HYDROLOGY OF THE GREAT PLAINS AQUIFER SYSTEM IN NEBRASKA, COLORADO, KANSAS, AND ADJACENT AREAS

REGIONAL AQUIFER-SYSTEM ANALYSIS

U. S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1414–E

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that are listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" are no longer available.

Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Map Distribution
Box 25286, MS 306, Federal Center
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, DC 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Map Distribution
Box 25286, Bldg. 810, Federal Center
Denver, CO 80225

Residents of Alaska may order maps from

U.S. Geological Survey, Earth Science Information Center
101 Twelfth Ave., Box 12
Fairbanks, AK 99701

OVER THE COUNTER

Books and Maps

Books and maps of the U.S. Geological Survey are available over the counter at the following U.S. Geological Survey offices, all of which are authorized agents of the Superintendent of Documents.

- **ANCHORAGE, Alaska**—4230 University Dr., Rm. 101
- **LAKEWOOD, Colorado**—Federal Center, Bldg. 810
- **MENLO PARK, California**—Bldg. 3, Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**—National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**—Federal Bldg., Rm. 8105, 125 South State St.
- **SPOKANE, Washington**—U.S. Post Office Bldg., Rm. 135, W. 904 Riverside Ave.
- **WASHINGTON, D.C.**—Main Interior Bldg., Rm. 2650, 18th and C Sts., NW.

Maps Only

Maps may be purchased over the counter at the U.S. Geological Survey offices:

- **FAIRBANKS, Alaska**—New Federal Building, 101 Twelfth Ave.
- **ROLLA, Missouri**—1400 Independence Rd.
- **STENNIS SPACE CENTER, Mississippi**—Bldg. 3101

Hydrology of the Great Plains Aquifer System in Nebraska, Colorado, Kansas, and Adjacent Areas

By JOHN O. HELGESEN, ROBERT B. LEONARD, *and* RONALD J. WOLF

REGIONAL AQUIFER-SYSTEM ANALYSIS—CENTRAL MIDWEST

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1414-E

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1993

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY

Robert M. Hirsch, *Acting Director*

Library of Congress Cataloging in Publication Data

Helgesen, John O.
Hydrology of the Great Plains aquifer system in Nebraska, Colorado, Kansas, and adjacent areas / by John O. Helgesen, Robert B. Leonard, and Ronald J. Wolf.
p. cm. — (Regional aquifer-system analysis—Central Midwest) (U.S. Geological Survey professional paper ; 1414–E)
Includes bibliographical references.
Supt. of Docs. no.: I 19.16:1414-E
1. High Plains Aquifer. 2. n-uss. I. Leonard, Robert B. II. Wolf, R. J. III. Title. IV. Series. V. Series: U.S. Geological Survey professional paper ; 1414–E.
GB1199.3.H53H45 1993 93-3584
551.49'0978—dc20 CIP

For sale by Book and Open-File Report Sales, U.S. Geological Survey
Federal Center, Box 25286, Denver, CO 80225

FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Robert M. Hirsch

Robert M. Hirsch
Acting Director

CONTENTS

ILLUSTRATIONS

[Plates are in separate volume]

TABLES

CONVERSION FACTORS AND ABBREVIATIONS

Multiply inch pound unit	By	To obtain metric units
inch (in.)	25.4	milimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.028317	cubic meter per second (m^3/s)

For temperature, degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) by using the formula °C=0.5556 (°F −32).

