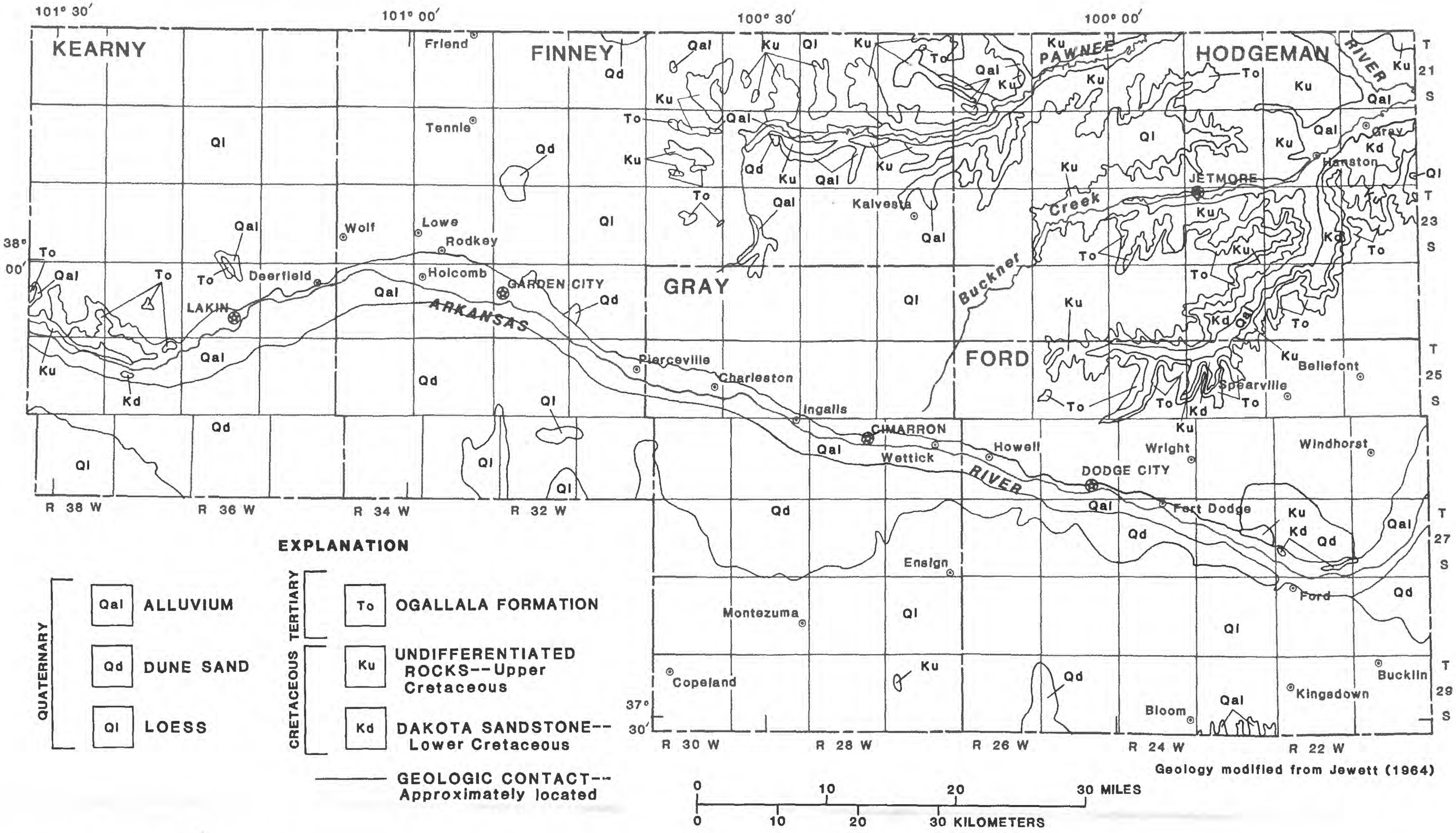



**Figure 3.** Surficial geology of study area.

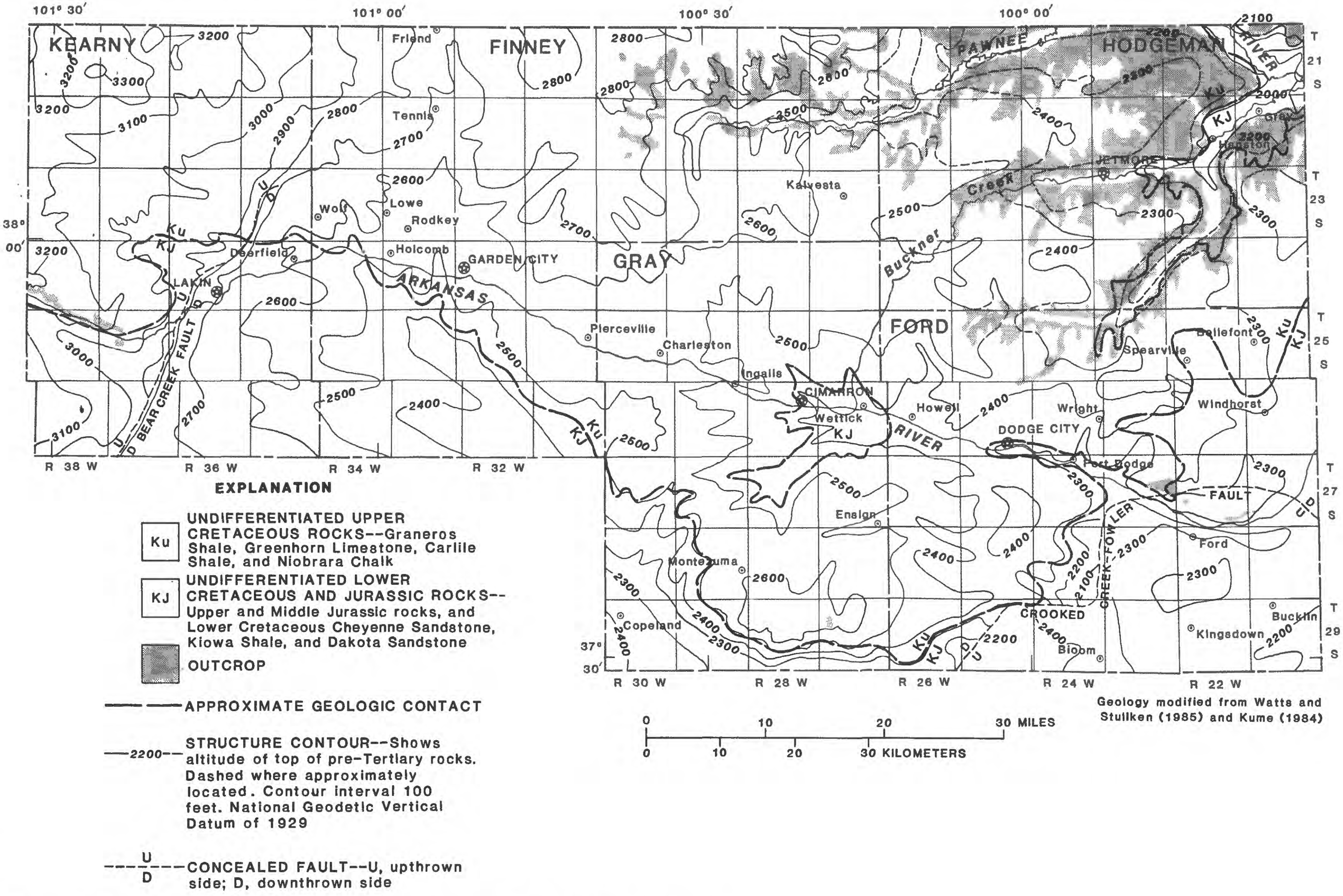



**Figure 4.** Generalized geology, altitude, and configuration of top of pre-Tertiary rocks.

vary considerably in short distances. Locally, the Dakota Sandstone may be subdivided into three units; a thick basal sandstone, an intermediate shale with interbedded sandstones, and an upper sandstone with interbedded shale. However, in some localities the Dakota Sandstone may consist predominantly of either sandstone or shale. Thickness of the Dakota Sandstone in the study area ranges from zero, in southwestern Gray County, to about 400 ft in east-central Ford County. Generally, the Dakota is 200–300 ft thick where it has not been subjected to erosion. The contact of the Dakota Sandstone with the Kiowa Shale, as identified from geophysical logs, may be distinct or gradational. Contact of the Dakota Sandstone with the overlying Graneros Shale is generally gradational.

### Tertiary and Quaternary Deposits

Tertiary and Quaternary deposits consist primarily of clay, silt, sand, and gravel of alluvial origin, which are overlain by eolian deposits of silt and clay (loess) and dune sand. Many reports describe the geology and ground-water resources of these deposits in the study area, including those by Gutentag and others (1972a; 1972b; 1981), McGovern and Long (1974), Spinazola and Dealy (1983), and Stullken and others (1985). Thickness of the Tertiary and Quaternary deposits in the study area ranges from zero, in areas of bedrock outcrop, to about 550 ft in parts of Gray County (McGovern and Long, 1974).

## Structure

Southwest Kansas lies in a broad syncline on the east flank of the Las Animas arch (Merriam, 1963). The syncline plunges to the northeast, away from the Sierra Grande uplift in southeastern Colorado. Local structure of the rocks above the Lower Permian Blaine Formation is affected by two faults—the Bear Creek fault that extends into Kearny County and the Crooked Creek-Fowler fault that extends from Meade County in an arcuate pattern across southern Ford County (see fig. 4). These faults are the result of dissolution of evaporites by ground water within the Blaine Formation, as well as the underlying Flowerpot Shale, and the subsequent collapse of the overlying strata. Vertical displacement along these faults may be as much as 275 ft (Gutentag and others, 1981; Spinazola and Dealy, 1983).

Solution and removal of the evaporites within the Blaine Formation and the Flowerpot Shale probably began during deposition of the Tertiary and Quaternary deposits, as indicated by the increase in thicknesses of these deposits on the downthrown sides of the Bear Creek and the Crooked Creek-Fowler faults. Subsidence may have begun during deposition of the Lower Cretaceous rocks, as indicated by the highly variable thickness of these rocks between the base of the Cheyenne Sandstone and the top of the Kiowa Shale in Ford and Hodgeman Counties.

### Permian Rocks

The surface of the top of the undifferentiated Permian rocks (fig. 5) is the result of a combination of tectonic and nontectonic structural movement and erosion. On the upthrown side of the Bear Creek fault, the Permian surface slopes to the northeast at about 13 ft/mi. The Permian surface in the study area was modified by erosion prior to the deposition of Jurassic and Lower Cretaceous rocks and by subsidence prior to and during deposition of Tertiary and Quaternary unconsolidated deposits. Dissolution of evaporites in the Blaine Formation and the Flowerpot Shale as well as collapse of overlying strata were continuing. This is indicated by the formation of large sinks during historical times, along the Bear Creek and the Crooked Creek-Fowler faults (McLaughlin, 1946; Frye, 1950).

### Cheyenne Sandstone

The altitude and configuration of the top of the Cheyenne Sandstone is shown in figure 6. Vertical displacement of up to 400 ft in the Cheyenne Sandstone occurs across the Bear Creek and the Crooked Creek-Fowler faults. The divergence between the surfaces of the Permian rock (fig. 5) and the Cheyenne Sandstone (fig. 6) indicates a general northward thickening of the Cheyenne Sandstone; however, in parts of Kearny and Finney Counties, rocks of Jurassic age are included in this interval. Maximum divergence between the top of the Permian rocks and the top of the Cheyenne Sandstone is about 300 ft in southwest Hodgeman County.

### Kiowa Shale

The altitude and configuration of the top of the Kiowa Shale is shown in figure 7. Comparison of this surface with that of the Cheyenne Sandstone indicates that the thickness of the Kiowa is highly variable, particularly in Ford County on the downthrown side of the Crooked Creek-Fowler fault, where it approaches 300 ft. In southern and central Gray County, the Kiowa is generally less than 100 ft thick. The variability of thickness may have resulted from the development of localized subsidence basins during deposition of the Kiowa but also may result from the difficulty in distinguishing the tops of both the Kiowa Shale and Cheyenne Sandstone on geophysical logs.

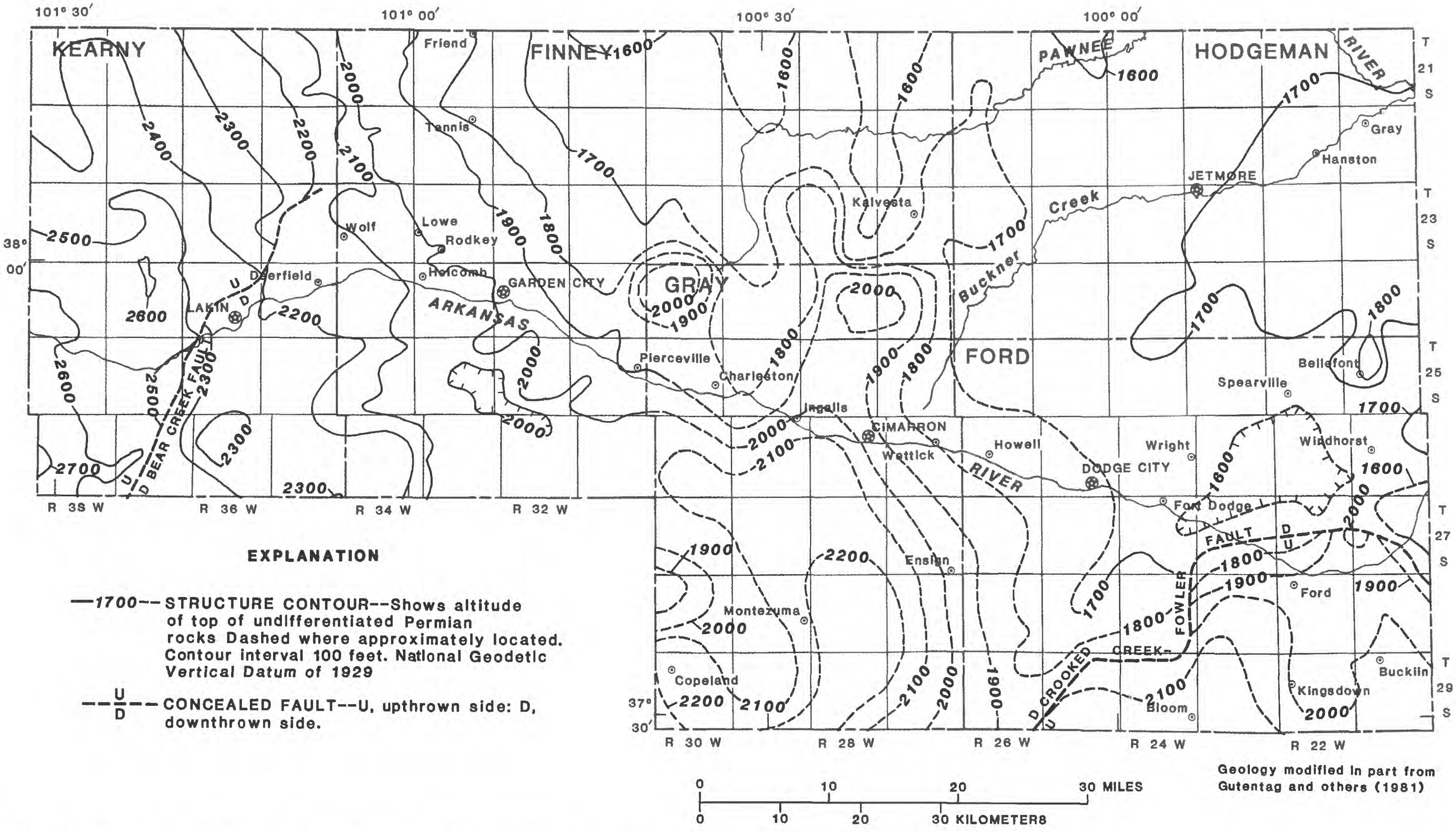



**Figure 5.** Generalized altitude and configuration of the top of undifferentiated Permian rocks.

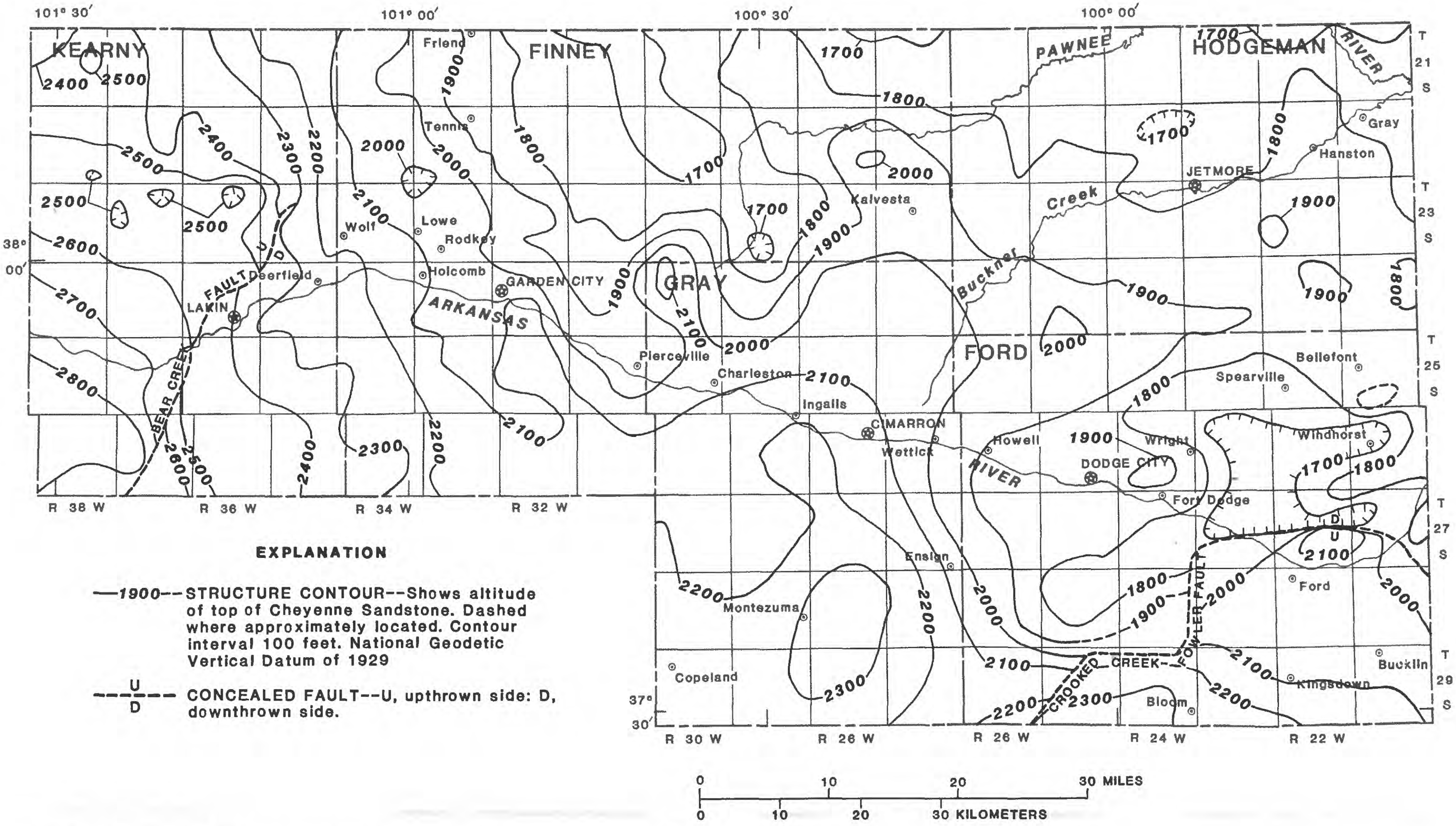



Figure 6. Generalized altitude and configuration of the top of Cheyenne Sandstone.

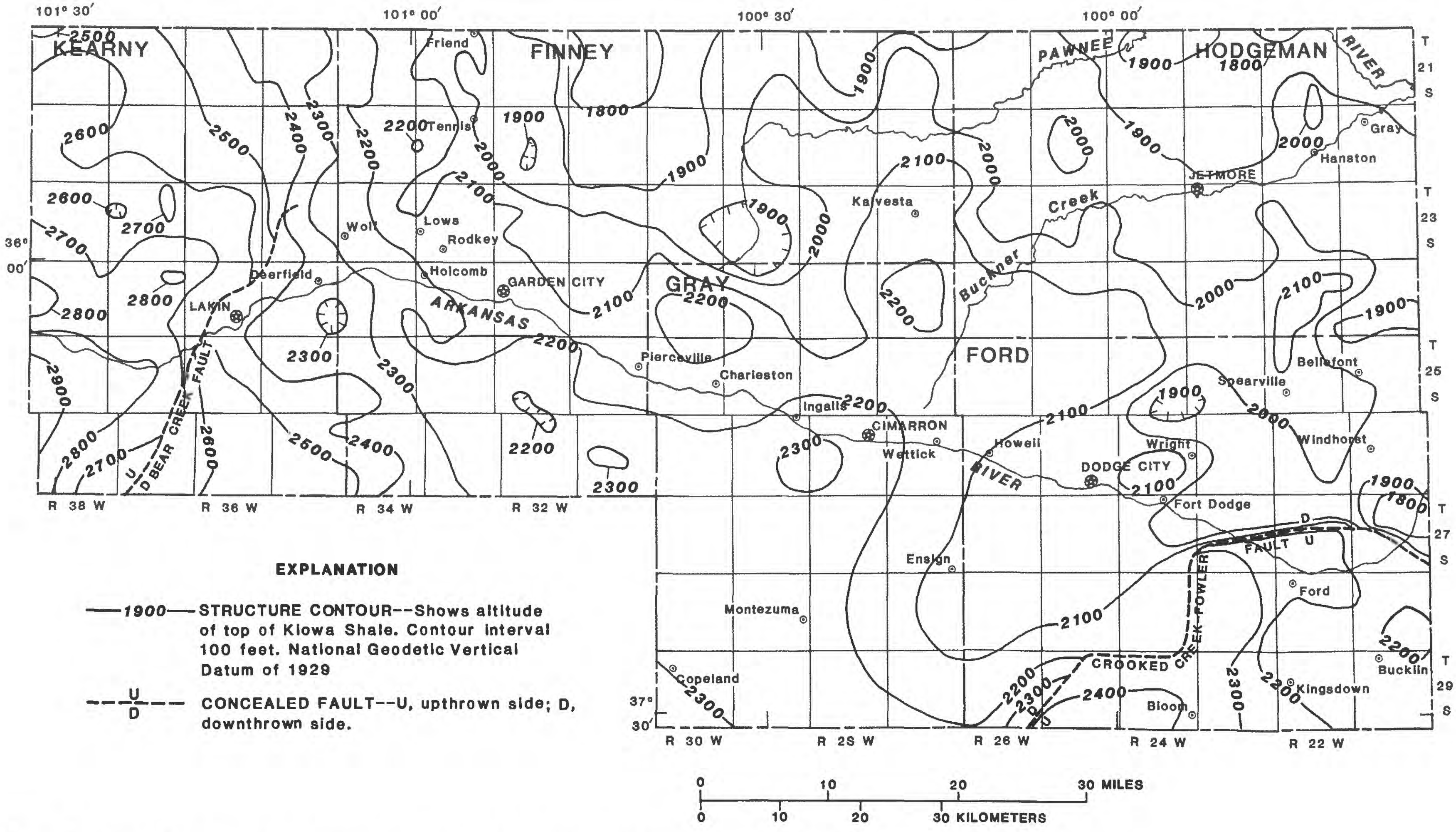



**Figure 7.** Generalized altitude and configuration of the top of Kiowa Shale.

### Dakota Sandstone

The altitude and configuration of the top of the Dakota Sandstone is shown in figure 8. Where the Dakota Sandstone is unconformably overlain by Tertiary and Quaternary deposits, the surface has been modified by post-Cretaceous erosion. Vertical displacement of the Dakota across the Bear Creek and Crooked Creek-Fowler faults is greater than 200 ft. The Dakota Sandstone has been cut into and, in some places, removed by post-Cretaceous erosion. The divergence between the Dakota surface (fig. 8) and the Permian surface (fig. 5) indicates a general northward thickening of the Lower Cretaceous and Jurassic rocks. Divergence between the top of the Dakota Sandstone (fig. 8) and the top of the Kiowa Shale (fig. 7) ranges from less than 25 ft to about 400 ft. The Dakota Sandstone in the study area is typically 175–250 ft thick where it is conformably overlain by the Graneros Shale.

## Ground Water

Ground water occurs in the rocks that underlie the study area but generally is mineralized in all but the upper five hydrologic units. These five hydrologic units are: (1) the High Plains aquifer (Tertiary and Quaternary unconsolidated deposits of clay, silt, sand, and gravel), (2) the Niobrara-Graneros confining unit (includes Upper Cretaceous chalk, limestone, and shale), (3) the Dakota aquifer (Lower Cretaceous Dakota Sandstone), (4) the Kiowa confining unit (Lower Cretaceous Kiowa Shale), and (5) the Cheyenne aquifer (Lower Cretaceous Cheyenne Sandstone and undifferentiated Middle and Upper Jurassic rocks). The geometric relationships between these hydrologic units are illustrated in figure 9.

### High Plains Aquifer

The High Plains aquifer, as defined by Gutentag and Weeks (1980), consists of the hydraulically connected geologic units of late Tertiary and Quaternary age. In the study area, the High Plains aquifer consists of the Upper Tertiary Ogallala Formation and alluvial deposits of Quaternary age. The High Plains aquifer is the principal aquifer in the study area and in the region. At a regional scale, the aquifer is considered to be a homogeneous, unconfined aquifer, although it consists of a heterogeneous mixture of lenticular deposits of clay, silt, sand, and gravel.

Saturated thickness of the High Plains aquifer in the study area during 1975 ranged from 0 to about 350 ft. Hydraulic conductivity of the aquifer is about 80 ft/d where it is composed of unconsolidated Tertiary and Quaternary deposits and about 800 ft/d where it is composed of Quaternary alluvial deposits in Hamilton and Kearny Counties (Barker and others, 1983).

Estimates of the specific yield of the High Plains aquifer in the study area are 0.14 to 0.20 for the Arkansas River alluvium (Barker and others, 1983), 0.18 for the unconfined High Plains aquifer, 0.01 for the semiconfined High Plains aquifer in Finney and Kearny Counties (Dunlap and others, 1985), and about 0.18 on a regional basis (Stullken and others, 1985).

### Niobrara-Graneros Confining Unit

The Niobrara-Graneros confining unit in the study area includes the Upper Cretaceous Graneros Shale, Greenhorn Limestone, Carlile Shale, and Niobrara Chalk. Thickness of the confining unit ranges from zero, where the rocks have been removed by erosion, to about 725 ft in northeastern Finney County. These rocks generally are not water bearing, except locally in northwest Finney County where solution openings or solution-enlarged fractures in the limestones are present (Gutentag and others, 1981). On a regional scale, horizontal flow in the Niobrara-Graneros confining unit is hydrologically insignificant. However, the storage properties and vertical hydraulic conductivity of the Niobrara-Graneros confining unit significantly affect flow in the Dakota aquifer. Vertical hydraulic conductivity of the Cretaceous shale confining layers in South Dakota was estimated at $5\times10^{-11}$ to $2\times10^{-10}$ ft/s ($4\times10^{-6}$ to $2\times10^{-5}$ ft/d) and specific storage at $5\times10^{-4}$ to $5\times10^{-5}$ $ft^{-1}$, based on model analyses (Bredehoeft and others, 1983).

### Dakota Aquifer

The Dakota aquifer is defined, for this study, to be the rocks that lie between the Upper Cretaceous rocks (or where Upper Cretaceous rocks are absent, the Tertiary and Quaternary unconsolidated deposits) and the Lower Cretaceous Kiowa Shale. Locally, the Dakota aquifer consists of two or more permeable sandstones separated by clay or shale; this separation, however, is not persistent throughout the study area. In some areas, the Dakota aquifer may be predominantly either sandstone or shale.

The hydraulic properties of the Dakota aquifer, in the study area, were estimated from the results of 13 aquifer tests (table 2) and from the calculation of specific capacities from 33 large-capacity wells (table 3). Transmissivity of the Dakota aquifer from aquifer-test data (table 2) ranged from 100–7,100 $ft^2/d$, with a median value of 1,700 $ft^2/d$. Specific capacities of the 33 large-capacity wells (table 3) ranged from 1–22 (gal/ min)/ft and averaged about 8 (gal/min)/ft. Estimates of the

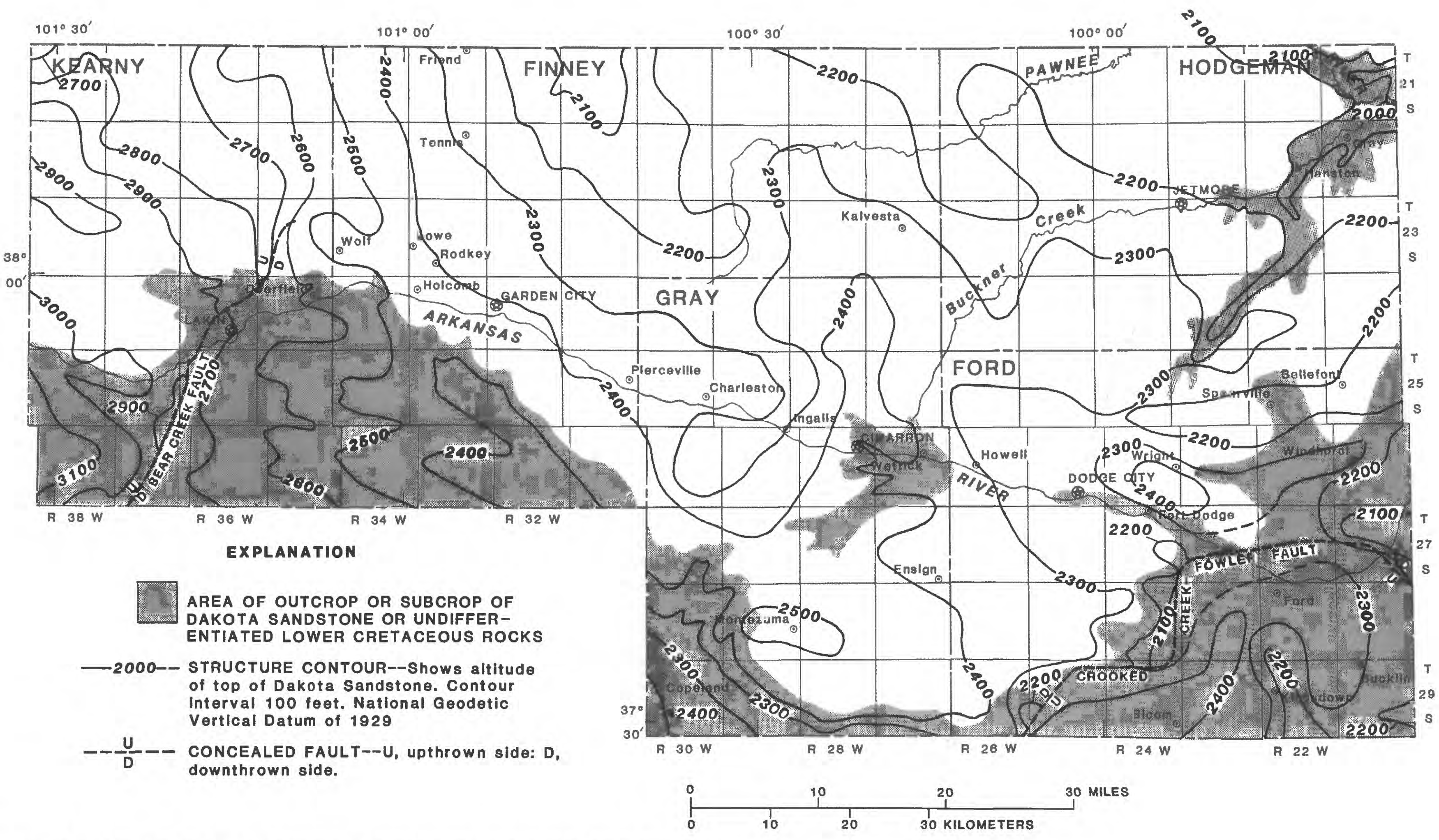



**Figure 8.** Generalized altitude and configuration of the top of Dakota Sandstone.

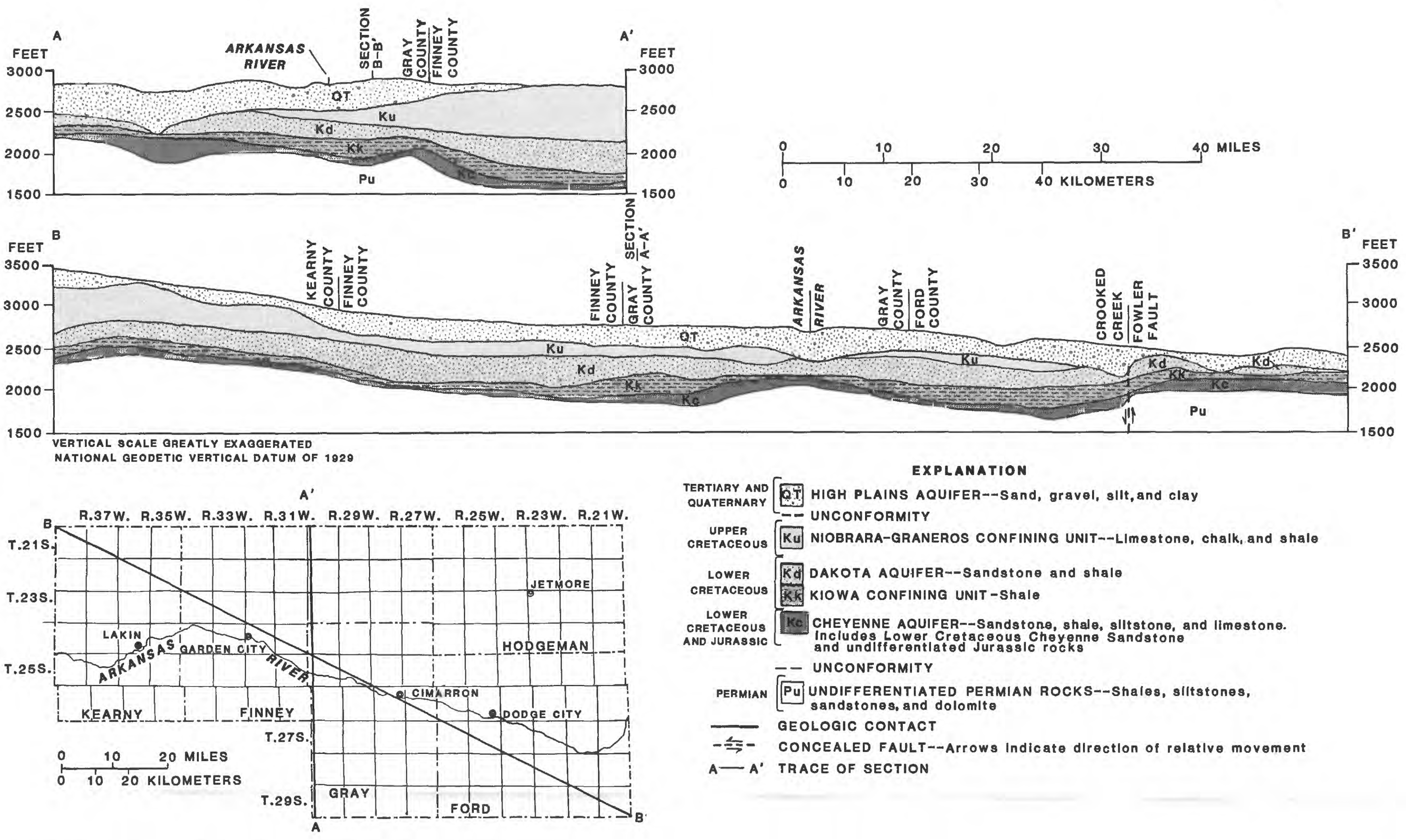



**Figure 9.** Generalized hydrogeologic sections of the study area.

**Table 2.** Summary of selected aquifer tests of the Dakota aquifer

| Well location | Sandstone thickness (feet) | Transmissivity (square feet per day) | Specific capacity (gallons per minute per foot) | Hydraulic conductivity (feet per day) | Storage coefficient (dimensionless) | Specific storage ($foot^{-1}$) | Source of data |
|---|---|---|---|---|---|---|---|
| 22 24W 16ADB | 125 | 2,000 | 6 | 16 | 0.0005 | $4\times10^{-6}$ | Lobmeyer and Weakly (1979) |
| 23 34W 13DDB | 195 | 700 | 2.5 | 4 | 0.0004 | $2\times10^{-6}$ | Dealy and others (1984) |
| 23 34W 14CCCC | 205 | 1,700 | 5 | 6 | 0.0002 | $1\times10^{-6}$ | Do. |
| 23 34W 15ACD | 261 | 1,900 | 9 | 7 | 0.0004 | $2\times10^{-6}$ | Do. |
| 23 34W 16ACD | 271 | 2,100 | 7 | 8 | 0.0007 | $3\times10^{-6}$ | Do. |
| 23 34W 26CBC | 250 | 2,000 | 11 | 8 | 0.0005 | $2\times10^{-6}$ | Do. |
| 24 33W 19DBD | 180 | 1,000 | 5 | 6 | 0.004 | $2\times10^{-5}$ | Burns and McDonnell, Inc. (1977) |
| 24 36W 23CCCC | 140 | 700 | 3.5 | 5 | 0.004 | $3\times10^{-5}$ | Dealy and others (1984) |
| 24 36W 29AAA | 78 | 100 | 0.6 | 1 | — | — | Do. |
| 25 23W 35DDB | 175 | 7,100 | 22 | 41 | 0.07 | — | Lobmeyer and Weakly (1979) |
| 25 25W 32CDD | 80 | 750 | 3 | 9 | 0.0001 | $1\times10^{-6}$ | Dealy and others (1984) |
| 27 24W 04CAA | 130 | 1,900 | 7 | 15 | 0.0001 | $1\times10^{-6}$ | Do. |
| 28 29W 24DCB | 132 | 500 | 4 | 4 | 0.001 | $8\times10^{-6}$ | Do. |
| Minimum | 78 | 100 | 0.6 | 1 | 0.0001 | $1\times10^{-6}$ | |
| Maximum | 271 | 7,100 | 22 | 41 | 0.07 | $3\times10^{-5}$ | |
| Median | 175 | 1,700 | 5 | 7 | 0.0005 | $2\times10^{-6}$ | |

transmissivity of the Dakota aquifer were also made from the specific-capacity data using an iterative method to solve the Jacob-Cooper approximation of the Theis equation (Lohman, 1972, eq. 51) and ranged from 250–7,700 $ft^2/d$ (table 3). The median value for the specific-capacity estimates of transmissivity was 1,900 $ft^2/d$, which is reasonably close to the median value estimated from analyses of aquifer-test data.

Dividing the median transmissivity of 1,700 $ft^2/d$ by an average aquifer thickness of 250 ft gives an estimated hydraulic conductivity of about 7 ft/d for the Dakota aquifer. The ratio of horizontal to vertical hydraulic conductivity of cemented, well-sorted sand with regular bedding can be expected to range from 100–1 (Pettijohn and others, 1973). Because the Dakota aquifer contains shale and clay interbeds, the ratio of horizontal to vertical hydraulic conductivity is probably greater than 100. Vertical hydraulic conductivity of the Dakota aquifer in the study area is estimated to range from $1\times10^{-1}$ ft/d, where the aquifer is predominantly sandstone, to $1\times10^{-5}$ ft/d, where the aquifer is predominantly shale.

The storage coefficient of the Dakota aquifer from 12 of the aquifer tests (table 2) ranged from 0.07, for unconfined conditions, to $1\times10^{-4}$, for confined conditions. Specific storage of the Dakota aquifer is estimated to be about $2\times10^{-6}$ $ft^{-1}$ (median value from table 2).

Analysis of aquifer tests of the Dakota aquifer in the study area may be complicated because the lithology and thickness of the Dakota Sandstone can vary significantly within relatively small areas. The departure from ideal conditions is illustrated by the analysis of the aquifer-test data given in table 4. Analysis of the test data was based on the Theis nonequilibrium method, as described by Lohman (1972). Drawdowns (s) were plotted versus time divided by radius squared ($t/r^2$). The Theis-type curve from plate 9 of Lohman (1972) was superimposed on the data plots to determine the matchpoint coordinates for $s$, $t/r^2$, $1/u$, and $W(u)$, where

$$u=\frac{r^2S}{4Tt}\text{, dimensionless;}$$

$T$ is transmissivity;

$S$ is storage coefficient; and

$$W(u)=[-0.577216-\log_e u+u-\frac{u^2}{2\cdot2!}+\frac{u^3}{3\cdot3!}-\ldots].$$

For given values of $1/u$ and $W(u)$, $T$ may be determined from

$$T=\frac{Q}{4\pi s}W(u), \quad (1)$$

where $Q$ is the constant discharge rate of the well, and $S$ is

$$S=\frac{4Tu}{r^2/t}. \quad (2)$$

Transmissivity of the Dakota aquifer calculated from the test data averaged about 1,700 $ft^2/d$. The

**Table 3.** Specific capacities of selected wells and estimated transmissivities of Dakota aquifer

| Local number | Altitude of land surface (feet) | Well depth (feet) | Saturated thickness (feet) | Sandstone thickness (feet) | Diameter of casing (inches) | Depth to static water level (feet) | Depth to pumping water level (feet) | Discharge rate (gallon per minute) | Duration of test (minute) | Specific capacity (gallon per minute per foot) | Estimated transmissivity (square feet per day) | Source of data |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 22 24W 03CDB | 2,450 | 577 | | 45 | 16 | 110 | 567 | 450 | 600 | 1 | 200 | Driller |
| 22 24W 15BDA | 2,463 | 585 | | | 12 | 250 | | 1,300 | 18,720 | 7 | 2,300 | Lobmeyer and Weakly (1979) |
| 23 23W 04AAD | 2,235 | 282 | | | 16 | 38 | | 290 | 57,600 | 2 | 600 | Do. |
| 23 23W 04DCA | 2,230 | 260 | | | 16 | 27 | | 760 | 18,720 | 4 | 1,300 | Do. |
| 23 23W 12CAC | 2,280 | 256 | | | 12 | 147 | | 130 | 33,120 | 6 | 2,000 | Do. |
| 23 23W 21AAC | 2,350 | 395 | | | 15 | | | 660 | 57,600 | 4 | 1,300 | Do. |
| 23 25W 22DBB | 2,522 | 575 | | | 16 | 233 | | 1,030 | 59,040 | 8 | 2,700 | Do. |
| 23 25W 28BBD | 2,520 | 508 | | 82 | 16 | 255 | 305 | 585 | 240 | 12 | 3,100 | Driller |
| 23 26W 07CCC | 2,612 | 490 | | | 16 | 306 | | 1,150 | 36,000 | 12 | 4,100 | Lobmeyer and Weakly (1979) |
| 24 23W 06AAB | 2,457 | 517 | | | 16 | 227 | | 750 | 57,600 | 5 | 1,700 | Do. |
| 24 23W 30DDD | — | 402 | | 101 | 16 | 120 | 265 | 650 | 300 | 4 | 1,100 | Driller |
| 24 24W 04CAD | 2,452 | 370 | | 130 | 12 | 90 | 198 | 535 | 1,753 | 5 | 1,400 | Southwest Groundwater Management District No. 3 (written commun., 1984) |
| 24 24W 32BBB | 2,505 | 368 | | 79 | 16 | 236 | 338 | 530 | 60 | 5 | 1,200 | Driller |
| 24 24W 32CAA | — | 362 | | 110 | 16 | 191 | 328 | 1,040 | 60 | 8 | 1,700 | Do. |
| 24 24W 32CBB | — | 380 | | 81 | 16 | 201 | 346 | 1,200 | 240 | 8 | 2,100 | Do. |
| 24 25W 20DBC | 2,560 | 455 | | 78 | 16 | 258 | 363 | 700 | 1,440 | 7 | 1,900 | Do. |
| 24 25W 33AD | — | 375 | | 111 | 16 | 180 | 280 | 750 | 180 | 8 | 1,900 | Do. |
| 25 21W 22BA | 2,320 | 207 | | 92 | 16 | 53 | 190 | 500 | 240 | 4 | 900 | Do. |
| 25 21W 23CBB | — | 171 | 131 | 94 | 16 | 52 | 120 | 800 | 180 | 12 | 3,000 | Do. |
| 25 22W 06CDD | — | 390 | 310 | 119 | 16 | 207 | 285 | 700 | 720 | 9 | 2,400 | Do. |
| 25 22W 07ACA | 2,441 | 350 | | | 16 | 164 | | 750 | 57,600 | 7 | 2,400 | Lobmeyer and Weakly (1979) |
| 25 23W 25CCC | 2,463 | 372 | | | 16 | 166 | | 1,280 | 54,720 | 9 | 3,100 | Do. |
| 25 23W 32DBB | 2,463 | 380 | | | 16 | 150 | | 520 | 54,720 | 2 | 600 | Do. |
| 25 23W 35ADC | 2,461 | 360 | | | 16 | 163 | | 1,200 | 57,600 | 17 | 6,600 | Do. |
| 25 23W 36BDA | 2,466 | 380 | | | 16 | 170 | | 1,200 | 41,760 | 22 | 7,700 | Do. |
| 26 22W 20DBB | 2,400 | 355 | 300 | 110 | 16 | 92 | 235 | 1,000 | 240 | 7 | 1,800 | Driller |
| 26 22W 21DCD | 2,377 | 360 | | | 16 | 35 | | 930 | 30,240 | 4 | 1,300 | Lobmeyer and Weakly (1979) |
| 26 23W 09C | 2,497 | 385 | 270 | 178 | 16 | 184 | 260 | 700 | 240 | 9 | 2,300 | Driller |
| 26 23W 10DAD | 2,463 | 278 | | | 16 | 140 | | 700 | 57,600 | 7 | 2,400 | Lobmeyer and Weakly (1979) |
| 26 23W 15ADA | 2,465 | 288 | | | 16 | 128 | | 700 | 59,040 | 6 | 2,000 | Do. |
| 26 23W 20CDA | — | 416 | 180 | 180 | 16 | 62 | 400 | 1,100 | 8,640 | 3 | 900 | Driller |
| 26 24W 36C | 2,525 | 445 | | | 16 | 178 | 325 | 1,342 | | 6 | 2,100 | Do. |
| 27 21W 31CBB | 2,335 | 115 | | | 12 | 10 | | 1,330 | 18,720 | 20 | 6,900 | Lobmeyer and Weakly (1979) |
| | | | | | | | | | Minimum | 1 | 200 | |
| | | | | | | | | | Maximum | 22 | 7,700 | |
| | | | | | | | | | Median | 7 | 1,900 | |

calculated storage coefficient ranged from $1 \times 10^{-4}$ to $4 \times 10^{-4}$. Inspection of the data plots (fig. 10) shows the data for each observation well plot as a separate curve. Ideally, plots of $s$ versus $t/r^2$ for multiple observation wells will fall on a single curve. The departure of the data plots from a single curve and the variation in $S$ indicate that the assumptions upon which the Theis nonequilibrium method is based are not strictly valid for this test.