SEA LEVEL

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

SYMBOLS USED IN THIS REPORT

Symbol	Dimensions (l, distance; f, force; t, time; m, mass)	Explanation
A	l^2	Cross-sectional area flow.
C	([1])	Ratio dependent on nature of aquifer material.
E_k	fl^{-2}	Bulk modulus of elasticity of solid skeleton of aquifer.
Ew	fl^{-2}	Bulk modulus of elasticity of water.
K	lt^{-1}	Hydraulic conductivity.
K'	lt^{-1}	Vertical hydraulic conductivity.
K'_l	lt^{-1}	Vertical hydraulic conductivity of lower geohydrologic unit.
K'_u	lt^{-1}	Vertical hydraulic conductivity of upper geohydrologic unit.
K_{xx}	lt^{-1}	Hydraulic-conductivity tensor.
K_{yy}	lt^{-1}	Hydraulic-conductivity tensor.
K_{zz}	lt^{-1}	Hydraulic-conductivity tensor.
M_{og}	m	Mass of oil and gas.
N	([1])	Number of grid cells.
Q	l^3t^{-1}	Recharge rate.
S_s	l^{-1}	Specific storage.
SD	l	Standard deviation.
V_{eq}	l^3	Equivalent volume of water.
V_s	l^3	Volume of gas.
V_o	l^3	Volume of oil.
VC	t^{-1}	Vertical cnductance (leakance).
W	t^{-1}	Volumetric flow per unit volume.
X_n	l	Absolute deviation at grid cell n.
$\overline{X}$	l	Mean deviation.
b	l	Confining-unit thickness.
b_l	l	Thickness of lower geohydrologic unit.
b_u	l	Thickness of upper geohydrologic unit.
d_g	ml^{-3}	Density of gas.
dh/dl	([1])	Hydraulic gradient.
d_o	ml^{-3}	Density of oil.
d_w	ml^{-3}	Density of water.
g	lt^{-2}	Acceleration of gravity.
h	l	Potentiometric head.
k	l^{-2}	Intrinsic permeability.
m	([1])	Cementation factor.
n	([1])	Porosity.
t	t	Time.
x	l	Cartesian coordinate.
y	l	Cartesian coordinate.
z	l	Cartesian coordinate.
γ_w	fl^{-3}	Specific weight of water.
ρ	ml^{-3}	Fluid density.
μ	$ml^{-1}t^{-1}$	Dynamic viscosity.
ΣX_n	l	Sum of absolute deviations.

[1]Dimensionless.

HYDROLOGY OF THE GREAT PLAINS AQUIFER SYSTEM IN NEBRASKA, COLORADO, KANSAS, AND ADJACENT AREAS

By John O. Helgesen, Robert B. Leonard, and Ronald J. Wolf

ABSTRACT

The Great Plains aquifer system extends throughout much of the midcontinent region and varies considerably in lithology, depth of occurrence, hydraulic properties, and resources development. The regional hydrology of the aquifer system is described in this report for a 170,000-square-mile area of the central Midwest United States. The aquifer system consists of the Apishapa aquifer (Cheyenne Sandstone and equivalents), Apishapa confining unit (Kiowa Shale and equivalents), and Maha aquifer (Dakota Sandstone and equivalents). Development of the system includes freshwater withdrawal from depths of less than 1,000 feet and oil and gas withdrawal from depths exceeding 3,000 feet.

Strata composing the aquifer system are mainly sandstone, siltstone, and shale. Total thickness generally ranges from 200 to 800 feet and is greatest in north-central Nebraska. Local stratigraphy is typically complex, reflecting a Cretaceous depositional environment that fluctuated between nearshore marine and nonmarine. Late Cretaceous and early Tertiary tectonic activity caused structural deformation in the western half of the study area, forming the asymmetric Denver and Raton basins. Faults form part of an abrupt western boundary to the system.

Hydraulic properties are spatially variable and dependent regionally on depth of burial. Porosity, hydraulic conductivity, and volumetric flow rates generally decrease from eastern and southern outcrop areas toward the western basins. Hydraulic-head distribution indicates a general west-to-east gradient of regional flow. The aquifer system is mostly confined but generally is underpressured (small confined heads). Recharge from the west is restricted, and transmissivity increases eastward toward discharge areas, allowing water to move laterally at a more rapid rate in the east than in the west. Flow is virtually stagnant in the Denver basin, where small hydraulic conductivity is reflected by very irregular hydraulic-head and water-quality conditions.