### Kiowa Confining Unit

The Kiowa confining unit consists of shales below the basal sandstone of the Dakota Sandstone and above the Cheyenne Sandstone. Thickness of this confining unit ranges from zero in southwestern Gray County to about 300 ft on the downthrown side of the Crooked Creek-Fowler fault in Ford County. Transmissivity and horizontal hydraulic conductivity of the confining unit are, for practical purposes, near zero. Vertical hydraulic conductivity of the Kiowa equivalent in South Dakota was estimated at $1.5 \times 10^{-11}$ ft/s ($1.3 \times 10^{-6}$ ft/d), and specific storage at $5 \times 10^{-5}$ ft$^{-1}$ (Bredehoeft and others, 1983, p. 20).

### Cheyenne Aquifer

The Cheyenne aquifer, as used in this report, includes the rocks between the base of the Kiowa Shale and the top of the undifferentiated Permian rocks. In the eastern part of the study area, the Cheyenne aquifer is equivalent in thickness to the Cheyenne Sandstone. In parts of Kearny and Finney Counties, the Cheyenne aquifer includes undifferentiated Jurassic rocks. Thickness of the aquifer ranges from near zero in southwestern Gray County to about 300 ft in parts of Ford and Hodgeman Counties.

Because no large-capacity wells are completed in the Cheyenne aquifer in the study area, its hydraulic properties were estimated. Transmissivity of the Cheyenne Sandstone Member of the Purgatoire Formation in Baca County, southeastern Colorado, ranges from 125–3,000 ft$^2$/d, and the storage coefficient from $4 \times 10^{-6}$ to $4 \times 10^{-4}$ (McLaughlin, 1954, p. 30). Using an average thickness for the Cheyenne Sandstone Member in Baca County of about 85 ft, and a median transmissivity of about 800 ft$^2$/d, the horizontal hydraulic conductivity of the Cheyenne aquifer is estimated to be about 9 ft/d. The vertical hydraulic conductivity of the Cheyenne aquifer was estimated to be about $1 \times 10^{-2}$ ft/d. Kume (1984, table 2, p. 19) estimated the porosity of sandstone from the Cheyenne Sandstone to range from 10–32 percent by volume. Specific storage is estimated to be about $2.0 \times 10^{-6}$ ft$^{-1}$.

## Surface Water

The only major source of surface water in the study area is the Arkansas River. The average annual discharge of the Arkansas River at Garden City was about 174,000 acre-ft from 1923 to 1950. During the 1950's and 1960's, flow in the Arkansas River was below average, and during the late 1970's the river was dry at Garden City with the exception of floodflows and the release of irrigation water from John Martin Reservoir, west of Lamar, Colo. Ground-water discharge to the Arkansas River decreased during this same period, so that the river was generally dry during the late 1970's in a 74-mi reach between Lakin in Kearny County and Dodge City in Ford County. Dunlap and others (1985) attribute the decrease in flow of the Arkansas River to the decrease in ground-water discharge to the river and to decreased surface-water inflow from Colorado.

Mean annual discharge of the Arkansas River and selected tributaries at eight streamflow-gaging stations in southwestern Kansas is shown in figure 11. Flow diverted from the Arkansas River, about 0.3 mi west of the Colorado-Kansas State line, to Frontier Ditch (site 2, streamflow-gaging station 07137000) was added to discharge of the Arkansas River near Coolidge (site 1, streamflow-gaging station 07137500) to show state-line flow. Discharge of the Pawnee River near Larned (site 7, streamflow-gaging station 07141200) was added to discharge of the Arkansas River near Kinsley (site 6, streamflow-gaging station 07140000) to show flow of the Arkansas River upstream from streamflow-gaging station 07141300 (site 8) at Great Bend (fig. 11).

Only floodflows above the base flow of 600 ft$^3$/s are recorded at gaging station 07139000 at Garden City. However, from 1977 to 1982 onsite observation revealed that the only flow in the Arkansas River at Garden City was due to local runoff. Therefore, mean annual discharge of the Arkansas River at Garden City for 1977–82 was considered to be zero and not shown in figure 11.

Generally, all flow in the Arkansas River between the Colorado-Kansas State line and Garden City is used during the irrigation season to fulfill surface-water appropriations. Dunlap and others (1985, p. 17) estimated streamflow loss of as much as 75 percent of flow in a 22-mi reach of the river from about 9 mi southwest of Lakin to about 2 mi east of Deerfield. During the nonirrigation season, October through March of 1983–84 and 1984–85, flow had resumed in the Arkansas River at Garden City to a point several miles downstream.

State-line flow of the Arkansas River increased in the early 1980's (fig. 11) due primarily to larger releases from John Martin Reservoir. Flow in the Arkansas River downstream from Dodge City is a combination of

**Table 4.** Data from Garden City Company aquifer test, March 12–17, 1982

| Well location | Well-construction data: Altitude of land surface (feet) | Borehole diameter (inches) | Casing diameter (inches) | Well depth (feet) | Depth to top of Dakota aquifer (feet) | Depth to base of Dakota aquifer (feet) | Depth of grouted interval (feet) | Depth of gravel packed interval (feet) | Depth of screened interval (feet) | Sandstone thickness (feet) | Aquifer thickness (feet) | Radial distance to pumped wells (feet) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23 34W 14CCCC 01 | 2,942 | 24 | 16 | 740 | 438 | 733 | 295–395 | 395–740 | 530–550<br>590–610<br>620–640<br>655–735 | 205 | 295 | — | Pumped well |
| 23 34W 15ACDB 01 | 2,945 | 24 | 16 | 765 | 440 | 765 | 300–400 | 400–765 | 440–480<br>504–564<br>592–612<br>641–761 | 261 | 295 | 3,600 | Observation well |
| 23 34W 13DBBB 01 | 2,929 | 24 | 16 | 778 | 444 | 772 | 300–400 | 400–778 | 445–485<br>541–581<br>610–620<br>640–650<br>666–736<br>752–772 | 195 | 328 | 8,210 | Observation well |
| 23 34W 26CBCC 02 | 2,948 | 24 | 16 | 760 | 427 | 754 | 285–385 | 385–754 | 435–475<br>485–495<br>515–555<br>570–620<br>652–752<br>655–735 | 327 | 327 | 9,220 | Observation well |

| Date | Time | Elapsed time (minute) | Aquifer-test data: Pumped well 23 34W 14CCCC: Depth to water (feet)[1] | Pumped well 23 34W 14CCCC: Drawdown (feet) | Observation Well 1 23 34W 15ACDB: Depth to water (feet)[1] | Observation Well 1: Drawdown (feet) | Observation Well 2 23 34W 13DBBB: Depth to water (feet)[1] | Observation Well 2: Drawdown (feet) | Observation Well 3 23 34W 26CBCC02: Depth to water (feet)[1] | Observation Well 3: Drawdown (feet) | Discharge: Instantaneous (gallon per minute) | Discharge: Cumulative (acre-feet) | Barometric pressure (inches of mercury) | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Feb. 16 | | ---- | 151 | ----- | 160.3 | ----- | ----- | ----- | 147.7 | ----- | | | | |
| Mar. 12 | 08:00 | ---- | 145.52 | ----- | 156.18 | ----- | 156.75 | ----- | 143.80 | ----- | 0 | 0.000 | 29.44 | |
| | 08:50 | 0 | | | | | | | | | | | 29.42 | Pump on |
| | 08:55 | 5 | 170 | 24.5 | | | | | | | | | | |
| | 08:57 | 7 | 175 | 29.5 | | | | | | | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 09:00 | 10 | 190 | 44.5 | | | | | | | | |
| | 09:05 | 15 | 252.5 | 107.0 | | | | | | | | |
| | 09:07 | 17 | 261.8 | 116.3 | | | | | | 1,100 | | |
| | 09:10 | 20 | 264.9 | 119.4 | | | | | | 1,100 | | |
| | 09:15 | 25 | 269.2 | 123.7 | | | | | | 1,100 | | |
| | 09:20 | 30 | 270.8 | 125.3 | | | | | | | | |
| | 09:30 | 40 | | | 156.20 | 0.02 | | | | | | |
| | 09:42 | 52 | 279.2 | 133.7 | | | | | | 1,050 | 0.154 | |
| | 09:50 | 60 | 278.8 | 133.3 | | | | | | | | |
| | 10:00 | 70 | 280.6 | 135.1 | | | | | | | | |
| | 10:10 | 80 | | | 156.21 | .03 | | | | | | |
| | 10:15 | 85 | 283.2 | 137.7 | | | | | | | | |
| | 10:25 | 95 | 282.54 | 137.02 | | | | | | 1,050 | | |
| | 10:50 | 120 | 285.6 | 140.1 | | | | | | | | |
| | 11:10 | 140 | | | 156.25 | .07 | | | | 1,040 | | 29.43 |
| | 11:20 | 150 | 287.3 | 141.8 | | | | | | | | |
| | 11:50 | 180 | 290.3 | 144.8 | | | | | | | | |
| | 12:00 | 190 | | | 156.40 | .12 | | | | | | 29.44 |
| | 12:30 | 220 | 292.86 | 147.34 | 156.53 | .35 | | | | 1,030 | | 29.47 |
| | 14:00 | 310 | | | 156.90 | .72 | | | | | | 29.56 |
| | 14:10 | 320 | 300.2 | 154.68 | | | | | | 1,050 | 1.000 | 29.56 |
| | 15:40 | 410 | | | 157.39 | 1.21 | | | | | | 29.61 |
| | 16:20 | 450 | 304.8 | 159.3 | | | | | | 1,035 | | 29.63 |
| | 16:30 | 460 | 310.3 | 164.8 | 157.71 | 1.53 | 156.75 | 0.00 | | 1,090 | 1.440 | 29.63 |
| | 19:00 | 610 | 317.8 | 172.3 | 158.59 | 2.41 | | | | 1,075 | 1.931 | 29.74 |
| Mar. 13 | 07:30 | 1,360 | | | 162.05 | 5.87 | | | | | | 30.02 |
| | 08:00 | 1,390 | 326.3 | 180.8 | | | 156.58[2] | -0.17 | 145.70 | 1.90 | 1,080 | 4.600 | 30.03 |
| | 10:00 | 1,510 | | | | | 157.25[2] | .50 | | | | | 30.06 |
| | 18:30 | 2,020 | 328.83 | 183.31 | 164.26 | 8.08 | | | | | 1,025 | 6.684 | 29.99 |
| Mar. 14 | 08:00 | 2,830 | | | 166.42 | 10.24 | 157.14 | .39 | | | | | 29.84 |
| | 08:30 | 2,860 | 333.2 | 187.7 | | | | | 148.70 | 4.90 | 1,080 | 9.420 | 29.84 |
| | 18:30 | 3,460 | 333.9 | 188.4 | 167.94 | 11.76 | | | 150.02 | 6.22 | | 11.380 | 29.79 |
| Mar. 15 | 08:30 | 4,300 | | | 169.60 | 13.42 | | | | | | | 29.60 |
| | 08:50 | 4,320 | 336.7 | 191.2 | | | 157.85 | 1.10 | 151.32 | 7.52 | | | 29.60 |
| | 10:10 | 4,400 | 336.7 | 191.2 | | | | | | | 1,060 | 14.460 | 29.55 |
| | 16:30 | 4,780 | | | 171.00 | 14.82 | 158.50 | 1.75 | 152.50 | 8.70 | | | 29.34 |
| Mar. 16 | 09:30 | 5,800 | 338.8 | 193.3 | 172.75 | 16.57 | 158.80 | 2.05 | 153.80 | 10.00 | 1,060 | 19.080 | 29.72 |
| Mar. 17 | 08:00 | 7,150 | 342.8 | 197.3 | 175.12 | 18.94 | 159.55 | 2.80 | 155.62 | 11.72 | 1,070 | 23.450 | 29.72 |

[1]Depth to water level is reported as depth below the measuring point.
[2]Depth to water values were not plotted in figure 10 because water levels were affected by changes in barometric pressure.

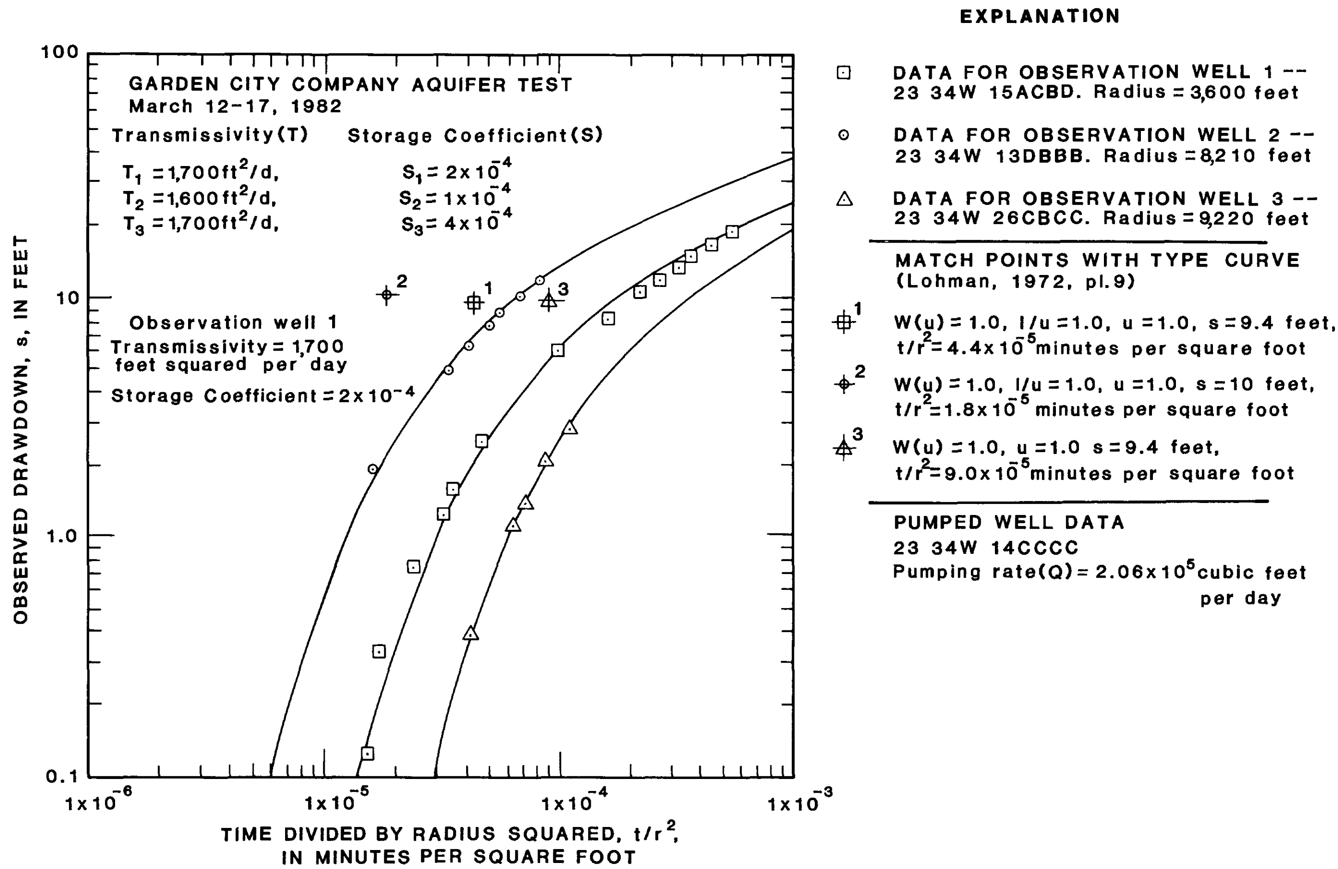



**Figure 10.** Data from Garden City Company aquifer test superimposed on Theis-type curves.

ground-water discharge to the river and local runoff. Generally, flow in the Arkansas River at Dodge City and near Kinsley showed decreases in mean annual discharge from 1975 through 1982, resulting from decreased ground-water discharge to the stream. Increased flows of the Arkansas River at Great Bend during 1979 and 1981 resulted from local runoff.

## WATER USE

The amount of water withdrawn from the High Plains and Dakota aquifers in the study area was estimated for 1975–82. Annual irrigation pumpage from the High Plains aquifer in most of the study and model areas was estimated from 1974 and 1978 irrigated acreage multiplied by crop-water demand (Heimes and Luckey, 1982) and divided by an irrigation efficiency of 0.8. Pumpage from the Arkansas River alluvial aquifer upstream of Lakin, Kans., was based on estimates by Barker and others (1983). A straight-line projection was used to estimate annual pumpage from the High Plains aquifer between 1974 and 1978. High Plains pumpage for 1979–82 was projected from the 1978 estimated pumpage and adjusted for changes in reported irrigated acreage for each county (Kansas State Board of Agriculture, Biennial Reports). Estimates made by Lindgren (1982) of the annual pumpage from the High Plains aquifer in parts of Finney and Kearny Counties were based on a detailed survey of irrigated acreages and crops and are better defined than the irrigated-acreage estimates compiled by Heimes and Luckey (1982). Estimated annual irrigation pumpage from the High Plains aquifer in Finney and Kearny Counties, based on data from Heimes and Luckey (1982), therefore, was increased by a common factor to more closely match Lindgren's estimates.

Estimates of the withdrawal from the Dakota aquifer were based on water-use reports obtained from the Kansas State Board of Agriculture, Division of Water Resources. Water-use reports were obtained for all large-capacity wells (wells with a discharge capacity of at least 100 gal/min) that had been identified during this and previous investigations as obtaining all or most of the water withdrawn from the Dakota aquifer.

Estimates of the annual water use from the Dakota and High Plains aquifers are given in table 5. Water use was estimated for all large-capacity wells in the study area completed in the Dakota aquifer and for irrigation wells

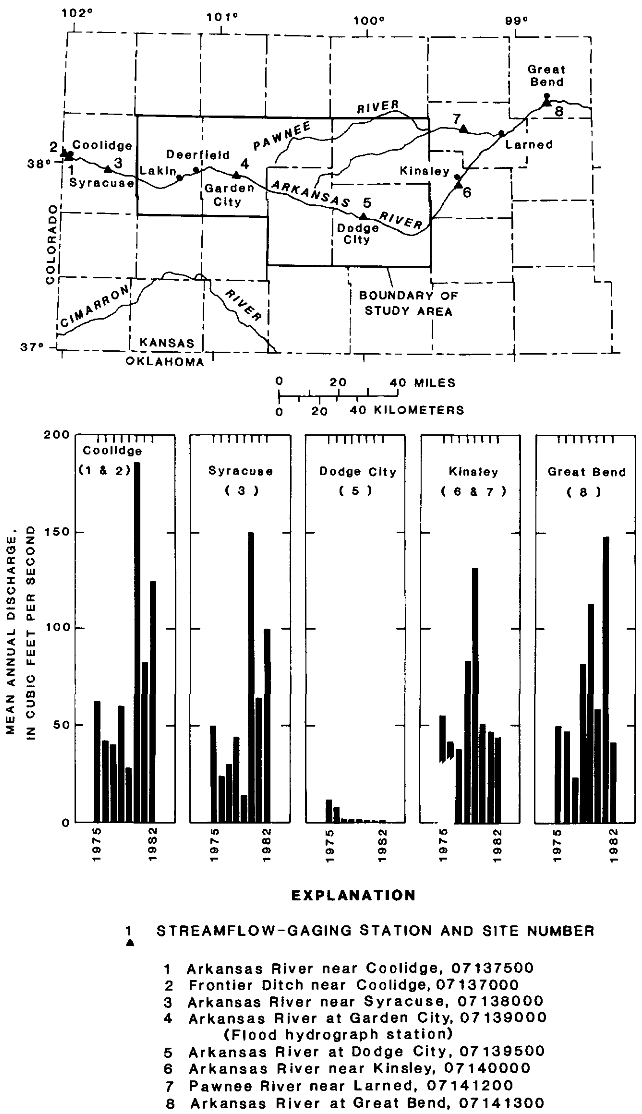



**Figure 11.** Mean annual discharge of Arkansas River and selected tributaries in southwestern Kansas, 1975–82, and location of streamflow-gaging stations.

completed in the High Plains aquifer. Public-supply and industrial use of water from the High Plains aquifer in the study area is insignificant in comparison with pumpage from the estimated 5,400 irrigation wells.

The distribution of large-capacity wells in the study area that are known to be completed in the Dakota aquifer and the principal use of water from these wells are shown in figure 12. Of the 137 large-capacity wells inventoried during this study, 116 are used for irrigation supply, 13 for industrial supply (including cattle-feeding operations), and 8 for public supply.

Total appropriated water rights from the Dakota aquifer in the study area are about 36,000 acre-ft/yr; however, this quantity reportedly has not been pumped (table 5). About 90 percent of this total is for irrigation use. Industrial users of water from the Dakota aquifer include feedlots, two meat-packing plants, a pet-food processor, two natural-gas compressor stations, and an electric-generation plant. Total appropriated water rights by industrial users is about 3,500 acre-ft/yr. The cities of Garden City, Jetmore, Lakin, Montezuma, Spearville, and Wright have public-supply wells that are completed in the Dakota aquifer. Total appropriated water rights from the Dakota aquifer for public supply is about 1,400 acre-ft/yr. No attempt was made to determine the water use by domestic and stock wells completed in the Dakota aquifer because the amount of water for these uses is insignificant in comparison to irrigation, industrial, and public-supply water use.

## CHEMICAL CHARACTERISTICS OF WATER FROM THE DAKOTA AND CHEYENNE AQUIFERS

The chemical characteristics of water in the Dakota and Cheyenne aquifers in the study area vary in both the type of water and in the concentrations of the dissolved constituents. The variability in the chemical characteristics of water in the sandstone aquifers is, in part, due to mixing with waters from different hydrologic units. Chemical analyses of water samples collected from the Dakota aquifer during this study were published previously (Kume, 1984, table 4, p. 32–33). No water samples were collected from the Cheyenne aquifer during this study, but Kume (1984) reported chemical analyses of water from both the Cheyenne Sandstone and the undifferentiated Middle and Upper Jurassic rocks at 22 35W 04DCC in Kearny County. Although only two chemical analyses are available for water from the Cheyenne aquifer in the study area, the response of the resistivity curves on geophysical logs of oil and gas wells indicates the presence of saline water in the Cheyenne aquifer in parts of the study area. A thorough evaluation of the water quality of the Cheyenne aquifer, based on interpretation of geophysical logs, was beyond the scope of this study. Further discussion of the chemical characteristics of the water from the sandstone aquifers is limited to the Dakota aquifer. Selected analyses of water from the Dakota aquifer (Lobmeyer and Weakly, 1979; Kume, 1984) are given in table 6.

The occurrence of chemical types of water and the generalized distribution of dissolved-solids concentrations in water from the Dakota aquifer (fig. 13, modified from Kume, 1984) show a change from a calcium bicarbonate type of water with less than 500 mg/L, where the Dakota aquifer is hydraulically connected with the High Plains aquifer, to a sodium bicarbonate type of water with more than 500 mg/L of dissolved solids, where the Dakota aquifer is confined by the Niobrara-Graneros confining unit (fig. 12). The sodium chloride type water in northeastern Hodgeman County is believed to indicate leakage

**Table 5.** Estimated annual pumpage from the Dakota and High Plains aquifers in Finney, Ford, Gray, Hodgeman, and Kearny Counties, 1975–82

| | Estimated pumpage, in thousands of acre-feet | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1975–82 |
| *Finney County* | | | | | | | | | |
| Dakota aquifer | 0.6 | 0.6 | 0.6 | 0.5 | 1.5 | 1.5 | 1.8 | 4.1 | 11.2 |
| High Plains aquifer | 383 | 411 | 422 | 468 | 332 | 498 | 655 | 602 | 3,771 |
| *Ford County* | | | | | | | | | |
| Dakota aquifer | 11.6 | 13.2 | 11.9 | 13.5 | 11.6 | 12.5 | 10.2 | 13.0 | 97.5 |
| High Plains aquifer | 40 | 46 | 52 | 64 | 45 | 71 | 89 | 84 | 491 |
| *Gray County* | | | | | | | | | |
| Dakota aquifer | 0 | 0 | 0 | 0 | 0 | .3 | .3 | .3 | .9 |
| High Plains aquifer | 259 | 275 | 291 | 323 | 226 | 361 | 451 | 422 | 2,608 |
| *Hodgeman County* | | | | | | | | | |
| Dakota aquifer | 6.6 | 6.0 | 5.4 | 6.5 | 4.9 | 5.2 | 5.5 | 7.0 | 47.1 |
| High Plains aquifer | 31 | 35 | 39 | 47 | 33 | 52 | 65 | 61 | 363 |
| *Kearny County* | | | | | | | | | |
| Dakota aquifer | 0 | 0 | 0 | 0 | 0 | .1 | .2 | .5 | .8 |
| High Plains aquifer | 149 | 168 | 169 | 191 | 149 | 188 | 267 | 239 | 1,520 |
| Total for study area | | | | | | | | | |
| Dakota aquifer | 18.8 | 19.8 | 17.9 | 20.5 | 18.0 | 19.6 | 18.0 | 24.9 | 157.5 |
| High Plains aquifer | 862 | 935 | 973 | 1,093 | 785 | 1,170 | 1,527 | 1,408 | 8,753 |

of mineralized water from Permian rocks, and the calcium sulfate type water in east-central Ford County indicates inflow to the Dakota aquifer from the nearby Arkansas River alluvium (Lobmeyer and Weakly, 1979).

The suitability of water from the Dakota aquifer for irrigation (fig. 14) was evaluated using a method of classification developed by the U.S. Salinity Laboratory (U.S. Salinity Laboratory Staff, 1954). In general, water from the Dakota aquifer presents a low alkali hazard and medium- to high-salinity hazard in most of the study area. Areas in which water in the Dakota aquifer presents high- to very high alkali and salinity hazards for irrigation are generally distant from the areas in which the Dakota and High Plains aquifer are hydraulically connected. Furthermore, samples of water from the Dakota aquifer have not been analyzed for some parts of the study area, and the suitability of water from the Dakota aquifer in those areas is unknown.

Water from the Dakota aquifer may contain concentrations of some constituents that exceed the recommended maximum contaminant level for drinking- and public-water supply established by the U.S. Environmental Protection Agency (1976; 1979). Chloride exceeded the maximum recommended concentration of 250 mg/L in 4 of the 81 analyses listed in table 6. Nitrate, an indication of contamination by animal and human wastes, exceeded the maximum contamination level of 10 mg/L in 16 of the 81 samples. Excessive concentrations of dissolved nitrate may enter the Dakota aquifer as the result of poor well-construction (grouting) practices and generally occur in areas where the aquifer is unconfined.

## HISTORIC HYDROLOGIC RESPONSE OF DAKOTA AQUIFER

Prior to the 1960's, the Dakota aquifer in the study area was relatively undeveloped. During the late 1960's and early 1970's (1967–73), 62 large-capacity wells were completed in the Dakota aquifer in Hodgeman and Ford

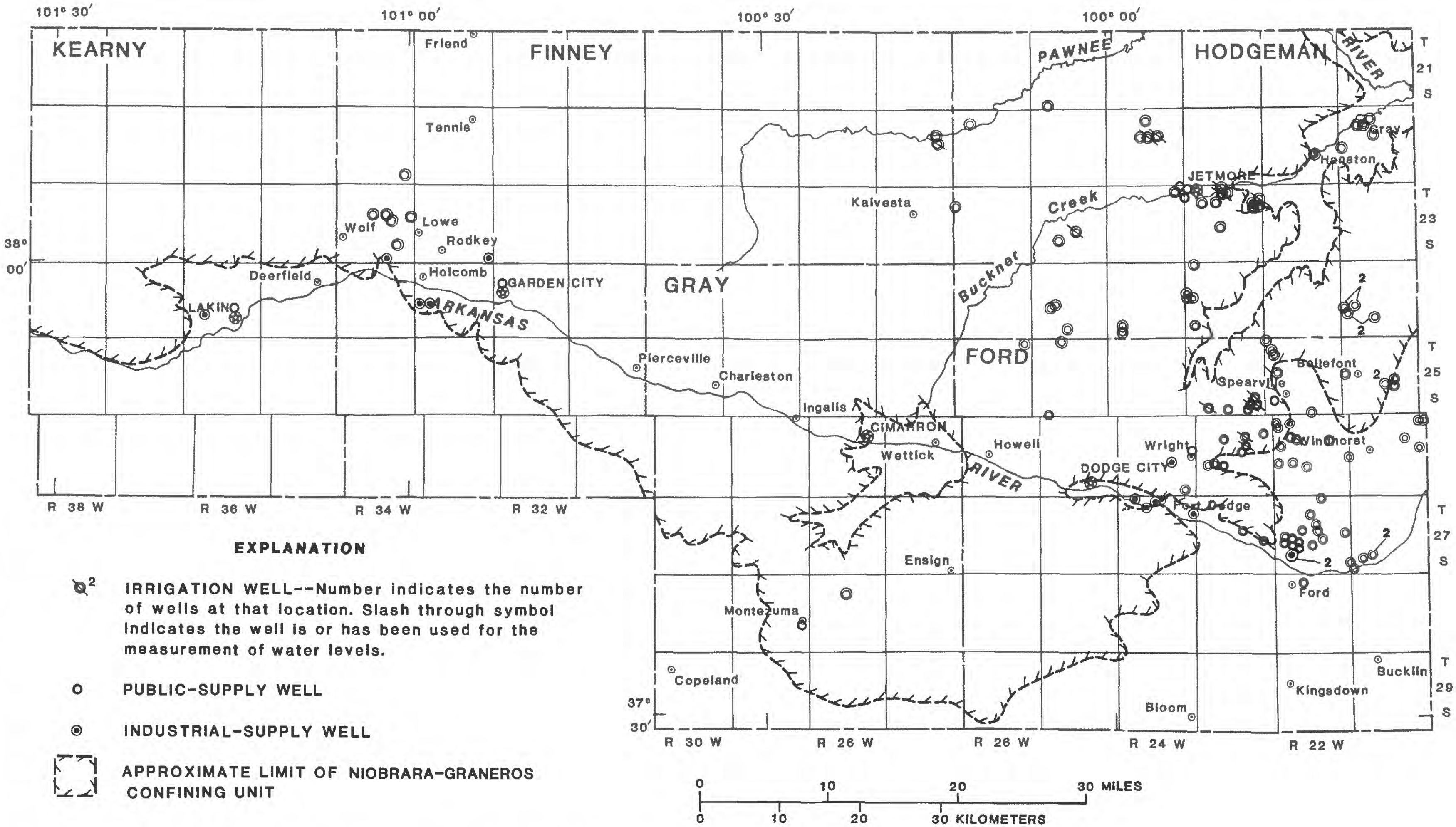



**Figure 12.** Location and use of water from large-capacity wells completed in the Dakota aquifer, 1984.

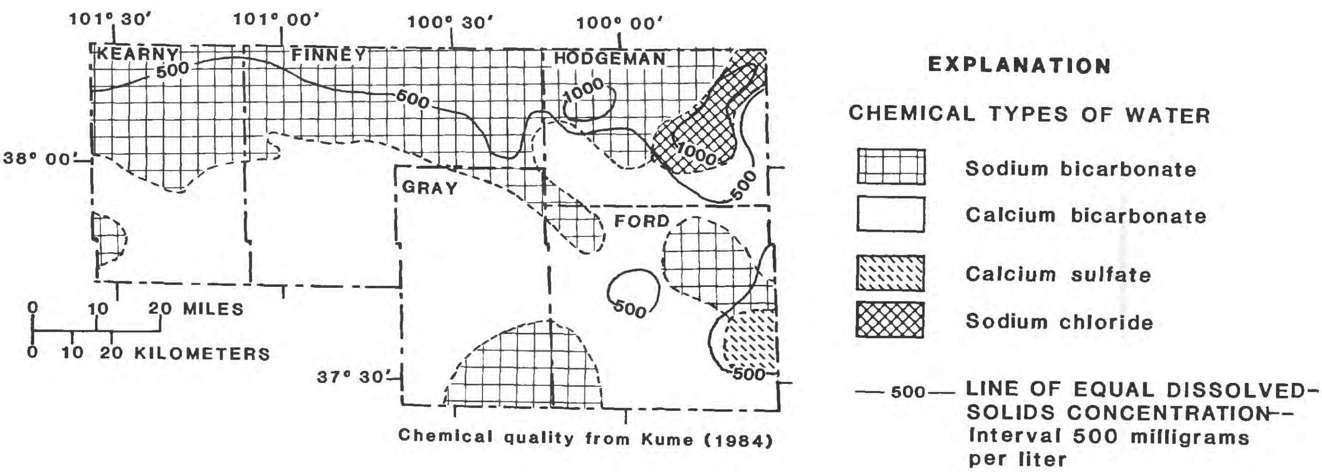



**Figure 13.** Occurrence of chemical types of water and generalized distribution of dissolved-solids concentrations in water from the Dakota aquifer.

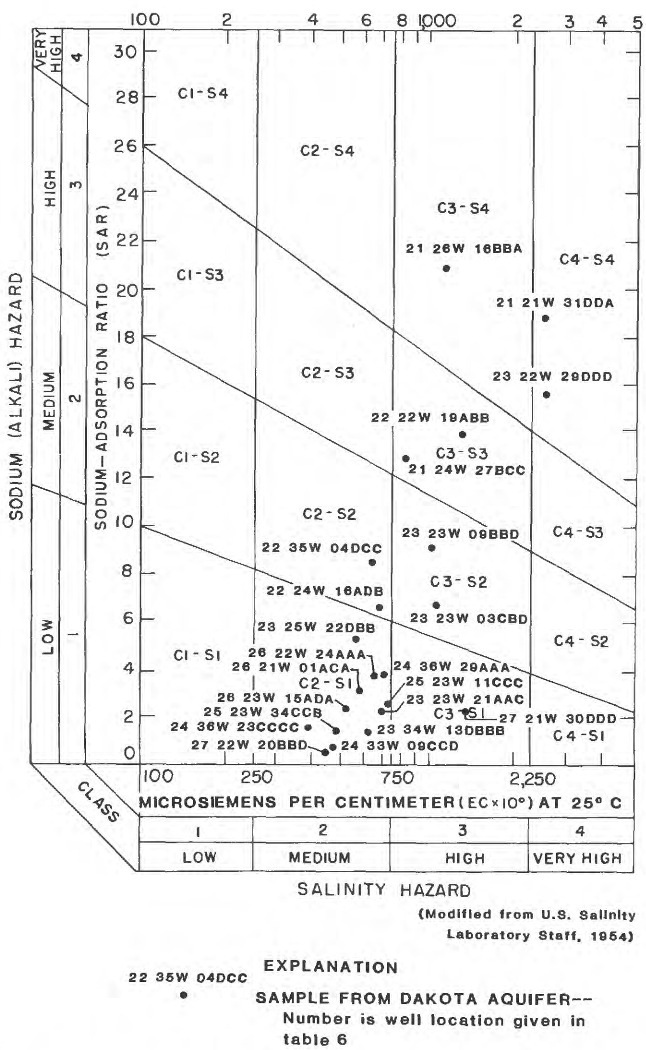



**Figure 14.** Classification of selected water samples from Dakota aquifer describing suitability for irrigation.

Counties (Lobmeyer and Weakly, 1979), and 2 large-capacity wells were in use in northeastern Finney County. By the end of 1984, a total of 137 large-capacity wells had been completed in the Dakota aquifer in the study area (fig. 12). During this same period, development of the High Plains aquifer was also occurring. Water levels in the Dakota aquifer declined in response to increasing rates of discharge from the Dakota aquifer and changes in rates of inflow resulting from declines in the hydraulic head of the High Plains aquifer.

Sources of inflow to the Dakota aquifer in the study area include: (1) downward leakage from the High Plains aquifer and Niobrara-Graneros confining unit, (2) ground-water flow across the boundaries of the study area, and (3) direct infiltration of precipitation. Upward leakage through the underlying Kiowa confining unit is negligible in most areas. The principal source of inflow to the Dakota aquifer is leakage from the High Plains aquifer. Stullken and others (1985) estimated downward leakage from the High Plains aquifer during predevelopment (pre-1950) to the "Lower Cretaceous aquifer" in southwest Kansas at a rate of about 14,000 acre-ft/yr (about 19 $ft^3/s$), based on the results from calibration of a steady-state model of the High Plains aquifer in southwestern Kansas. Their results support the conclusion of Lobmeyer and Weakly (1979, p. 20) that, "Most of the water enters the Dakota aquifer in areas of Kansas southeast of Hodgeman and northern Ford Counties." Ground-water flow in the Dakota aquifer across the western boundary of the study area (Hamilton-Kearny and Gray-Haskell County lines) is estimated at about 7,000 acre-ft/yr, based on Darcian flow and average aquifer conditions. Recharge to the Dakota aquifer directly from precipitation, which is limited to the outcrop areas (fig. 3) and to parts of eastern Ford County where the Dakota aquifer is unconfined, is insignificant.

**Table 6.** Chemical analyses of water from the Dakota aquifer

[Modified from Kume (1984, table 4, p. 32–33) and Lobmeyer and Weakly (1979, table 6, p. 40–41). Values given in milligrams per liter (mg/L), except as noted]

| Well location | Date of collection | Well depth (feet) | Specific conductance (microsiemens)[1] | pH (standard units) | Temperature (°C)[2] | Hardness as $CaCO_3$ (total) | Hardness (noncarbonate) | Dissolved calcium (Ca) | Dissolved magnesium (Mg) | Dissolved sodium (Na) | Sodium adsorption ratio (SAR) | Dissolved potassium (K) | Bicarbonate ($HCO_3$) | Carbonate ($CO_3$) | Dissolved sulfate ($SO_4$) | Dissolved chloride (Cl) | Dissolved fluoride (F) | Dissolved silica ($SiO_2$) | Dissolved solids (sum of constituents) | Dissolved nitrate (as N) | Total iron (Fe) | Dissolved manganese (Mn) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Finney County** | | | | | | | | | | | | | | | | | | | | | | |
| 23 34W 13DBBB | 2-23-82 | 778 | 600 | 7.4 | 19.0 | 200 | 9 | 47 | 22 | 47 | 1.4 | 5.6 | 240 | 0 | 92 | 18 | 1.5 | 11 | 364 | 0 | -- | -- |
| 23 34W 14CCCC | 2-16-82 | 740 | 610 | 7.1 | 19.0 | 200 | 21 | 47 | 24 | 45 | 1.3 | 5.7 | 240 | 0 | 105 | 13 | 1.4 | 11 | 370 | .2 | -- | -- |
| 23 34W 15ACDB | 1-25-82 | 765 | 650 | 6.8 | 19.0 | 210 | [4]-- | 50 | 23 | 56 | 1.6 | 4.9 | -- | -- | 130 | 15 | 1.5 | 10 | -- | -- | -- | -- |
| 23 34W 16ACB | 4-05-82 | 755 | 580 | 7.2 | 19.0 | 200 | -- | 49 | 20 | 50 | 1.5 | 5.8 | -- | -- | 94 | 9.0 | 1.5 | 10 | -- | -- | -- | -- |
| 23 34W 26CBCC | 1-14-81 | 760 | 620 | 7.4 | 19.0 | 200 | 33 | 46 | 22 | 52 | 1.6 | 6.0 | 210 | 0 | 120 | 15 | -- | 11 | 390 | .89 | -- | -- |
| [3]23 34W 26CBCC | 1-14-81 | 760 | 580 | 7.5 | 19.0 | 180 | 13 | 42 | 19 | 52 | 1.7 | 5.0 | 210 | 0 | 120 | 14 | -- | 12 | 364 | .44 | -- | -- |
| 24 33W 09CCD 03 | 8-12-80 | 560 | 470 | 8.1 | 17.0 | 190 | 25 | 46 | 19 | 29 | .9 | 4.0 | 200 | 0 | 83 | 11 | 1.3 | 9.0 | 304 | .44 | -- | -- |
| 24 33W 19DBDD | 7-07-80 | 714 | 460 | 7.6 | 21.5 | 150 | 0 | 40 | 12 | 43 | 1.5 | 3.0 | 180 | 0 | 84 | 10 | 1.2 | 12 | 298 | 1.3 | -- | -- |
| **Ford County** | | | | | | | | | | | | | | | | | | | | | | |
| 25 21W 23BCB | 7-06-73 | 127 | 520 | 7.5 | — | 204 | 0 | 64 | 11 | 34 | 1.0 | 3.0 | 283 | 0 | 16 | 16 | 0.8 | 30 | 310 | 2.2 | 0.03 | 0 |
| 25 22W 07ACA | 7-18-73 | 350 | 560 | 7.9 | -- | 179 | 0 | 42 | 18 | 59 | 1.9 | 5.8 | 283 | 0 | 46 | 20 | 2.2 | 44 | 374 | 1.2 | 2.9 | 0.02 |
| 25 22W 34DDB | 7-20-73 | 410 | 570 | 7.4 | -- | 256 | 40 | 78 | 15 | 24 | .7 | 4.0 | 264 | 0 | 21 | 35 | .6 | 49 | 390 | 18 | .11 | 0 |
| 25 23W 11CCC | 8-19-68 | 385 | 740 | 8.1 | 18.0 | 158 | 0 | 32 | 19 | 95 | 3.3 | 10.0 | 278 | 0 | 36 | 67 | 3.6 | -- | 440 | 8.0 | 1.3 | 0 |
| 25 23W 25CCC | 7-31-73 | 372 | 540 | 7.3 | -- | 166 | 0 | 35 | 19 | 59 | 2.0 | 5.2 | 266 | 0 | 43 | 17 | 2.0 | 43 | 356 | 2.0 | .03 | 0 |
| 25 23W 32DBB | 7-24-72 | 380 | 540 | 7.3 | -- | 154 | 0 | 37 | 15 | 62 | 2.2 | 5.5 | 271 | 0 | 50 | 12 | 2.4 | 28 | 352 | .9 | .11 | 0 |
| 25 23W 34CCB | 7-24-73 | 350 | 490 | 7.4 | -- | 170 | 0 | 35 | 20 | 45 | 1.5 | 4.8 | 256 | 0 | 39 | 10 | 2.2 | 46 | 334 | 2.7 | .05 | 0 |
| 25 23W 35ADC | 7-18-73 | 360 | 480 | 7.4 | -- | 179 | 0 | 42 | 18 | 38 | 1.3 | 4.5 | 261 | 0 | 31 | 12 | 2.0 | 50 | 314 | 2.4 | .46 | 0 |
| 25 23W 36BDA | 7-09-73 | 380 | 530 | 7.3 | -- | 174 | 0 | 43 | 16 | 50 | 1.7 | 4.5 | 261 | 0 | 32 | 18 | 2.0 | 42 | 340 | 7.3 | .04 | 0 |
| 25 25W 32CDD | 4-06-81 | 383 | 540 | 6.3 | 17.0 | 140 | 0 | 34 | 14 | 61 | 2.2 | 5.0 | -- | -- | 49 | 11 | 1.8 | 18 | 324 | 3.5 | -- | -- |
| 26 21W 01ACA | 7-11-73 | 165 | 660 | 7.5 | -- | 168 | 0 | 46 | 13 | 88 | 3.0 | 3.5 | 307 | 0 | 54 | 34 | 1.6 | 25 | 410 | 1.3 | .44 | 0 |
| 26 21W 01BCA | 7-11-73 | 135 | 620 | 8.2 | -- | 144 | 0 | 42 | 9.5 | 88 | 3.2 | 3.2 | 281 | 0 | 55 | 30 | 1.6 | 26 | 384 | .4 | .07 | 0 |
| 26 21W 11CBD | 7-18-73 | 174 | 940 | 7.3 | -- | 410 | 142 | 123 | 25 | 35 | .8 | 3.2 | 327 | 0 | 54 | 93 | .5 | 30 | 580 | 32 | .40 | 0 |
| 26 21W 13BD | 5-20-64 | 25 | 1,250 | 7.5 | -- | 433 | 155 | 101 | 44 | 108 | 2.3 | 4.7 | 339 | 0 | 180 | 137 | 1.4 | 21 | 780 | 16 | .00 | 0 |
| 26 22W 05CBA | 7-20-73 | 435 | 560 | 7.4 | -- | 121 | 0 | 27 | 13 | 81 | 3.2 | 5.0 | 261 | 0 | 51 | 17 | 2.2 | 35 | 360 | 2.9 | .33 | 0 |
| 26 22W 06BCD | 7-11-73 | 350 | 550 | 7.3 | -- | 126 | 0 | 29 | 13 | 74 | 2.9 | 5.0 | 256 | 0 | 50 | 15 | 2.4 | 34 | 364 | 2.2 | .03 | 0 |
| 26 22W 06CCA | 8-23-72 | -- | 550 | 7.8 | 16.5 | 136 | 0 | 30 | 15 | 72 | 2.7 | 5.2 | 261 | 0 | 53 | 17 | 2.0 | 37 | 360 | 2.7 | .05 | 0 |
| 26 22W 08CAD | 7-24-73 | 243 | 600 | 7.4 | -- | 136 | 0 | 30 | 15 | 90 | 3.4 | 4.5 | 259 | 0 | 80 | 22 | 2.0 | 19 | 382 | .2 | .03 | 0 |
| 26 22W 08DDC | 7-18-73 | -- | 540 | 7.6 | -- | 110 | 0 | 26 | 11 | 82 | 3.4 | 4.2 | 234 | 0 | 77 | 16 | 2.4 | 21 | 352 | .3 | .25 | 0 |
| 26 22W 11CDC | 7-18-73 | 154 | 470 | 7.3 | -- | 204 | 0 | 64 | 11 | 20 | .6 | 3.8 | 273 | 0 | 17 | 13 | .4 | 31 | 296 | .1 | .42 | 0 |
| 26 22W 21DCD | 7-24-73 | 360 | 920 | 7.8 | -- | 152 | 0 | 43 | 11 | 148 | 5.2 | 5.2 | 283 | 0 | 137 | 74 | 3.1 | 14 | 578 | 2.1 | .07 | 0 |
| 26 22W 24AAA | 8-14-73 | 250 | 660 | 7.3 | -- | 125 | 0 | 32 | 11 | 100 | 3.9 | 3.8 | 259 | 0 | 70 | 42 | 1.1 | 26 | 410 | .5 | .06 | 0 |
| 26 23W 10DAD | 8-23-73 | 278 | 540 | 8.4 | -- | 129 | 0 | 27 | 15 | 69 | 2.6 | 5.0 | 234 | 10 | 49 | 12 | 2.4 | 41 | 348 | 1.5 | .08 | 0 |
| 26 23W 15ADA | 7-31-73 | 288 | 540 | 7.4 | -- | 145 | 0 | 30 | 17 | 67 | 2.4 | 4.5 | 256 | 0 | 55 | 15 | 2.0 | 37 | 350 | 1.6 | .02 | 0 |
| 26 23W 15DCD | 7-18-73 | 330 | 530 | 7.4 | -- | 128 | 0 | 30 | 13 | 70 | 2.7 | 5.0 | 256 | 0 | 53 | 11 | 2.2 | 41 | 342 | 2.0 | .05 | 0 |