The distribution of dissolved solids in the aquifer system appears to be related mainly to environment of deposition, with limited modification by later introduction of meteoric water. Water in much of the aquifer system is brackish (1,000 to 10,000 milligrams per liter dissolved solids). The formation of the Denver and Raton basins, associated faulting, and resulting structural attitude of the region apparently has restricted recharge and prevented complete flushing of original formation water from the aquifer system.

A four-layer computer model was used to evaluate the flow system for both predevelopment and development conditions. Predevelopment recharge to the system primarily occurred as leakage through overlying units and direct infiltration at outcrop areas. Major recharge areas are in the southwestern and northwestern parts of the study area. Most discharge was leakage to overlying units; lesser amounts of discharge occurred as seepage to streams at outcrop areas or as leakage to underlying units. Simulations indicate that the predevelopment steady-state flow through the regional system was about 340 cubic feet per second, approximately 60 percent of which was interchange with the High Plains aquifer where that aquifer directly overlies the Great Plains aquifer system. The model was calibrated to assumed predevelopment heads, discharge to streams, and head declines in response to oil, gas, and water withdrawals. Declines in hydraulic head are inferred to have been several hundreds of feet where oil and gas development has been intensive and several tens of feet in response to the most intensive freshwater withdrawals. Model-calculated hydraulic heads are most sensitive to lateral hydraulic conductivity and recharge at outcrop areas, particularly in the areas of small hydraulic conductivity in the western basins.

Recent (1970–79) pumpage rates are more than twice the recharge rate of 340 cubic feet per second. Although a significant part of pumpage is derived from intercepted or induced vertical leakage, equilibration in response to pumping is generally slow and storage-depletion effects can be significant. However, the aquifer system is capable of providing substantial amounts of water for years or decades if some storage depletion is tolerated. Sustained water-yielding potential is greatest where flow can be induced directly from the overlying High Plains aquifer.

Effective hydraulic confinement and very small flow rates within much of the aquifer system may lend feasibility for liquid-waste disposal. However, careful studies must be made before any disposal practice. Also, the depth of the aquifer system and insulating effect of the overlying confining system afford potential for development of low-temperature geothermal energy in the northwestern half of the study area.

INTRODUCTION

The investigation of the Great Plains aquifer system is part of the Central Midwest Regional Aquifer-System Analysis (CMRASA). The CMRASA project area (fig. 1) encompasses more than 370,000 square miles in the central United States and includes strata from the Dakota Sandstone and equivalents down to the Precambrian basement. Younger strata, including the High Plains aquifer, which overlies most of the western half of the CMRASA project area are not included in this study.

Objectives of the CMRASA (Jorgensen and Signor, 1981) are as follows:

1. Describe the hydrologic system, including delineation of aquifers and confining units and evaluation of hydraulic characteristics and quality of water.
2. Create a region-wide data base consisting of selective data on water use, water levels, lithologic logs, geophysical logs, chemical analyses of water samples, and related data.
3. Describe historical, present, and future problems associated with the use of water.
4. Evaluate the aquifer or aquifer-system response to future conditions.

The extent of the Great Plains aquifer system (fig. 1) encompasses about 170,000 square miles. This aquifer system is the uppermost geohydrologic unit within the CMRASA study interval (table 1) and consists mostly of Lower Cretaceous clastic sedimentary rocks, stratigraphically equivalent to the Dakota Sandstone, Kiowa Shale, and Cheyenne Sandstone. These rock units extend beyond the study area across much of the central United States and Canada (fig. 2). The term "Great Plains aquifer system" logically applies to the entire extent of these water-bearing strata, which generally coincides with the physiographic Great Plains of North America. The system exhibits a wide range in hydraulic properties and in properties of fluids contained within it. This aquifer