**Table 6.** Chemical analyses of water from the Dakota aquifer—Continued

[Modified from Kume (1984, table 4, p. 32-33) and Lobmeyer and Weakly (1979, table 6, p. 40-41). Values given in milligrams per liter (mg/L), except as noted]

| Well location | Date of collection | Well depth (feet) | Specific conductance (microsiemens)[1] | pH (standard units) | Temperature (°C)[2] | Hardness as $CaCO_3$ (total) | Hardness (noncarbonate) | Dissolved calcium (Ca) | Dissolved magnesium (Mg) | Dissolved sodium (Na) | Sodium adsorption ratio (SAR) | Dissolved potassium (K) | Bicarbonate ($HCO_3$) | Carbonate ($CO_3$) | Dissolved sulfate ($SO_4$) | Dissolved chloride (Cl) | Dissolved fluoride (F) | Dissolved silica ($SiO_2$) | Dissolved solids (sum of constituents) | Dissolved nitrate (as N) | Total iron (Fe) | Dissolved manganese (Mn) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 27 21W 29DBB02 | 7-12-73 | 126 | 960 | 7.7 | -- | 269 | 83 | 75 | 20 | 106 | 2.8 | 3.5 | 227 | 0 | 228 | 40 | 1.2 | 47 | 654 | 22 | .58 | 0 |
| 27 21W 30DDD | 7-12-73 | 126 | 1,380 | 7.4 | -- | 483 | 209 | 144 | 30 | 132 | 2.6 | 4.0 | 334 | 0 | 348 | 68 | .8 | 31 | 974 | 41 | .04 | 0 |
| 27 21W 31CBB | 8-23-73 | 115 | 1,360 | 7.6 | -- | 558 | 288 | 171 | 32 | 86 | 1.6 | 5.5 | 329 | 0 | 366 | 49 | 1.6 | 21 | 948 | 42 | 1.5 | 0.17 |
| 27 22W 09DAB | 7-23-73 | 390 | 520 | 7.3 | -- | 228 | 0 | 70 | 13 | 24 | .7 | 3.5 | 288 | 0 | 16 | 12 | .4 | 42 | 338 | 15 | .19 | 0 |
| 27 22W 13CDD | 7-20-73 | 246 | 480 | 7.4 | -- | 204 | 0 | 70 | 7.2 | 22 | .7 | 3.2 | 256 | 0 | 12 | 11 | .5 | 47 | 316 | 18 | 1.3 | 0 |
| 27 22W 16CCA | 7- -73 | 240 | 450 | 7.8 | -- | 188 | 0 | 59 | 10 | 20 | .6 | 2.2 | 242 | 0 | 17 | 10 | .4 | 58 | 302 | 11 | 1.6 | 0 |
| 27 22W 19AAC | 7-18-73 | -- | 460 | 7.4 | -- | 209 | 3 | 69 | 9.0 | 16 | .5 | 2.8 | 251 | 0 | 6.6 | 12 | .4 | 46 | 310 | 14 | .46 | 0 |
| 27 22W 19DAB | 7-31-73 | -- | 460 | 7.4 | -- | 208 | 8 | 72 | 6.9 | 16 | .5 | 3.0 | 244 | 0 | 9.9 | 13 | .3 | 37 | 324 | 24 | .03 | 0 |
| 27 22W 20BBD | 7-18-73 | -- | 460 | 7.5 | -- | 216 | 6 | 70 | 10.0 | 14 | .4 | 3.2 | 256 | 0 | 12 | 11 | .4 | 40 | 310 | 8.5 | .03 | 0 |
| 27 22W 20CAC | 7-18-73 | -- | 480 | 7.5 | -- | 220 | 16 | 75 | 8.0 | 16 | .5 | 3.0 | 249 | 0 | 11 | 16 | .4 | 45 | 320 | 24 | .93 | .14 |
| 27 22W 20DCD | 7-18-73 | -- | 470 | 7.5 | -- | 212 | 22 | 74 | 6.7 | 15 | .5 | 3.0 | 232 | 0 | 4.9 | 13 | .5 | 49 | 320 | 33 | .03 | 0 |
| 27 22W 29BDD | 7-18-73 | -- | 480 | 7.4 | -- | 204 | 16 | 70 | 7.2 | 23 | .7 | 3.0 | 229 | 0 | 14 | 15 | .4 | 47 | 336 | 34 | .07 | 0 |
| 27 22W 29CAA | 7-18-73 | 110 | 480 | 7.4 | -- | 200 | 12 | 70 | 6.2 | 23 | .7 | 2.5 | 229 | 0 | 14 | 17 | .4 | 48 | 340 | 34 | .03 | 0 |
| 27 22W 36AAD | 8-23-73 | 115 | 770 | 7.5 | -- | 268 | 22 | 91 | 10 | 60 | 1.6 | 4.2 | 300 | 0 | 86 | 41 | .3 | 46 | 506 | 10 | .12 | 0 |
| 27 23W 15DCB | 7-09-73 | 442 | 720 | 7.5 | -- | 180 | 0 | 51 | 13 | 88 | 2.9 | 4.8 | 259 | 0 | 66 | 61 | 1.6 | 23 | 450 | 6.2 | .35 | 0 |
| 27 23W 24BCB | 7-18-73 | 220 | 520 | 7.3 | -- | 186 | 0 | 50 | 15 | 40 | 1.3 | 4.2 | 239 | 0 | 43 | 25 | .4 | 27 | 324 | 6.8 | 9.3 | .19 |
| 27 24W 04CAA | 8-09-80 | 248 | 920 | 7.2 | 16.0 | 33 | 140 | 99 | 21 | 78 | 1.9 | 5.0 | 230 | 0 | 260 | 33 | 1.3 | 19 | 635 | 8.0 | -- | -- |
| Gray County | | | | | | | | | | | | | | | | | | | | | | |
| 28 28W 09DBB | 8-26-81 | 462 | 440 | 7.6 | 16.0 | 180 | 27 | 57 | 9.0 | 18 | .6 | 3.0 | -- | -- | 24 | 16 | .5 | 31 | 273 | 12 | -- | -- |
| Hodgeman County | | | | | | | | | | | | | | | | | | | | | | |
| 21 21W 31DDA | 6-16-72 | 360 | 2,440 | 8.0 | 15.5 | 125 | 0 | 27 | 14 | 480 | 19 | 19 | 271 | 0 | 190 | 540 | 3.0 | 8.4 | 1,420 | 5.3 | 3.1 | .14 |
| 21 22W 27CBC | 5-21-72 | 287 | 1,210 | 7.9 | 18.4 | 238 | 0 | 59 | 22 | 180 | 5.1 | 13 | 337 | 0 | 235 | 81 | 2.2 | 13 | 768 | .4 | 2.5 | .19 |
| 21 23W 03CDB | 6-16-72 | 400 | 880 | 8.1 | 18.0 | 32 | 0 | 8.0 | 2.9 | 186 | 14 | 6.6 | 246 | 0 | 111 | 89 | 2.4 | 8.4 | 548 | .7 | .31 | 0 |
| 21 24W 27BCC | 5-21-72 | 330 | 850 | 8.1 | 18.0 | 36 | 0 | 6.4 | 4.9 | 175 | 13 | 6.8 | 237 | 0 | 112 | 75 | 2.6 | 7.6 | 502 | .2 | .13 | 0 |
| 21 26W 16BBA | 5-15-69 | 368 | 1,060 | 7.9 | 15.5 | 24 | 0 | 6.4 | 2.0 | 232 | 21 | 7.0 | 278 | 0 | 152 | 96 | 4.0 | 6.8 | 648 | 1.7 | .62 | 0 |
| 22 22W 19ABB | 5-21-72 | 228 | 1,370 | 7.8 | 16.5 | 76 | 0 | 16 | 8.8 | 272 | 14 | 11 | 307 | 0 | 178 | 166 | 3.0 | 6.2 | 810 | .9 | .87 | .17 |
| 22 24W 14BCC | 7-24-73 | 560 | 740 | 7.6 | -- | 97 | 0 | 19 | 12 | 128 | 5.7 | 5.5 | 242 | 0 | 79 | 65 | 2.0 | 11 | 460 | .1 | .28 | 0 |
| 22 24W 15BDA | 7-18-73 | 585 | 690 | 7.5 | -- | 72 | 0 | 16 | 7.8 | 128 | 6.6 | 5.0 | 244 | 0 | 64 | 62 | 1.6 | 11 | 410 | .1 | .14 | 0 |
| 22 24W 16ADB | 7-18-73 | 565 | 700 | 7.6 | 19.5 | 76 | 0 | 16 | 8.8 | 134 | 6.7 | 5.5 | 242 | 0 | 85 | 49 | 2.4 | 10 | 434 | .6 | .06 | 0 |
| 22 24W 24DDC | 5-21-72 | 430 | 850 | 7.8 | 18.5 | 56 | 0 | 12 | 6.3 | 168 | 9.8 | 7.6 | 259 | 0 | 77 | 94 | 2.4 | 7.9 | 500 | 1.5 | .59 | 0 |
| 22 24W 34CDD | 5-09-69 | 390 | 770 | 7.6 | -- | 92 | 0 | 19 | 11 | 140 | 6.3 | 8.6 | 266 | 0 | 82 | 64 | 2.4 | 8.7 | 464 | .9 | .05 | .03 |
| 22 26W 23DCC | 5-21-72 | 505 | 2,020 | 8.2 | 16.5 | 24 | 0 | 4.8 | 2.9 | 447 | 40 | 11 | 393 | 0 | 244 | 291 | 5.6 | 7.9 | 1,220 | .7 | .28 | 0 |
| 23 22W 29DDD | 5-22-72 | 350 | 2,450 | 7.8 | 16.5 | 166 | 0 | 35 | 19 | 460 | 16 | 18 | 332 | 0 | 107 | 560 | 3.0 | 7.0 | 1,400 | 1.1 | .74 | 0 |
| 23 23W 03CBD | 7-17-73 | 257 | 1,120 | 7.3 | 16.5 | 141 | 0 | 40 | 10 | 189 | 6.9 | 8.2 | 293 | 0 | 108 | 143 | 2.4 | 11 | 652 | 1.1 | .03 | 0 |
| 23 23W 04AAD | 7-17-73 | 282 | 1,490 | 6.8 | 18.0 | 150 | 110 | 42 | 11 | 192 | 6.8 | 8.2 | 49 | 0 | 125 | 147 | 2.0 | 13 | 816 | 230 | .05 | 0 |

| | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23 23W 06CAB | 6-19-72 | 385 | 1,730 | 7.9 | 18.5 | 96 | 0 | 17 | 13 | 326 | 14 | 14 | 268 | 0 | 115 | 340 | 2.6 | 11 | 974 | 0 | 1.2 | .20 |
| 23 23W 09BBD | 7-17-73 | 290 | 1,030 | 7.3 | -- | 88 | 0 | 19 | 9.8 | 195 | 9.1 | 7.2 | 278 | 0 | 88 | 131 | 2.4 | 9.6 | 606 | .3 | 1.4 | 0 |
| 23 23W 12ABD | 7-17-73 | 245 | 1,240 | 7.6 | -- | 150 | 0 | 40 | 12 | 213 | 7.6 | 7.8 | 312 | 0 | 87 | 190 | 2.4 | 15 | 740 | 1.1 | .05 | 0 |
| 23 23W 12CAC | 7-17-73 | 256 | 920 | 7.2 | -- | 158 | 0 | 32 | 19 | 142 | 4.9 | 8.0 | 283 | 0 | 76 | 110 | 2.4 | 15 | 546 | 1.4 | .10 | 0 |
| 23 23W 21AAC | 7-17-73 | 395 | 730 | 7.5 | 17.0 | 196 | 0 | 59 | 12 | 90 | 2.8 | 5.0 | 283 | 0 | 69 | 60 | 2.0 | 22 | 460 | .7 | .05 | 0 |
| | | | | | | | | | | | | | | | | | | | | | | |
| 23 24W 01AAC | 6-19-72 | 395 | 1,100 | 7.7 | 18.0 | 120 | 0 | 30 | 11 | 191 | 7.6 | 10 | 283 | 0 | 109 | 144 | 2.4 | 13 | 652 | 1.5 | -- | .24 |
| 23 25W 07B | 6-21-72 | 505 | 930 | 8.1 | 18.0 | 24 | 0 | 4.8 | 2.9 | 200 | 18 | 8.2 | 256 | 0 | 156 | 59 | 3.6 | 10 | 578 | .7 | .66 | .08 |
| 23 25W 11ADA | 5-15-69 | 200 | 720 | 7.8 | 16.5 | 84 | 0 | 18 | 9.4 | 132 | 6.3 | 8.2 | 254 | 0 | 114 | 33 | 2.8 | 5.8 | 447 | .7 | .42 | 0 |
| 23 25W 22DBB | 7- -73 | 575 | 590 | 7.6 | -- | 68 | 0 | 16 | 6.8 | 104 | 5.5 | 4.8 | 227 | 0 | 63 | 29 | 2.0 | 11 | 362 | .2 | .48 | .05 |
| 23 26W 07CCC | 5-29-68 | 490 | 500 | 8.4 | -- | 173 | 35 | 38 | 19 | 35 | 1.2 | 5.5 | 149 | 10 | 57 | 39 | .8 | 25 | 322 | 4.2 | .15 | 0 |
| | | | | | | | | | | | | | | | | | | | | | | |
| 24 23W 06AAB | 7-18-73 | 517 | 1,220 | 7.8 | -- | 117 | 0 | 27 | 12 | 220 | 8.9 | 8.0 | 300 | 0 | 87 | 181 | 2.4 | 11 | 712 | .1 | .63 | .08 |
| 24 23W 22B | 5-09-69 | 200 | 1,330 | 7.5 | 17.0 | 117 | 0 | 14 | 20 | 252 | 10 | 18 | 307 | 0 | 186 | 160 | 4.0 | 6.6 | 804 | .2 | .23 | 0 |
| Kearny County | | | | | | | | | | | | | | | | | | | | | | |
| 22 35W 04DCC | 11-19-81 | 564 | 630 | -- | 18.0 | 39 | -- | 10 | 3.5 | 130 | 8.7 | -- | -- | -- | 75 | 13 | 2.0 | 15 | 390 | -- | -- | -- |
| 24 36W 23CCCC | 7-23-81 | 560 | 400 | 7.1 | 17.0 | 170 | 0 | 40 | 18 | 52 | 1.7 | -- | -- | -- | 100 | 7.4 | 1.3 | 10 | 331 | 0 | -- | -- |
| 24 36W 29AAA | 9-22-81 | 618 | 740 | 7.7 | 18.0 | 130 | 120 | 33 | 12 | 100 | 3.8 | -- | -- | -- | 150 | 8.0 | 1.8 | 10 | 450 | .4 | -- | -- |
| Number of analyses | | | 81 | 80 | 34 | 81 | 78 | 81 | 81 | 81 | 81 | 78 | 74 | 74 | 81 | 81 | 79 | 80 | 79 | 78 | 66 | 66 |
| Minimum value | | | 400 | 6.3 | 15.5 | 24 | 0 | 4.8 | 2.0 | 14 | 0.4 | 2.2 | 49 | 0 | 4.9 | 7.4 | 0.3 | 5.8 | 296 | 0.1 | 0.00 | 0 |
| Maximum value | | | 2,450 | 8.4 | 21.5 | 558 | 288 | 171 | 44 | 480 | 40 | 19 | 393 | 10 | 366 | 560 | 5.6 | 58 | 1,420 | 230 | 9.3 | .24 |
| Mean | | | 793 | 7.6 | 17.7 | 165 | 20 | 45.1 | 13.8 | 108 | 4.9 | 6.0 | 262 | 0 | 89 | 66 | 1.8 | 23.8 | 498 | 9.5 | .59 | .02 |

1 Microsiemens per centimeter at 25 °Celsius (microsiemens).
2 Degrees Celsius (°C).
3 Analysis by U.S. Geological Survey.
4 Not reported.

Outflow from the Dakota aquifer in the study area occurs as: (1) ground-water withdrawals by wells, (2) upward leakage, (3) ground-water flow across the boundaries of the study area, and (4) spring-flow and seepage in outcrop areas. Total pumpage from the Dakota aquifer in the study area during 1975–82 was about 158,000 acre-ft or less than 20,000 acre-ft/yr (table 5). Upward leakage from the Dakota aquifer occurs in the areas of subcrop (fig. 8) where hydraulic heads in the Dakota aquifer are higher than those in the High Plains aquifer. Because hydraulic-head data for the Dakota aquifer are poorly defined in the subcrop areas, estimating upward leakage from the Dakota aquifer was not possible. Flow in the Dakota aquifer across the eastern boundary of the study area is estimated to be about 5,000 acre-ft/yr, based on average aquifer conditions. Discharge of the Dakota aquifer to springs and seeps along Buckner, Sawlog, and Coon Creeks in Hodgeman and northern Ford Counties is estimated at a rate of about 1,100 acre-ft/yr (Lobmeyer and Weakly, 1979). Evapotranspiration from the Dakota aquifer was assumed to be negligible because of the small areas in which the Dakota is unconfined.

Hydrographs of three observation wells completed in the Dakota aquifer (fig. 15) illustrate the aquifer's response to pumpage. The hydrograph of well 22 24W 16ADB (fig. 15*A*) shows the effects of pumpage from the Dakota aquifer in an area where the aquifer is confined and distant from the subcrop. Water levels during the winter-spring recovery periods declined at a rate of about 15 ft/yr from 1973 to 1977 but had recovered to 1973 levels by 1982. This indicates that pumpage from the Dakota aquifer in nearby areas may have decreased during 1978–82. In contrast, the hydrograph of well 23 26W 07CCC shows a fairly steady rate of decline during 1969–83 of about 4 ft/yr (fig. 15*B*). This well is also in an area remote from the subcrop, and the nearest large-capacity well in the Dakota is about 4 mi north and 1.25 mi west. As declines in the hydraulic head of the Dakota aquifer continue, the aquifer may temporarily convert from confined to unconfined conditions, as indicated by the hydrograph of the irrigation-observation well at 25 23W 12BBB (fig. 15*C*). Water levels in this well fell below the base of the upper confining layer (a clay layer in the upper part of the Dakota aquifer) during the late 1970's. The rate of decline in water level in this well was about 6 ft/yr from 1973 to 1976. However, 1977–83 water levels during the winter-spring recovery periods show little change in storage in the aquifer; this lack of change could result from decreased pumpage from the Dakota aquifer. This well is within 2 mi of the area where the alluvium of Sawlog Creek is in contact with the Dakota aquifer; therefore, the lack of change in recovery-period water levels during 1977–83 also may result from the capture of discharge to springs and seeps or the infiltration of water from the alluvial aquifer.

The responses of the Dakota aquifer to long-term water-level declines in the High Plains aquifer and to pumpage from the High Plains aquifer in or near areas of the subcrop of the Dakota aquifer are shown in figure 16. Long-term declines of water levels in the High Plains aquifer in northeastern Stanton County (southwest of the study area) are indicated by the response of the hydrograph of well 27 38W 15BBB in the Dakota aquifer (fig. 16*A*). Depth to water in the Dakota aquifer declined rapidly during the late 1950's and early- to mid-1960's. The High Plains aquifer and Dakota aquifer are not separated by the Niobrara-Graneros confining unit at this location, but the fine-grained material in the High Plains aquifer acted as a semiconfining layer until the mid-1960's when water levels declined to a level below the top of the Dakota aquifer. The rate of decline slowed during the late 1960's and indicates the conversion of the Dakota aquifer from confined to unconfined conditions.

The hydrographs of three observation wells located at 24 33W 09CCD in Finney County (fig. 16*B*) show the effect of pumping from the High Plains aquifer on the hydraulic heads in the Dakota aquifer. Observation well 01 is completed to a depth of 210 ft in the High Plains aquifer and shows response of the hydraulic head to irrigation withdrawals from the High Plains aquifer in nearby wells. Observation well 02 is completed to a depth of 65 ft in sand and gravel of the Arkansas River alluvium. Locally, a clay layer acts as a semiconfining layer beneath the alluvial aquifer. Water levels in well 02 show no response to pumping from the High Plains aquifer but do show a slight rise during 1983 when streamflow resumed in the nearby Arkansas River. Observation well 03 is completed to a depth of 560 ft in the Dakota aquifer and is grouted opposite the Niobrara-Graneros confining unit. The hydrograph for the Dakota observation well (03) shows the effect of pumpage from the High Plains aquifer on the hydraulic head in the Dakota aquifer. The hydraulic head of the Dakota aquifer was generally greater than that of the High Plains aquifer (well 01) during 1980–83 and shows a response to drawdown in the High Plains aquifer. Distance from well 03 to the area of subcrop is about 2 mi.

## POTENTIAL EFFECTS OF GROUND-WATER WITHDRAWALS ON THE AQUIFER SYSTEM

A numerical model of three-dimensional ground-water flow was used to simulate the potential effects of ground-water withdrawals from the Dakota aquifer on the five-layer aquifer system of the study area. The aquifer system is composed of the High Plains aquifer, the Niobrara-Graneros confining unit, the Dakota aquifer, the Kiowa confining unit, and the Cheyenne aquifer. For the purposes of this model, the Permian

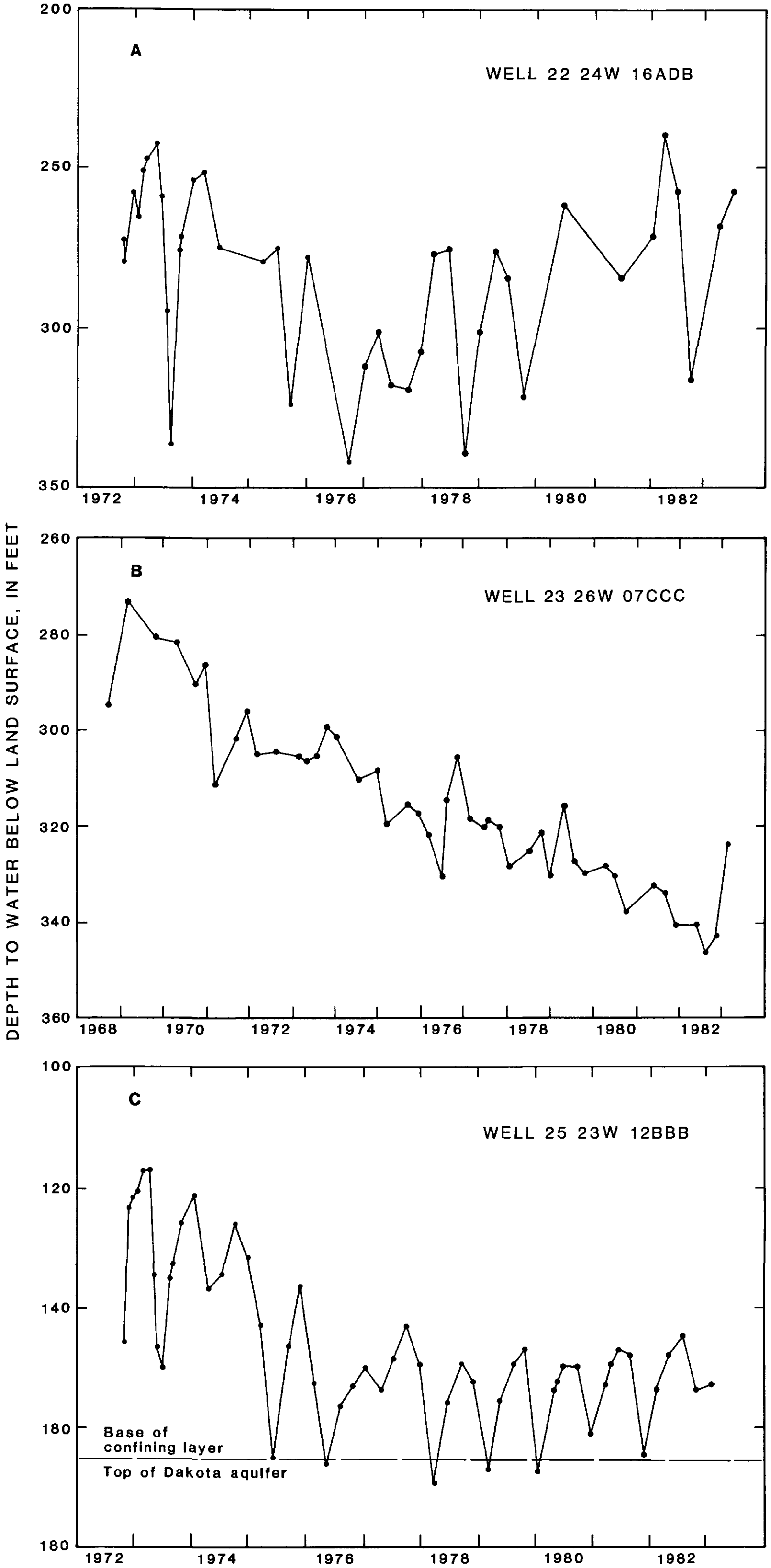



**Figure 15.** Hydrographs of selected wells completed in the Dakota aquifer.

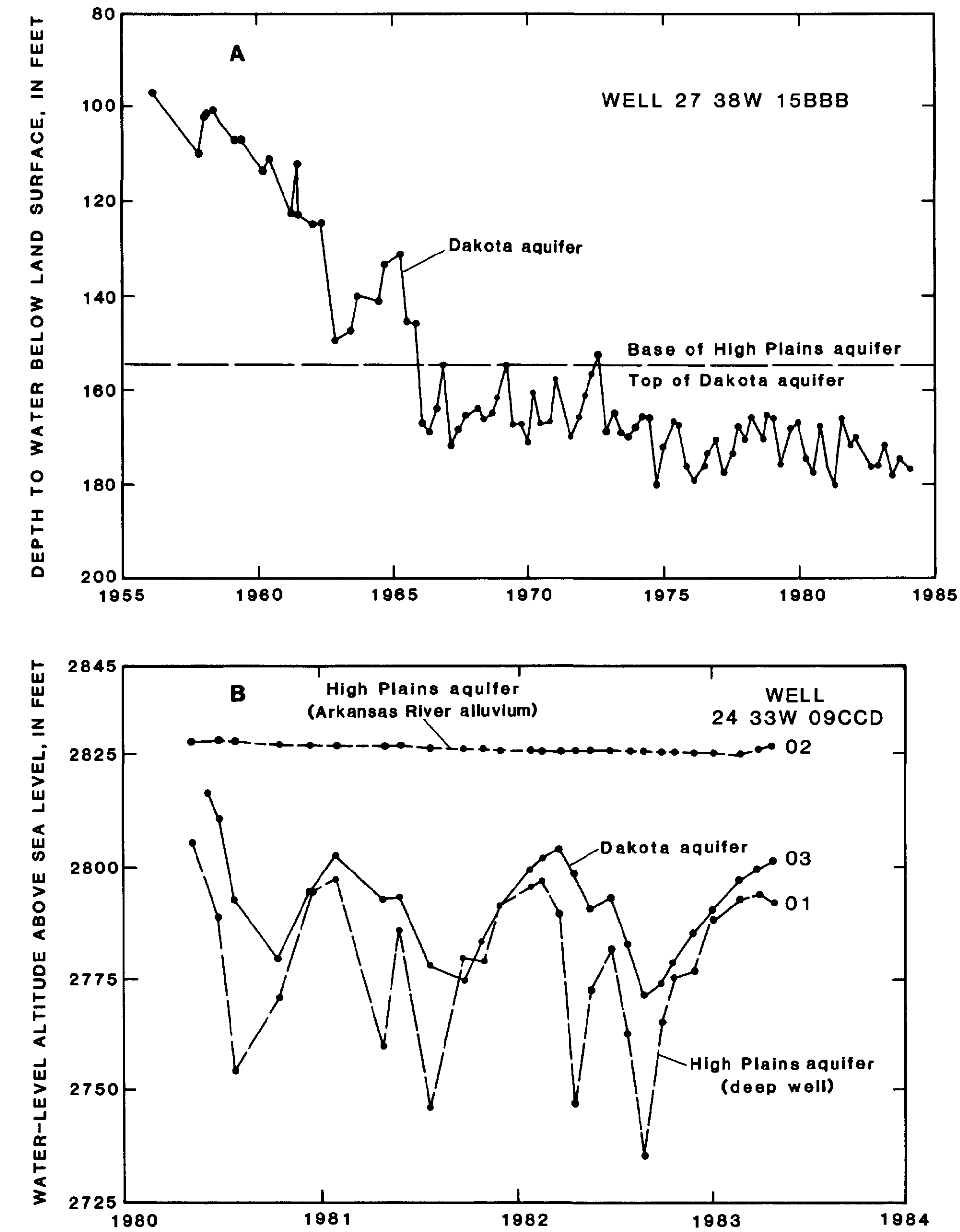



**Figure 16.** Hydrographs showing response of the Dakota aquifer to pumpage from the High Plains aquifer.

rocks were assumed to be an impermeable boundary at the base of the Cheyenne aquifer. The model was calibrated using data from a period of time during which the system was in a transient state. The calibrated model was used to evaluate the impact of potential pumpage from the Dakota aquifer on the five-layer aquifer system.

## Model Development

The three-dimensional, numerical model, which solves a set of finite-difference equations, utilized the computer code of McDonald and Harbaugh (1984). The computer code was modified to run on a minicomputer located at U.S. Geological Survey offices in Lawrence, Kans. Minor modifications also were made to the computer code to provide simulated water budgets for each layer of the aquifer system.

The basic equation, upon which the model was developed, describes movement of ground water of constant density through porous earth material. McDonald and Harbaugh (1984, p. 7) utilized the following equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}, \quad (1)$$

where

- $x$, $y$, and $z$ are cartesian coordinates aligned along the major axes of hydraulic conductivity $K_{xx}$, $K_{yy}$, $K_{zz}$;
- $h$ is the potentiometric head (L);
- $W$ is a volumetric flux per unit volume and represents sources and(or) sinks of water ($t^{-1}$);
- $S_s$ is the specific storage of the porous material ($L^{-1}$); and
- $t$ is time ($t$).

In general, $S_s$, $K_{xx}$, $K_{yy}$, $K_{zz}$ may be functions of space [$S_s=S_s(x,y,z)$, and $K_{xx}=K_{xx}(x,y,z)$] and so forth, and $h$ and $W$ may be functions of space and time [$h=h(x,y,z,t)$, $W=W(x,y,z,t)$] so that equation 1 describes ground-water flow under nonequilibrium conditions in a heterogeneous and anisotropic medium.

The area to be modeled was partitioned into a finite-difference grid of rectangular blocks (fig. 17), within which the hydrologic characteristics were considered to be uniform. The minimum size of the blocks in the model grid (fig. 17) was 6 by 6 mi, approximating the township range grid of the study area. A 6-by-6 mi grid spacing was used in an area of primary interest for this study, and the spacing was expanded to the east, north, and south of the study area so that model boundaries could be located sufficiently distant from the study-area boundaries to minimize external boundary effects on the model analysis. Maximum grid size was 20.25 by 20.25 mi.

The model allows designation of four aquifer types: (1) confined aquifers with constant transmissivity and storage coefficient; (2) one unconfined aquifer, the top layer, in which transmissivity varies with saturated thickness and the storage coefficient is constant; (3) confined-unconfined aquifers with constant transmissivity and a storage coefficient that can become specific yield when the aquifer converts from confined to unconfined conditions; and (4) confined-unconfined aquifers for which transmissivity is calculated from saturated thickness and hydraulic conductivity and in which the storage coefficient is dependent on the confined or unconfined conditions.

### Descriptions of Model Layers

The High Plains aquifer, layer 1, was treated as an unconfined aquifer. Transmissivity was calculated by the

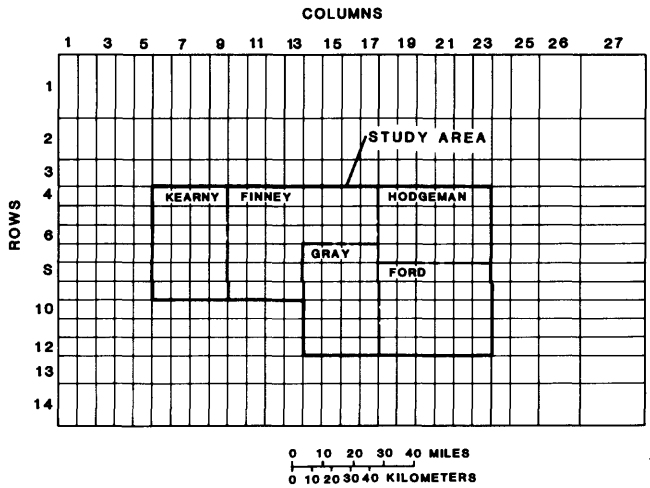



**Figure 17.** Finite-difference grid of model and approximate boundaries of study area.

model as the product of saturated thickness and hydraulic conductivity. Hydraulic conductivity was assigned a constant value of 80 ft/d, except in areas where the High Plains aquifer includes the Arkansas River valley alluvium. Hydraulic conductivity of the High Plains aquifer was assumed to be about 800 ft/d where it is composed entirely of the Arkansas River valley alluvium and 160 ft/d where it is composed of both the Arkansas River valley alluvium and the thick, older Tertiary and Quaternary sediments. Specific yield of the High Plains aquifer was initially set at 0.18, and the vertical hydraulic conductivity was set at 1.0 ft/d.

The Niobrara-Graneros confining unit, layer 2, was treated as a confined hydrologic unit. Horizontal-flow components in the Niobrara-Graneros confining unit were assumed to be insignificant, and transmissivity was set to zero. A specific storage of $1\times10^{-5}$ $ft^{-1}$ and a vertical hydraulic conductivity of $1\times10^{-5}$ ft/d were initially assumed for the Niobrara-Graneros confining unit.

The Dakota aquifer, layer 3, was treated as a confined-unconfined aquifer in which both transmissivity and storage coefficient could change with time, depending on the confined or unconfined conditions. A horizontal hydraulic conductivity of 7 ft/d was assigned to all grid blocks. Vertical hydraulic conductivity was initially set at $1\times10^{-1}$ ft/d. The specific storage was set at $3\times10^{-6}$ $ft^{-1}$ and specific yield at 0.07.

The Kiowa confining unit, layer 4, was treated as a confined unit with no significant horizontal flow. Therefore, the Kiowa confining unit was assigned a transmissivity of zero. Estimated vertical hydraulic conductivity was set at $1.3\times10^{-6}$ ft/d and specific storage at $5\times10^{-5}$ $ft^{-1}$.

The Cheyenne aquifer, layer 5, was treated as a confined aquifer. Transmissivity was calculated as estimated horizontal hydraulic conductivity (9 ft/d) multiplied by aquifer thickness. Vertical hydraulic conductivity was estimated to be $1 \times 10^{-2}$ ft/d, and the specific storage to be $2 \times 10^{-6}$ ft$^{-1}$. The basal contact of the Cheyenne aquifer with Permian rocks was assumed to be an impermeable boundary; therefore, vertical flow was simulated only across the upper boundary of the Cheyenne aquifer.

#### Boundary Conditions

Model boundaries should simulate, as nearly as possible, physical and hydrologic boundaries of the aquifer system. Because horizontal flow was assumed to be negligible in the Niobrara-Graneros and the Kiowa confining units, no-flow boundaries were used to represent the external boundaries of the confining units.

The boundaries simulated for each aquifer and confining unit are shown in figure 18. The simulated constant-head boundaries of the High Plains, Dakota, and Cheyenne aquifers were located sufficiently far from the study-area boundaries to minimize their effect on hydraulic heads of the aquifers in the study area. No-flow grid blocks represent areas in which a hydrologic unit is not present, unless the block was needed to maintain vertical continuity of flow.

The springs and seeps issuing from the Dakota aquifer in Ford and Hodgeman Counties were simulated in the model as drains. The bottom elevations of the simulated drains were picked from the map of the top of the Dakota Sandstone (fig. 8). Conductance of the interface between the drain and the aquifer was based on the hydraulic conductivity of the Dakota aquifer and the estimated proportion of each grid block that is occupied by the drains.

The streams that cross the eastern and southern boundaries of the study and model areas generally act as partially penetrating drains of the High Plains aquifer. As water levels in the High Plains aquifer decline below the stream bottoms, streamflows cease, except for occasional floods produced by overland runoff. Therefore, the streams crossing the eastern and southern boundaries were simulated as drains to prevent the simulation of recharge to the High Plains aquifer from streams. The bottom elevations of the streams were picked from topographic maps. The conductance of the interface was based on a vertical hydraulic conductivity of 1 ft/d and an area-proportion factor.

Recharge from precipitation was simulated at constant rates throughout the calibration period. A recharge rate of 2 in./yr was assumed for areas where the surficial deposits consist primarily of dune sand, terrace, and alluvial deposits (Barker and others, 1983). A rate of 0.28 in./yr was assumed for areas of bedrock outcrop and loess-covered areas (Stullken and others, 1985). Where different types of surficial deposits are present in an area, the recharge rate was adjusted, based on the type of deposits and proportionate areas to which each rate applied. The distribution of surficial materials upon which the recharge rates were based is shown in figure 3.

#### Vertical Conductance

The vertical conductance between vertically adjacent grid blocks in the model was calculated as a function of the thickness and vertical hydraulic conductivity of vertically adjacent hydrologic units using the following equation (McDonald and Harbaugh, 1984, eq. 49, p. 142):

$$Vcont_{i,j,k+1/2} = \frac{2}{\left(\frac{DELV_{i,j,k}}{KV_{i,j,k}}\right) + \left(\frac{DELV_{i,j,k+1}}{KV_{i,j,k+1}}\right)}, \quad (2)$$

where

$Vcont_{i,j,k+1/2}$ is the vertical conductance across the lower face of grid block; $i,j,k$, $DELV_{i,j,k}$, and $DELV_{i,j,k+1}$ are the thicknesses of the upper and lower grid blocks, respectively; and

$KV_{i,j,k}$ and $KV_{i,j,k+1}$ are the vertical hydraulic conductivities of the upper and lower grid blocks, respectively.

Vertical hydraulic conductivity was assumed to be uniform within each hydrologic unit. When an intermediate grid block in the model represented a hydrologic unit that is not physically present and the grid block was used to maintain vertical continuity in the flow equation, a vertical conductance of 1 was assigned for the lower face of the block.

### Calibration

The calibration of a numerical model of ground-water flow is a subjective process because the data upon which a model is based usually contain some errors of measurement, the model may be based on possible conceptual errors, and the results of a model may not be a unique solution to the ground-water flow equations. The model of the hydrologic system for this study was calibrated by adjusting selected aquifer properties within reasonable limits to simulate the measured water-level changes of the High Plains and the Dakota aquifers for January 1, 1975, through December 31, 1982. Calibrating the model using water-level data for the other hydrologic units was not possible because of the scarcity of reliable data. Prior to 1975 little data for the Dakota are available with which to calibrate the model.

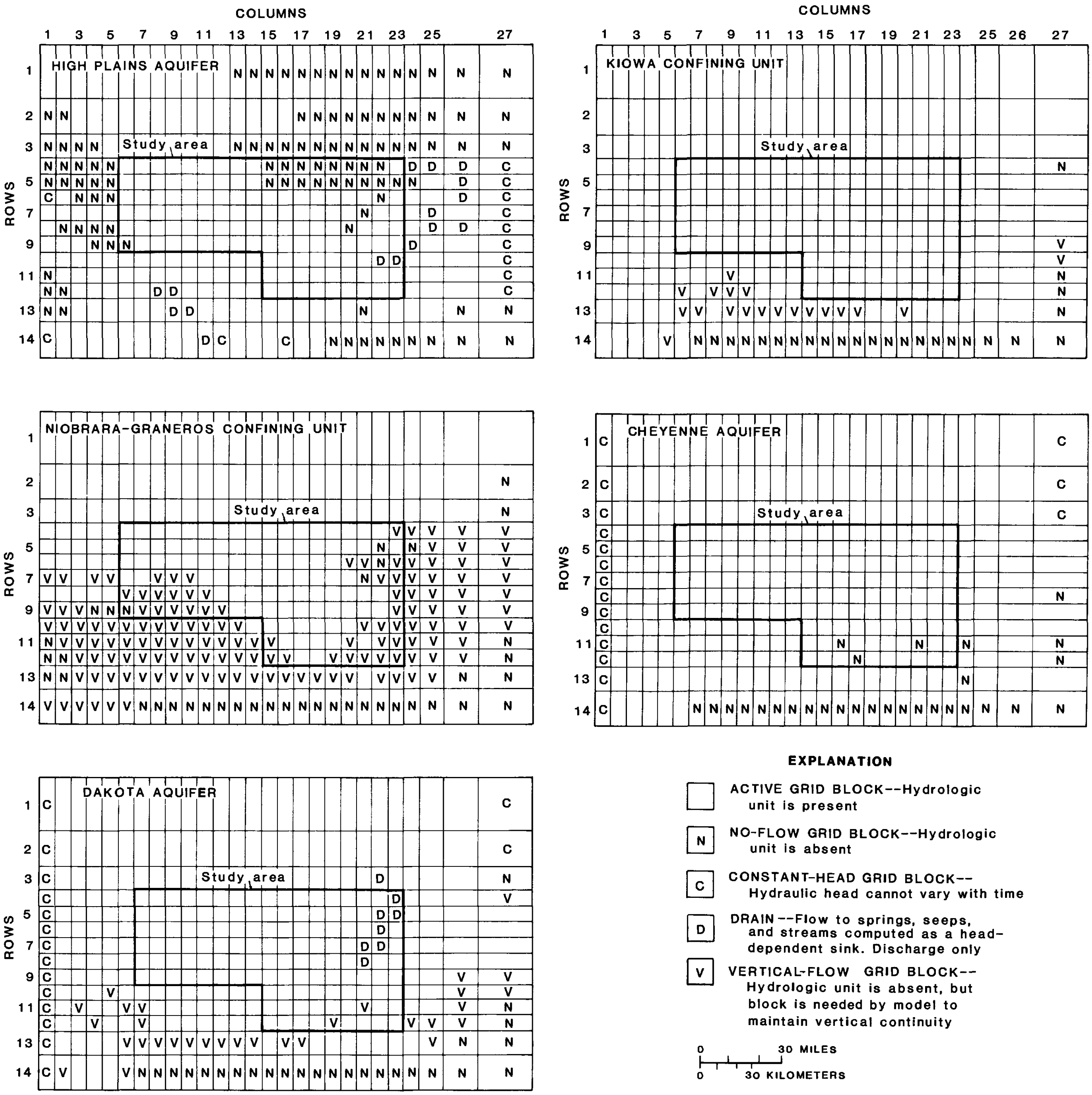



**Figure 18.** Model-area boundary conditions assumed for the High Plains aquifer, Niobrara-Graneros confining unit, Dakota aquifer, Kiowa confining unit, and Cheyenne aquifer.