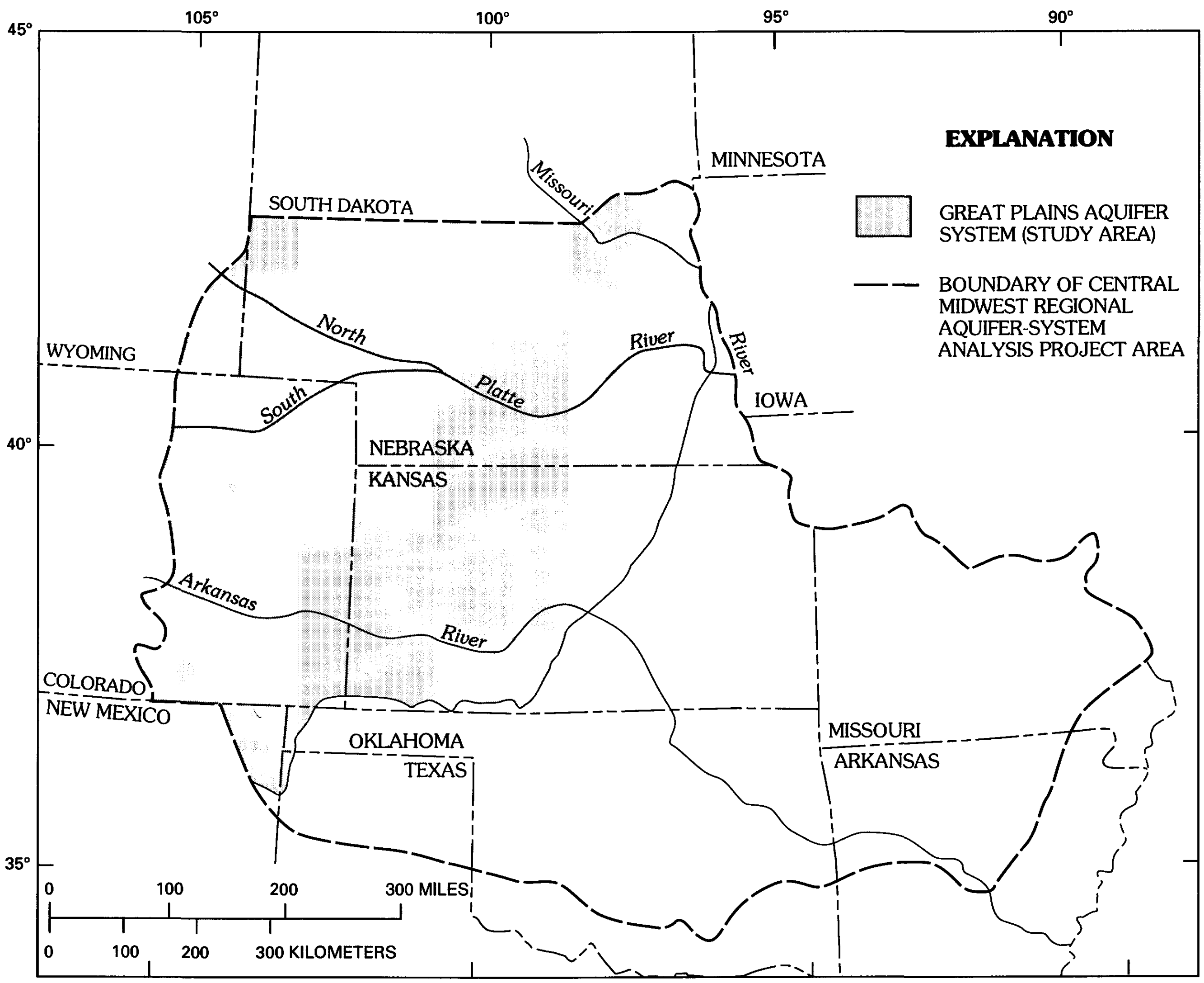


Figure 1.—Location and extent of Great Plains aquifer system within Central Midwest Regional Aquifer-System Analysis (CMRASA) project area.

TABLE 1.—*Regional geohydrologic units and generalized geologic time scale*

		GEOHYDROLOGIC UNITS		GEOLOGIC TIME SCALE
		High Plains aquifer	unnamed	CENOZOIC Quaternary Tertiary
		Great Plains confining system		MESOZOIC Cretaceous
Central Midwest Regional Aquifer-System Analysis study interval	Interval described in this report	Great Plains aquifer system		
		Western Interior Plains confining system		Jurassic Triassic PALEOZOIC Permian Pennsylvanian Mississippian
		Western Interior Plains aquifer system		Devonian Silurian Ordovician Cambrian
		Basement confining unit		PRECAMBRIAN

system has long been recognized (Darton, 1905; Meinzer, 1923; Russell, 1928) as one of the largest artesian reservoirs in the world. Within the Midwestern United States, the system has been an important source of water in parts of southern Colorado, southwestern and central Kansas, northwestern Iowa, and eastern Nebraska and South Dakota. The system is becoming more important as a potential source of water supplies as shallower sources of ground water are depleted in response to drought or sustained withdrawals. Deep parts of the system also have been an important source of oil and gas in northeastern Colorado and southwestern Nebraska. Understanding the regional hydrology is important for evaluating activities of development of the aquifer system.

The terminology used to designate subsurface hydrologic units, such as "aquifer systems" and "confining system," is discussed by Jorgensen and others (1992). An aquifer system consists of two or more aquifers in the same hydraulic system, which are separated at most locations by one or more confining units. A confining system contains two or more confining units separated at most locations by one or more aquifers that are not in the same hydraulic system.

PURPOSE AND SCOPE

The findings of the CMRASA project are reported in five chapters of Professional Paper 1414: chapter A is the summary chapter, which collates the important findings reported in other chapters; chapter B describes the geohydrologic framework; chapter C describes modeling analysis of the regional aquifer systems; chapter D describes the geohydrologic and ground-water-flow analysis of the Ozark Plateaus aquifer system; and chapter E (this report) describes the geohydrologic and flow analysis of the Great Plains aquifer system.

The purpose of this report (chapter E) is to provide hydrologic information and interpretations of the Great Plains aquifer system. The study is regional in scope; therefore, results may not be appropriate for local evaluations.

PHYSICAL SETTING OF STUDY AREA

The study area lies within the Interior Plains physiographic division of the United States (fig. 3). It is mainly within the Great Plains province; a small part of the study area (eastern Nebraska and southeastern South Dakota) is in the Central Lowland province.

Land-surface altitude (fig. 4) ranges from about 1,000 feet above sea level at the east-central edge of Nebraska to as much as 10,000 feet along the western margin of the study area. Regional surface-water drainage is eastward (fig. 4). Most of the study area is drained by tributaries of the Missouri River, whereas the southern quarter of the area forms part of the Arkansas River basin. The low surface is generally flat to moderately rolling. However, local relief of a few hundred feet has developed along some streams and in the foothills of the Rocky Mountains along the western margin of the area.

Mean annual precipitation ranges from about 28 inches in the east to less than 12 inches in the west (fig. 5). Natural vegetation is mainly grass; forested