The calibration criteria for the model were based on the ability of the model to simulate the potentiometric surfaces of the High Plains and Dakota aquifers at the end of the seventh year of the calibration period (December 31, 1981). The closeness of fit of the measured and simulated potentiometric surfaces of the High Plains aquifer and of the Dakota aquifer was evaluated using the average difference between measured and simulated hydraulic heads where the measured potentiometric surface of each aquifer was defined reasonably well. Because many more water levels were available for the High Plains aquifer than were available for the Dakota aquifer, the accuracy of the model was judged more on the simulated response of the High Plains aquifer. The average difference ($\overline{D}$) was calculated as:

$$\overline{D} = \sum_{i=1}^{n} (h_o - h_s)/n \ , \qquad (3)$$

where

$h_o$ is the measured hydraulic head for the area represented by grid block;
$h_s$ is the simulated hydraulic head at the grid block; and
$n$ is the total number of grid blocks with both $h_o$ and $h_s$.

### Stress Periods and Time Steps

The calibration period, 1975–82, was divided into 24 stress periods during which external stresses (pumpage and recharge) were assumed to be constant. Each year of the calibration period was divided into three stress periods for convenience of data input and model output. Stress periods 1, 4, 7, 10, 13, 16, 19, and 22 were divided into four equal time steps representing the months January through April during which water levels are fairly static; stress periods 2, 5, 8, 11, 14, 17, 20, and 23 were divided into five time steps representing the months May through September during which ground-water withdrawals and water-level drawdowns are greatest; and stress periods 3, 6, 9, 12, 15, 18, 21, and 24 were divided into three time steps representing the months October through December during which water levels begin recovery from the drawdowns of the irrigation season.

Irrigation pumpage from the High Plains aquifer and from the Dakota aquifer were simulated during the second stress period of each year. Nonirrigation pumpage from the High Plains aquifer was relatively insignificant, when compared with irrigation pumpage, and was not simulated in the model. Industrial pumpage from the Dakota aquifer was assumed to be constant during each year. Municipal pumpage from the Dakota aquifer during the second period of each year was assumed to be at three times the rate used for the first and third pumping periods, to reflect increased water use during summer months. Ground-water pumpage from the High Plains aquifer and the Dakota aquifer for 1982 (stress periods 22, 23, and 24), the last year of the calibration period, are shown in figure 19.

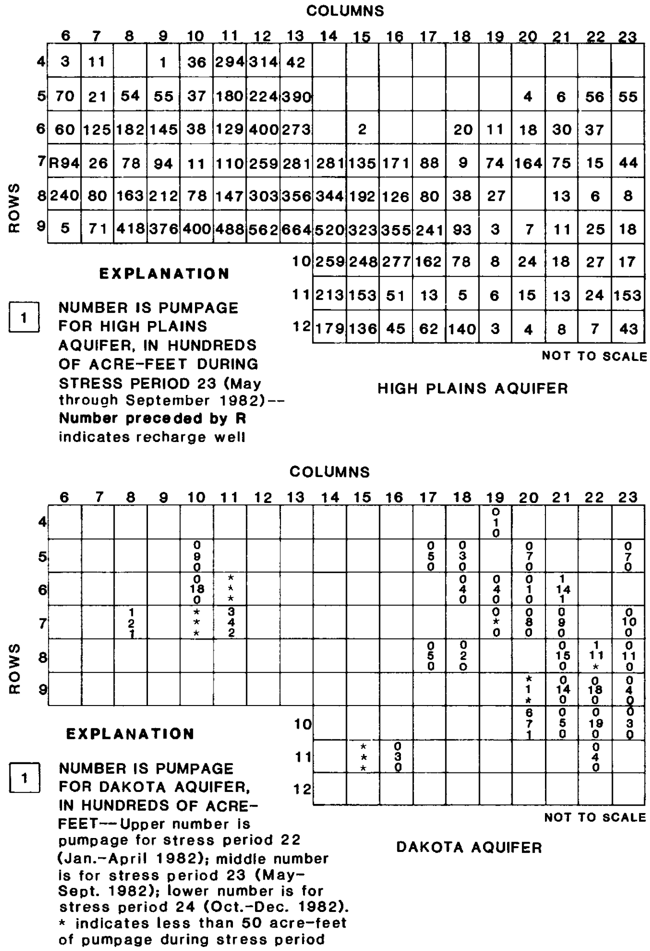
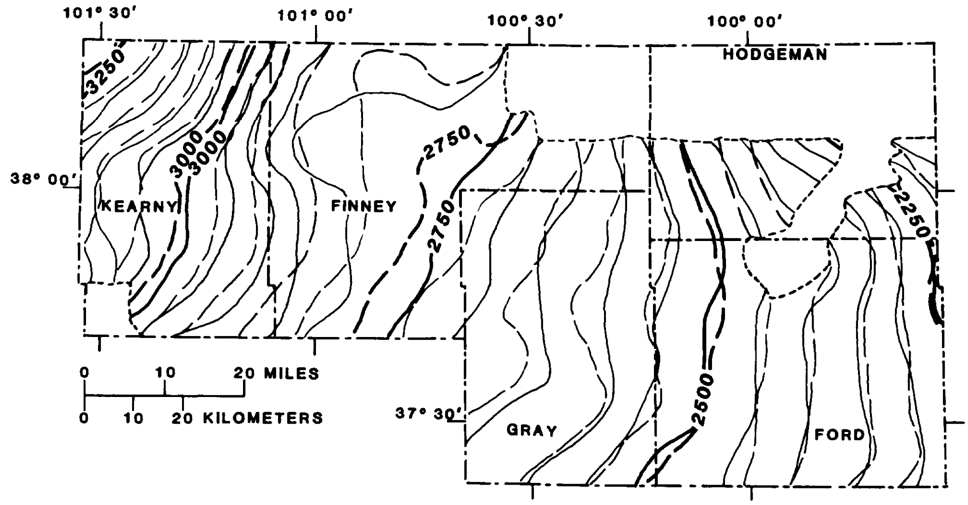



**Figure 19.** 1982 cumulative pumpage from the High Plains and Dakota aquifers in study area.

### Simulated Response

The measured (January 1982) and simulated (December 31, 1981) potentiometric surfaces in the High Plains aquifer (fig. 20) have an average difference of 1.04 ft in the study area. The standard deviation of the differences is about 17 ft. Greatest differences between the simulated and measured potentiometric surfaces occur in western Finney and eastern Kearny Counties. These differences result partially from treatment of the specific yield of the High Plains aquifer in this model as a constant value and from errors in the distribution of pumpage. Dunlap and others (1985), in a modeling study of the High Plains aquifer in parts of Finney and Kearny Counties, observed that the High Plains aquifer could be simulated as an upper unconfined aquifer, a semiconfining layer, and a deep semiconfined aquifer. Their model indicated that by December 31, 1980, the deep aquifer north of the Arkansas River had converted from semiconfined to unconfined conditions, and the specific yield had changed from a value of 0.01 to 0.18 (Dunlap and others, 1985, p. 38). Treatment of the High Plains aquifer in this investigation as a single-layered, unconfined aquifer results in some error during the period in which parts of the High Plains aquifer are semiconfined. However, on a regional basis, unconfined conditions will prevail as the High Plains aquifer is desaturated, and treatment of the aquifer as a single aquifer in this study is justified.

The differences between measured and simulated potentiometric surfaces for December 1981–January 1982 in the Dakota aquifer in the study area (fig. 21) have an average difference of −0.09 ft and a standard deviation



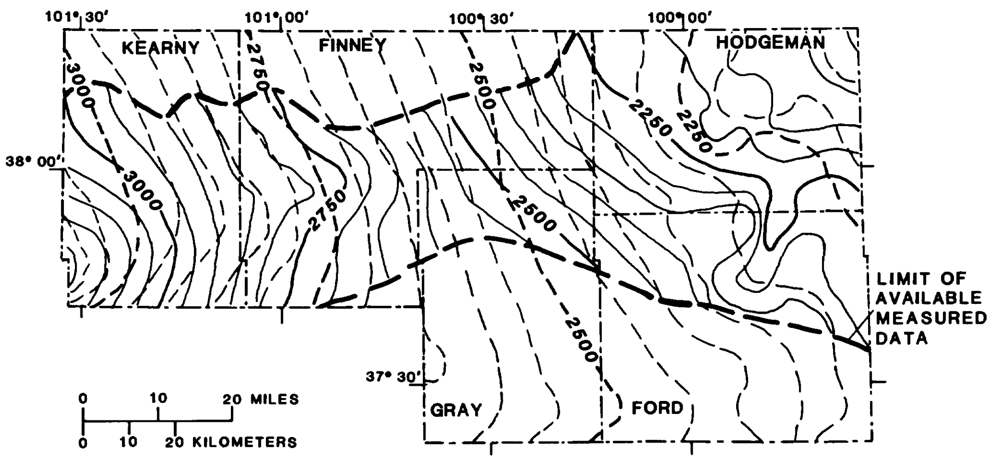

EXPLANATION

——2750—— MEASURED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, January 1982. Contour interval 50 feet. National Geodetic Vertical Datum of 1929

— —2750— — SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, December 31,1981. Contour interval 50 feet. National Geodetic Vertical Datum of 1929

---------- APPROXIMATE LIMIT OF HIGH PLAINS AQUIFER

**Figure 20.** Comparison of measured and simulated potentiometric surfaces in the High Plains aquifer, January 1982.




EXPLANATION

——2750—— MEASURED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, October 1981 to March 1982. Contour interval 50 feet. National Geodetic Vertical Datum of 1929

— —2750— — SIMULATED POTENTIOMETRIC CONTOUR -- Shows altitude at which water level would have stood in tightly cased wells, December 31, 1981. Contour interval 50 feet. National Geodetic Vertical Datum of 1929

**Figure 21.** Comparison of measured and simulated potentiometric surfaces in the Dakota aquifer, January 1982.

of differences of about 55 ft. The standard deviation of the differences for the Dakota aquifer's measured and simulated surfaces is about three times the standard deviation of the differences for the High Plains aquifer's measured and simulated surfaces. The differences between the measured and simulated potentiometric surfaces for the Dakota aquifer may result from errors in both the data used to prepare the map of the potentiometric surface and in hydrologic variables specified in the model.

### Water Budgets

The 1975–82 simulated water budget for the model area (table 7) shows the average rates of outflow and inflow and the change in storage of the aquifer system. Because outflow exceeded inflow, water levels declined and ground water was mined. The average 1975–82 rate of outflow from the aquifer system was about $3.2 \times 10^6$ acre-ft/yr. Inflow to the aquifer system was about $0.6 \times 10^6$ acre-ft/yr during the same period. Simulated decrease in storage was about $2.6 \times 10^6$ acre ft/yr in the model area.

Simulated water budgets of the aquifers modeled in this study are shown in table 8 for the year ending December 31, 1982. The water budgets include the rates of leakage between adjacent aquifers. As obvious from table 8, outflow from and decrease in storage in the High Plains aquifer dominate the water budgets of both the model and study areas. Although downward leakage was only a minor component of the water budget of the High Plains aquifer during 1982, it was a major source of inflow to the Dakota aquifer. A comparison of previous estimates of the Dakota water budget for the study area (table 5, and p. 23) and that simulated by the model for 1982 conditions indicates some discrepancies. Recharge to the Dakota from precipitation was not estimated, but the model simulated about 2,000 acre-ft recharge. Boundary inflow to the Dakota was estimated at about 6,000 acre-ft/yr and simulated at about 7,000 acre-ft/yr. Net leakage into the Dakota aquifer ("Lower Cretaceous rocks") from the High Plains aquifer was estimated previously at about 14,000 acre-ft/yr under steady-state conditions (Stullken and others, 1985) and simulated at about 24,000 acre-ft/yr under 1982 conditions. (These estimates are not strictly comparable because of the difference in size of the model areas and differences in boundary conditions.) Boundary outflow was estimated at 5,000 acre-ft/yr plus 1,100 acre-ft/yr of discharge to springs, seeps, and alluvial aquifers in Hodgeman and northern Ford County (Lobmeyer and Weakly, 1979, p. 20) and was simulated at 10,000 acre-ft/yr. Discharge to wells during 1982 was estimated at about 25,000 acre-ft (table 5) and simulated at 25,000 acre-ft. Leakage from the Dakota aquifer was not estimated but was simulated at a rate of about 3,000 acre-ft during 1982. The simulated water budgets for the Kiowa confining unit and the Cheyenne aquifer indicated fairly static conditions during 1982 and limited hydraulic interaction with overlying hydrologic units.

During 1982, leakage across the base of the High Plains aquifer in the modeled area (fig. 22) is simulated as predominately downward in areas where the Niobrara-Graneros confining unit is present and upward where the Dakota aquifer subcrops below the High Plains aquifer (fig. 8). Leakage from the High Plains aquifer and the Niobrara-Graneros confining unit into the the Dakota aquifer in the study area was the major source of recharge to the Dakota aquifer during 1982. Leakage from the Dakota aquifer into the High Plains aquifer occurs in parts of southern Finney and Kearny Counties and is insignificant in the 1982 simulated water budget of the High Plains aquifer (table 8). Simulated leakage into the Dakota aquifer from the Kiowa confining unit was insignificant.

**Table 7.** Simulated water budget of aquifer system in the model area, 1975–82

[Average annual values in thousands of acre-feet]

| | Inflow | Outflow | Difference (Inflow-Outflow) |
|---|---|---|---|
| Precipitation | 462 | --- | 462 |
| Boundary flow | 110 | 148 | -38 |
| Rivers and drains[1] | 3 | 54 | -51 |
| Wells | --- | 2,973 | -2,973 |
| Totals | 575 | 3,175 | -2,600 |
| Storage: | | | |
| Increase | | 517 | |
| Decrease | 3,120 | | |
| Net change | | | 2,603 |

[1]In the model, loss from the Arkansas River in Hamilton and Kearney Counties was simulated as recharge wells in the High Plains aquifer.

### Sensitivity Tests

Tests were performed during calibration of the model to identify the hydrologic variables to which the model is most sensitive. The effects of changing the value of a hydrologic variable on the average difference between measured and simulated hydraulic heads and on the standard deviations of the differences were used to evaluate the sensitivity of the model. The average difference and standard deviation of the differences should be zero when the simulated surface exactly matches the mapped surface. The differences of the measured and simulated surfaces were computed only for those grid blocks representing the High Plains and the Dakota aquifers where the measured potentiometric surfaces were well defined.

The results of selected sensitivity tests (table 9) indicate that simulated hydraulic heads of the High Plains and Dakota aquifers are most sensitive to changes in the specific yield of the High Plains aquifer. Increasing the specific yield of the High Plains aquifer from 0.18 to 0.27 resulted in increases in the average difference of the hydraulic heads of the High Plains aquifer from 1.0 to -3.5 ft and in the average difference of the hydraulic heads in the Dakota aquifer from -0.1 to -2.4 ft.

**Table 8.** Simulated 1982 water budgets of the layered aquifer system
[Values in hundreds of thousands of acre-feet]

| | Model area | | | Study area | | |
|---|---|---|---|---|---|---|
| | Inflow | | Outflow | Inflow | | Outflow |
| *High Plains aquifer* | | | | | | |
| Precipitation | 3.6 | | --- | 1.3 | | --- |
| Lateral boundaries and drains | 0.5 | | 1.1 | 0.1 | | 0.7 |
| Wells[1] | .1 | | 37.7 | .1 | | 14.2 |
| Leakage across base | .3 | | .6 | 0 | | .2 |
| Totals | 4.5 | | 39.4 | 1.5 | | 15.1 |
| Decrease of water in storage | | 34.6 | | | 13.7 | |
| *Niobrara-Graneros confining unit* | | | | | | |
| Precipitation | 0.9 | | --- | 0.1 | | --- |
| Leakage across base | .3 | | 0.8 | 0 | | 0.2 |
| Leakage across top | .6 | | .3 | .2 | | 0 |
| Totals | 1.8 | | 1.1 | .3 | | .2 |
| Increase of water in storage | | 0.7 | | | 0.1 | |
| *Dakota aquifer* | | | | | | |
| Precipitation | 0.1 | | --- | 0 | | --- |
| Lateral boundaries and drains | .1 | | 0.3 | 0.1 | | 0.1 |
| Wells | 0 | | .3 | 0 | | .3 |
| Leakage across base | .1 | | 0 | 0 | | 0 |
| Leakage across top | .8 | | .3 | .2 | | 0 |
| Totals | 1.1 | | .9 | .3 | | .4 |
| Increase of water in storage | | 0.2 | | | --- | |
| Decrease of water in storage | | --- | | | 0.1 | |
| *Kiowa confining unit* | | | | | | |
| Precipitation | 0.1 | | --- | 0 | | --- |
| Leakage across base | .1 | | 0.1 | 0 | | 0 |
| Leakage across top | 0 | | .1 | 0 | | 0 |
| Totals | .2 | | .2 | 0 | | 0 |
| Change in storage | | 0 | | | 0 | |
| *Cheyenne aquifer* | | | | | | |
| Lateral boundaries and and drains | 0.2 | | 0 | 0.1 | | 0 |
| Leakage across top | 0 | | 0.1 | 0 | | 0 |
| Totals | .2 | | .1 | .1 | | 0 |
| Increase of water in storage | | .1 | | | 0 | |

[1]Inflow to the High Plains aquifer from the Arkansas River was simulated as recharge wells so that recharge rates could be based on gaged streamflows.

Decreasing the specific yield of the High Plains aquifer from 0.18 to 0.09 resulted in average declines in the average difference for the High Plains aquifer from 1.0 to 13.5 ft and for the Dakota aquifer from -0.1 to 6.1 ft. The sensitivity of the simulated hydraulic heads in the Dakota aquifer to changes in specific yield of the High Plains aquifer results from changes in the magnitude and direction of leakage in response to declining hydraulic heads in the High Plains aquifer. The High Plains aquifer, as simulated, was insensitive to changes in horizontal and vertical hydraulic conductivity within the ranges tested. The Dakota aquifer was slightly sensitive to changes in the vertical hydraulic conductivity of the Niobrara-Graneros confining unit and to changes in the horizontal hydraulic conductivity, specific storage, and specific yield of the Dakota aquifer.

During calibration of the model, the values of some hydrologic variables were changed within limits to

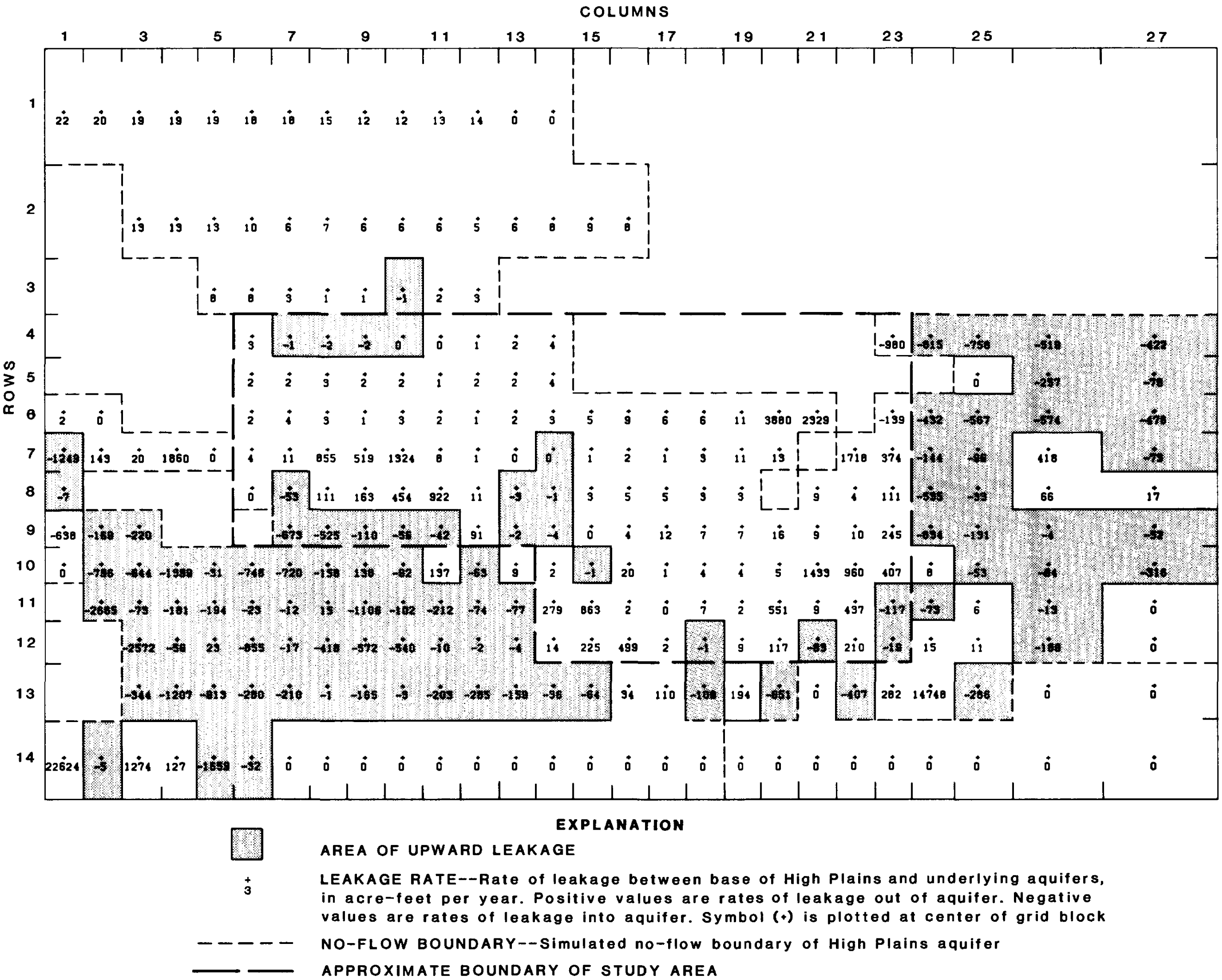



**Figure 22.** Simulated leakage between High Plains and underlying aquifers, 1982.

improve the fit of the simulated hydraulic heads with measured potentiometric levels. The specific storage of the Niobrara-Graneros confining unit was decreased from $1 \times 10^{-5}$ to $1 \times 10^{-6}$ ft$^{-1}$ and the vertical hydraulic conductivity from $1 \times 10^{-5}$ to $1 \times 10^{-6}$ ft/d. Specific storage of the Dakota aquifer was decreased from $3 \times 10^{-6}$ to $1.5 \times 10^{-6}$ ft$^{-1}$, vertical hydraulic conductivity from $1 \times 10^{-1}$ to $1 \times 10^{-2}$ ft/d, and specific yield was increased from 0.07 to 0.105. The specific storage of the Kiowa confining unit was decreased from $5 \times 10^{-5}$ to $1 \times 10^{-6}$ ft$^{-1}$ and the vertical hydraulic conductivity from $1.3 \times 10^{-6}$ to $1 \times 10^{-6}$ ft/d. Many of the hydrologic variables used in the model have not been verified with measured data and are considered to be rough estimates.