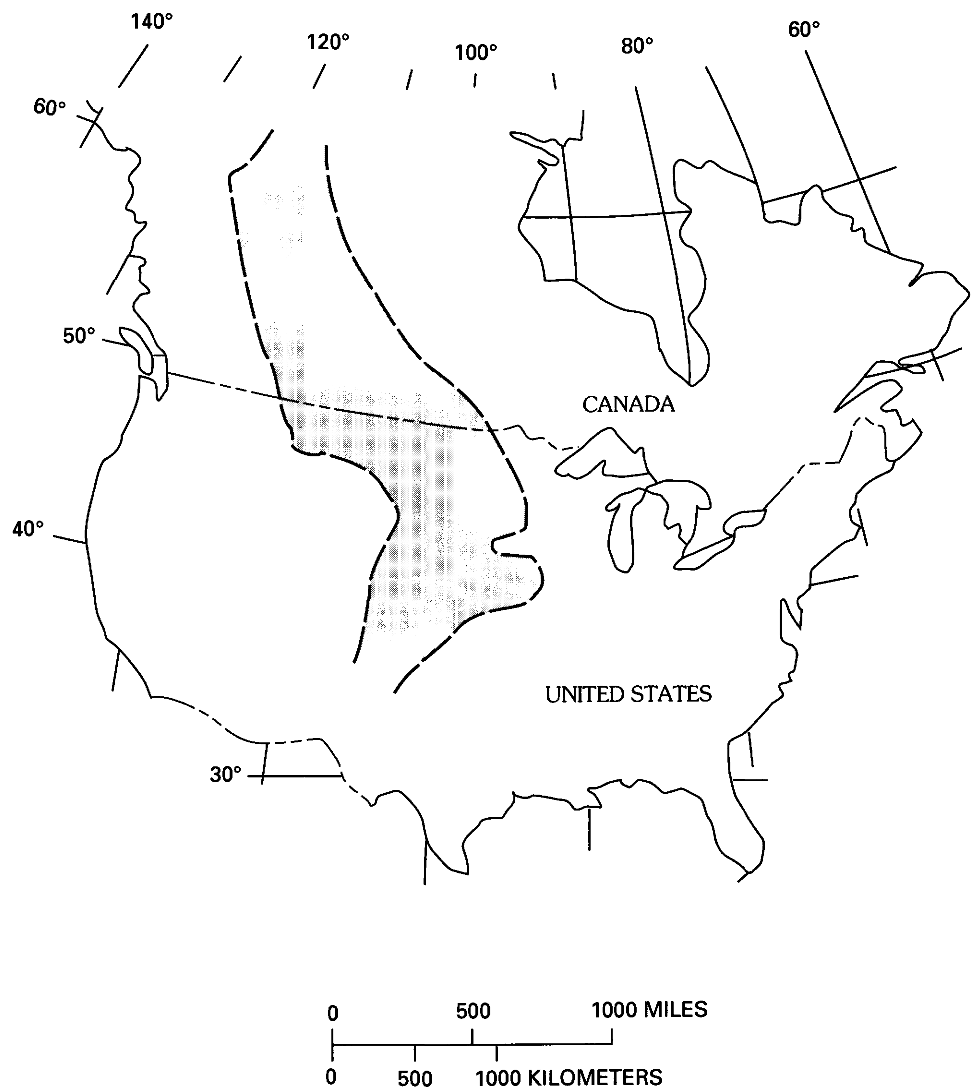


FIGURE 2.—Areal extent of Great Plains aquifer system (shaded area) in North America.

areas are concentrated along major streams. Land is used predominantly for growing crops or grazing. Agriculture is the main economic activity.

Strata of Cenozoic age cover approximately three-fourths of the study area, and underlying Mesozoic and Paleozoic rocks extend across the entire area (figs. 6, 7). As for structural features (fig. 8), uplifts of the Rocky Mountain system occur to the west. Large-offset faults form an abrupt boundary along much of the western boundary of the study area. Asymmetric structural basins (Denver and Raton) occur immediately adjacent to the uplifts. Structural disruption in the remainder of the study area is relatively minor; faulting and folding are local, and most strata east of the Denver and Raton basins are flat-lying.