## Potential Effects of Pumpage from Dakota Aquifer

The calibrated model was used to evaluate the potential effects of pumpage from the Dakota aquifer on the potentiometric surfaces of the High Plains and Dakota aquifers. Nine projection simulations were made using 1982 rates of pumpage from the High Plains aquifer and various rates and distributions of pumpage from the Dakota aquifer. Pumpage from the Dakota aquifer for the projection simulations was based on eight sets of hypothetical ground-water management guidelines for development of the Dakota aquifer as provided by the staff of Groundwater Management District No. 3 and from a baseline projection showing continuation of pumpage from the Dakota aquifer at 1982 rates (approximately 25,000 acre-ft/yr).

The criteria used in the development of the hypothetical rates of pumpage from the Dakota aquifer and the simulated rates of pumpage at the end of the simulations are given in table 10. The estimated 1982 pumpage from the Dakota aquifer, shown in table 5 as 24,900 acre-ft, is less than the rate shown in table 10. The difference resulted from rounding errors introduced during

**Table 9.** Summary of selected sensitivity tests

| Aquifer and hydrologic characteristic varied | Hydrologic value simulated | Percent change[1] | Resulting changes: Average difference (feet)[2] | Standard deviation (feet)[3] | Average difference (feet)[2] | Standard deviation (feet)[3] |
|---|---|---|---|---|---|---|
| *High Plains aquifer* | | | *High Plains aquifer* | | *Dakota aquifer* | |
| Specific yield | 0.27 | +50 | -3.5 | 15.8 | -2.4 | 53.1 |
| (dimensionless) | .225 | +25 | -1.7 | 16.2 | -1.2 | 53.6 |
| | .18 | 0 | 1.0 | 17.0 | -0.1 | 54.7 |
| | .135 | -25 | 5.3 | 18.8 | 1.9 | 55.6 |
| | .09 | -50 | 13.5 | 23.7 | 6.1 | 60.0 |
| Horizontal | 120 | +50 | 1.0 | 17.6 | -0.1 | 54.1 |
| hydraulic | 80 | 0 | 1.0 | 17.0 | -0.1 | 54.7 |
| conductivity | 40 | -50 | 0.8 | 16.4 | -0.7 | 54.8 |
| (feet per day) | | | | | | |
| Vertical | 1.5 | +50 | 1.0 | 17.0 | -0.1 | 54.7 |
| hydraulic | 1.0 | 0 | 1.0 | 17.0 | -0.1 | 54.7 |
| conductivity | .5 | -50 | 1.0 | 17.0 | -0.1 | 54.7 |
| (feet per day) | | | | | | |
| *Niobrara-Graneros confining unit* | | | | | | |
| Vertical | .0000015 | +50 | 1.0 | 17.0 | -1.2 | 55.3 |
| hydraulic | .000001 | 0 | 1.0 | 17.0 | -0.1 | 54.7 |
| conductivity | .0000005 | -50 | 1.0 | 17.0 | 0.9 | 54.1 |
| (feet per day) | | | | | | |
| *Dakota aquifer* | | | | | | |
| Specific yield | .14 | +33 | 1.0 | 17.0 | -1.8 | 54.9 |
| (dimensionless) | .105 | 0 | 1.0 | 17.0 | -0.1 | 54.7 |
| | .07 | -33 | 1.0 | 17.1 | -1.8 | 54.9 |
| Specific | .0000075 | +50 | 1.0 | 17.0 | -1.1 | 56.4 |
| storage | .000015 | 0 | 1.0 | 17.0 | -0.1 | 54.7 |
| (per foot) | .0000225 | -50 | 1.0 | 17.0 | -1.1 | 54.3 |
| Horizontal | 10.5 | +50 | 1.0 | 17.1 | -0.8 | 55.0 |
| hydraulic | 7.0 | 0 | 1.0 | 17.0 | -0.1 | 54.7 |
| conductivity | 3.5 | -50 | 1.1 | 17.0 | -1.4 | 56.2 |
| (feet per day) | | | | | | |

[1]Percentage change from calibrated value.
[2]Average difference between simulated hydraulic heads for test and for calibrated model.
[3]Standard deviation of the differences between simulated hydraulic heads for test and for calibrated model.

distribution of the simulated pumpage. The guidelines specify the maximum annual rate of withdrawal from each well in the Dakota aquifer, the minimum distances between wells in the Dakota aquifer, and the minimum distance from the well to the area of Dakota aquifer subcrop.

The guidelines specified in table 10 for cases 1 and 4, 2 and 5, and 3 and 6 differed only in the method in which pumpage was implemented. In cases 1, 2, and 3, the maximum rates of withdrawal were begun at the beginning of the projection simulation. In cases 4, 5, and 6, the pumpage rates were assumed to increase by 5 percent/yr during the projection period to attain the maximum rates applied in cases 1, 2, and 3.

The guidelines (table 10) were used in conjunction with the pre-Tertiary geology map (fig. 4) and the 1982 distribution of pumpage from the Dakota aquifer to determine the projected maximum rates of pumpage from the Dakota aquifer for each grid block in the study area. The distribution and rates of pumpage from the Dakota aquifer for the management projections are illustrated in figure 23. The distribution of pumpage from the High Plains and Dakota aquifers for the baseline projection are the same as those shown in figure 19.

All projections were simulated for a 20-yr period. The projection period was divided into 20 stress periods, each representing 1 yr, and each stress period was subdivided into 12 time steps of 30.4 days each. The use of time steps of this duration may result in slight rounding errors. Pumpage was assumed to be uniform within each stress period. The simulated hydraulic heads of each hydrologic unit at the end of the calibration period

**Table 10.** Hypothetical management guidelines and simulated initial and final pumping rates from the Dakota aquifer

| Simulation number or name | Minimum distance of well to Dakota subcrop (miles) | Minimum distance between Dakota wells (miles) | Maximum pumping rate (acre-feet per year per well) | Initial pumping rate during projection year 1 (thousands of acre-feet) | Final pumping rate during projection year 20 (thousands of acre-feet) |
|---|---|---|---|---|---|
| Baseline[1] | -- | -- | --- | 25 | 25 |
| Case 1 | 5 | 2 | 300 | 191 | 191 |
| Case 2 | 2 | 1 | 100 | 294 | 294 |
| Case 3 | 5 | 2 | 300 | 241 | 241 |
| | 2 | 1 | 100 | | |
| [2]Case 4 | 5 | 2 | 300 | 33 | 191 |
| [2]Case 5 | 2 | 1 | 100 | 38 | 294 |
| [2]Case 6 | 5 | 2 | 300 | 36 | 241 |
| | 2 | 1 | 100 | | |
| [2]Case 7 | 5 | 4 | 300 | 28 | 78 |
| Case 8 | 10 | 2 | 300 | 138 | 138 |

[1]Continuation at estimated 1982 pumping rates for the 20-year projection period.

[2]Pumpage rates were incrementally increased from the estimated 1982 pumping rate (about 25,000 acre-feet) to attain the maximum pumping rates in year 20 of the projection period.

(December 31, 1982) were used as starting heads for all the projection simulations. Other hydrologic variables specified in the calibrated model were unchanged in the projection simulations. The simulated response of the hydraulic heads of the High Plains and Dakota aquifers in the study area to the projected rates of pumpage from the Dakota aquifer were subtracted from the simulated response of these surfaces from the baseline projection to determine the average difference for each of the eight projection simulations.

### Response of High Plains Aquifer

The response of the hydraulic heads of the High Plains aquifer to the projected rates of simulated pumpage from the Dakota aquifer was relatively insignificant when compared with changes caused by pumpage from the High Plains aquifer. The mean difference of the simulated hydraulic heads of the High Plains aquifer for the management projections from the hydraulic heads simulated for the baseline projection (table 11) ranged from 0.67 ft for case 7 to 1.17 ft for case 2 at the end of the 20-yr projections.

Continuation of 1982 rates of pumpage from the High Plains aquifer during the projection simulations resulted in numerous grid blocks representing the High Plains aquifer going dry. No attempt was made to reduce the simulated pumpage rates from the High Plains aquifer during the projection simulations.

### Response of Dakota Aquifer

The average difference of the simulated hydraulic heads in the Dakota aquifer at the end of the projection simulations from the baseline projection (table 11) ranged from 92.95 ft for case 7 to 137.12 ft for case 2. By the end of the projection periods, many of the grid blocks in the model that represent the Dakota aquifer had converted from confined to unconfined conditions.

The ratio of leakage into the Dakota aquifer and net change in storage of the aquifer to the net pumpage from the Dakota at the end of the projection period are illustrated in figure 24. At the end of the 20-yr baseline projection, about 81 percent of the water pumped from the Dakota aquifer was derived from leakage and about 19 percent from decrease in storage in the Dakota aquifer. As the simulated rate of pumpage from the Dakota aquifer increases, the proportion of the pumpage derived from change in storage in the Dakota aquifer increases, while that proportion derived from leakage decreases.

### Response of Cheyenne Aquifer

The average simulated drawdown in the Cheyenne aquifer at the end of case 2 (the worst case) was about 8 ft lower than hydraulic heads simulated for the baseline projection. Because calibrating the model for the Cheyenne aquifer was not possible, the actual response of the

COLUMNS

| ROWS | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 24 | | |
| 5 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 33 | | | 13 |
| 6 | 27 | 9 | 9 | 9 | 38 | 16 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 21 | 24 | | |
| 7 | | | 5 | | | 8 | 9 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 15 | 13 | | 18 |
| 8 | | | | | | | | 15 | 27 | 27 | | | 18 | 27 | 9 | 18 | 22 | 11 |
| 9 | | | | | | | | | 12 | 12 | | | | | 4 | 27 | 32 | 8 |
| 10 | | | | | | | | | | | | | 12 | | 27 | 11 | 54 | 9 |
| 11 | | | | | | | | | | 1 | 6 | 24 | 21 | | | | 1 | |
| 12 | | | | | | | | | | | | | | | | | | |

NOT TO SCALE

CASES 1 AND 4

COLUMNS

| ROWS | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 6 | | |
| 5 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 33 | | | 13 |
| 6 | 6 | 3 | 3 | 3 | 38 | 5 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 5 | 24 | | |
| 7 | | | 5 | | | 8 | 5 | 7 | 7 | 7 | 7 | 7 | 7 | 10 | 8 | 13 | | 18 |
| 8 | | | | | | | | 4 | 7 | 7 | | | 5 | 7 | 3 | 18 | 22 | 11 |
| 9 | | | | | | | | | 3 | 3 | | | | | 4 | 27 | 32 | 8 |
| 10 | | | | | | | | | | | | | 3 | | 27 | 11 | 54 | 9 |
| 11 | | | | | | | | | | 1 | 3 | 6 | 5 | | | | 1 | |
| 12 | | | | | | | | | | | | | | | | | | |

NOT TO SCALE

CASE 7

COLUMNS

| ROWS | 8 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 13 | |
| 5 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 24 | | 13 |
| 6 | 36 | 27 | 20 | 20 | 38 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 24 | | |
| 7 | 25 | 8 | 5 | | | 12 | 33 | 36 | 36 | 36 | 36 | 36 | 36 | 36 | 30 | 13 | | 18 |
| 8 | | | | | | | 5 | 33 | 36 | 36 | 24 | 19 | 35 | 36 | 20 | 18 | 22 | 11 |
| 9 | | | | | | | | 7 | 33 | 34 | 4 | | 26 | 19 | 16 | 27 | 32 | 8 |
| 10 | | | | | | | | | 3 | 5 | 2 | 18 | 35 | 20 | 27 | 10 | 54 | 9 |
| 11 | | | | | | | | | | 6 | 36 | 36 | 35 | 22 | | | 1 | |
| 12 | | | | | | | | | | | 11 | 12 | 5 | | | | | |

NOT TO SCALE

CASES 2 AND 5

COLUMNS

| ROWS | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 12 | | | |
| 5 | 21 | 12 | 9 | 9 | 9 | 18 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 33 | | | 13 |
| 6 | 3 | | | | 36 | 3 | 12 | 24 | 27 | 27 | 27 | 27 | 27 | 24 | 1 | 24 | | |
| 7 | | | 5 | | | 8 | 5 | 6 | 24 | 18 | | | 15 | 18 | 8 | 13 | | 18 |
| 8 | | | | | | | | | 9 | | | | 5 | 5 | | 18 | 22 | 11 |
| 9 | | | | | | | | | | | | | | | 4 | 27 | 32 | 8 |
| 10 | | | | | | | | | | | | | | | 27 | 11 | 54 | 9 |
| 11 | | | | | | | | | | 1 | 3 | | | | | | 1 | |
| 12 | | | | | | | | | | | | | | | | | | |

NOT TO SCALE

CASE 8

COLUMNS

| ROWS | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 26 | 13 | |
| 5 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 33 | 24 | | 13 |
| 6 | 28 | 24 | 17 | 17 | 38 | 18 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 29 | 24 | | |
| 7 | 25 | 8 | 5 | | | 12 | 30 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 25 | 13 | | 18 |
| 8 | | | | | | | 5 | 28 | 27 | 27 | 24 | 20 | 29 | 27 | 17 | 18 | 22 | 11 |
| 9 | | | | | | | | 7 | 29 | 30 | 4 | | 26 | 20 | 16 | 27 | 32 | 8 |
| 10 | | | | | | | | | 3 | 5 | 2 | 18 | 31 | 20 | 27 | 10 | 54 | 9 |
| 11 | | | | | | | | | | 6 | 34 | 28 | 28 | 22 | | | 1 | |
| 12 | | | | | | | | | | | 11 | 12 | 5 | | | | | |

NOT TO SCALE

CASES 3 AND 6

EXPLANATION

27 — ANNUAL PUMPAGE RATE, IN HUNDRED ACRE-FEET, AT THE END OF THE PROJECTION PERIOD

**Figure 23.** Projected rates of pumpage from the Dakota aquifer in study area.

Cheyenne aquifer to stress on the aquifer system cannot be predicted.

## SUMMARY AND CONCLUSIONS

The High Plains aquifer is the major source of water in most of Finney, Ford, Gray, Hodgeman, and Kearny Counties in southwestern Kansas. However, in parts of the study area, these unconsolidated deposits are absent or thinly saturated, and the Dakota and Cheyenne aquifers are the potential sources of water supply.

The aquifer system underlying the 5,000-mi$^2$ study area includes three aquifers and two confining units and overlies Permian rocks that contain mineralized water. The hydraulic conductivity of the High Plains aquifer ranges from 80-800 ft/d; specific yield is 0.18. Locally, water in the lower part of the aquifer is under semiconfined conditions. About 5,400 irrigation wells pumped an estimated $8.8 \times 10^6$ acre-ft of water from the aquifer during 1975–82.

Underlying the High Plains aquifer are Upper and Lower Cretaceous rocks. The Upper Cretaceous rocks consist of chalk, limestone, and shale and are a

**Table 11.** Average difference between simulated hydraulic heads in the High Plains and Dakota aquifers at end of projection simulations and baseline projection

| Case | *High Plains aquifer* Average difference (feet)[1] | *Dakota aquifer* Average difference (feet)[1] |
|---|---|---|
| 1 | 0.87 | 124.30 |
| 2 | 1.17 | 137.12 |
| 3 | 1.14 | 133.15 |
| 4 | .76 | 119.02 |
| 5 | .91 | 129.59 |
| 6 | .88 | 127.13 |
| 7 | .67 | 92.95 |
| 8 | .69 | 110.30 |

[1]The average difference is the mean of the differences between the simulated hydraulic heads from the baseline projection with those from the hypothetical cases (cases 1-8) for grid blocks in the study area.

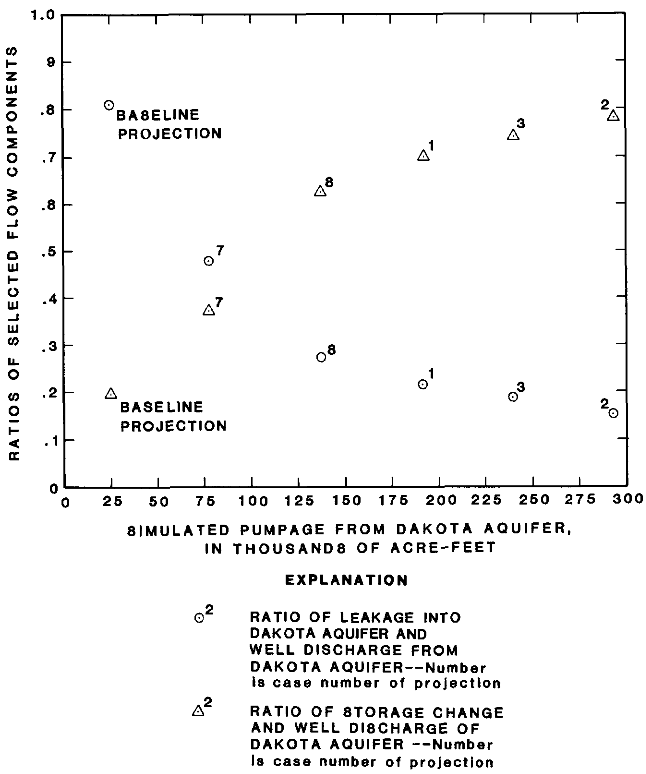



**Figure 24.** Relation between ratios of selected flow components of the Dakota aquifer and net pumpage.

confining unit (Niobrara-Graneros confining unit). Maximum thickness of the Niobrara-Graneros confining unit in the study area is about 725 ft in northeastern Finney County. The vertical hydraulic conductivity of the Niobrara-Graneros confining unit from the transient-model calibration is $1 \times 10^{-6}$ ft/d, and the specific storage is $1 \times 10^{-6}$ ft$^{-1}$. In some places post-Cretaceous erosion has removed the Niobrara-Graneros confining unit.

Locally, the Dakota aquifer provides the major supply of water. Thickness of the Dakota aquifer is as much as 400 ft. Transmissivity of the Dakota aquifer ranges from 100-7,100 ft$^2$/d, and the storage coefficient is about $2 \times 10^{-4}$. By the end of 1984, 137 large-capacity wells had been completed in the Dakota aquifer in the study area. Total pumpage from the Dakota aquifer during 1975-82 is an estimated $1.6 \times 10^{-5}$ acre-ft. The Dakota aquifer overlies the Lower Cretaceous Kiowa Shale, a confining unit that is as much as 300 ft thick in the study area.

Underlying the Kiowa Shale is the Lower Cretaceous Cheyenne Sandstone and undifferentiated Middle and Upper Jurassic rocks (Cheyenne aquifer). Locally, the Cheyenne aquifer has a maximum thickness of more than 300 ft. Water in the Cheyenne aquifer may be mineralized as a result of the aquifer's contact with Permian rocks, which contain mineralized water. No large-capacity wells are completed in the Cheyenne aquifer in the study area.

Water in the Dakota aquifer in subcrop areas is a calcium bicarbonate type water with dissolved-solids concentrations of less than 500 mg/L, and in areas distant from the subcrop, a sodium bicarbonate type water with dissolved-solids concentrations in excess of 500 mg/L. In some parts of the study area, water in the Dakota aquifer, when used for irrigation, has a high to very high salinity hazard and a high to very high sodium hazard to crops and soil. In 16 of 81 samples, dissolved nitrate in water from the Dakota aquifer exceeded the recommended maximum contaminant level established by the U.S. Environmental Protection Agency (1976; 1979). High nitrate levels may indicate pollution of water by animal and human wastes or fertilizer.

Hydrographs of wells completed in the Dakota aquifer show a rapid decline in water levels during the mid-1970's but a varied response during the late-1970's and early 1980's. In some areas, water levels in the Dakota aquifer have declined below the base of the Niobrara-Graneros confining unit, and the aquifer is under unconfined conditions. Water levels in the Dakota aquifer respond to pumping of wells completed in the High Plains aquifer in areas near the subcrop.

A transient model was calibrated to simulate the aquifer system that included the High Plains aquifer, the Niobrara-Graneros confining unit, the Dakota aquifer, the Kiowa confining unit, and the Cheyenne aquifer. The simulated 1982 water budget (table 8) showed that inflow to the High Plains aquifer in the study area was from the following sources:

1. precipitation ($1.3 \times 10^5$ acre-ft),
2. flow from the High Plains aquifer outside the study area ($8.0 \times 10^3$ acre-ft),

3. leakage from underlying aquifers to the High Plains aquifer ($3 \times 10^3$ acre-ft), and
4. streamflow loss and reduction of ground-water discharge by use of surface water (approximately $1.2 \times 10^4$ acre-ft).

Outflow from the High Plains aquifer was to the following sinks:

1. wells ($1.4 \times 10^6$ acre-ft),
2. flow to the High Plains aquifer outside the study area and discharge to streams ($6.8 \times 10^4$ acre-ft), and
3. leakage from the High Plains aquifer to underlying aquifers ($2.1 \times 10^4$ acre-ft).

Decrease of water in storage in the High Plains aquifer in the study area was about $1.4 \times 10^6$ acre-ft during 1982.

The simulated 1982 water budget (table 8) showed that inflow to the Dakota aquifer in the study area was from the following sources:

1. leakage from adjacent aquifers to the Dakota aquifer ($2.5 \times 10^4$ acre-ft),
2. flow from the Dakota aquifer outside the study area ($6 \times 10^3$ acre-ft), and
3. precipitation ($2 \times 10^3$ acre-ft).

Outflow from the Dakota aquifer was to the following sinks:

1. wells ($2.5 \times 10^4$ acre-ft),
2. flow to the Dakota aquifer outside the study area and to springs and seeps ($1.0 \times 10^4$ acre-ft), and
3. leakage from the Dakota aquifer to adjacent aquifers ($3 \times 10^3$ acre-ft).

Decrease of water in storage in the Dakota aquifer in the study area was about $5 \times 10^3$ acre-ft during 1982.

Sensitivity tests conducted during calibration of the model indicated that the simulated potentiometric surface of the High Plains aquifer was most sensitive to changes in the specific yield of the High Plains aquifer. The sensitivity tests also showed that the Dakota aquifer was more sensitive to changes in the specific yield of the High Plains aquifer than to changes in the hydrologic variables of the Dakota aquifer.

Model projections were made for a 20-yr period using 1982 simulated hydraulic heads from the calibrated model, pumpage from the High Plains aquifer at 1982 rates, and variable pumping rates from the Dakota aquifer, based on eight hypothetical management guidelines in which pumping varied from about 78,000 to more than 290,000 acre-ft/yr. The projection simulations showed that at the end of the 20-yr period:

1. average drawdowns of the High Plains aquifer, attributable to pumpage from the Dakota aquifer, range from 0.67–1.17 ft;
2. numerous grid blocks representing the High Plains aquifer would go dry if 1982 rates of withdrawal from the High Plains aquifer continue;
3. average drawdown in the Dakota aquifer ranges from 92.95–137.12 ft;
4. much of the Dakota aquifer will convert from a confined to an unconfined aquifer; and
5. as pumpage from the Dakota aquifer increases, the proportion of water derived from changes in storage in the Dakota aquifer increases in relation to that derived from leakage from the overlying aquifers.

Development of the Dakota aquifer as simulated in the projections did not significantly affect the High Plains aquifer but did result in significant declines in the potentiometric surface of the Dakota aquifer and its conversion to an unconfined aquifer in most of the study area.

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