The Great Plains aquifer system is exposed along small parts of the eastern, southern, and western margins of the study area (fig. 9). Elsewhere, it is buried by younger strata to depths of several thousand feet in the Denver and Raton basins (figs. 9, 10). A prominent surficial feature over much of the study area is the High Plains aquifer, which principally

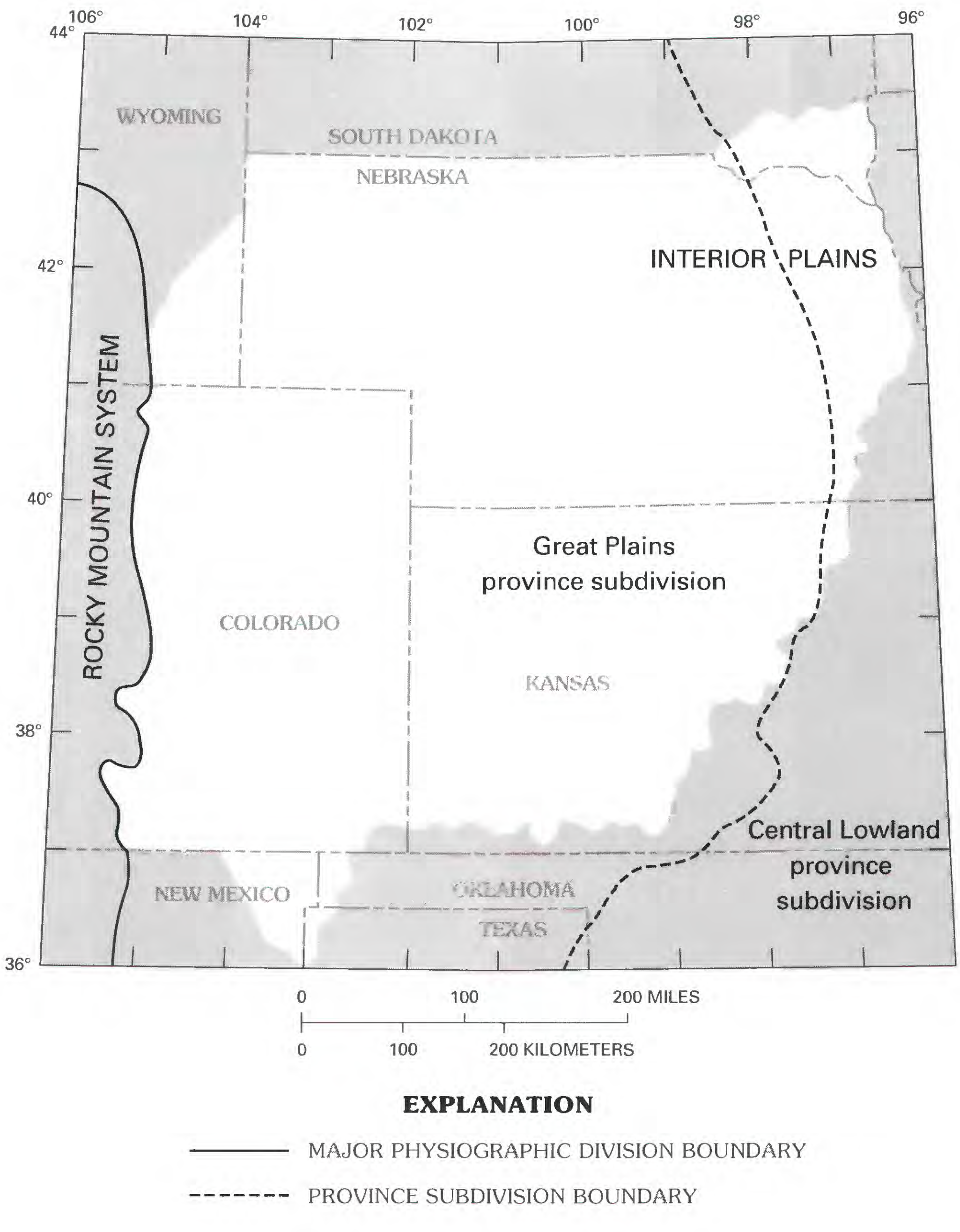


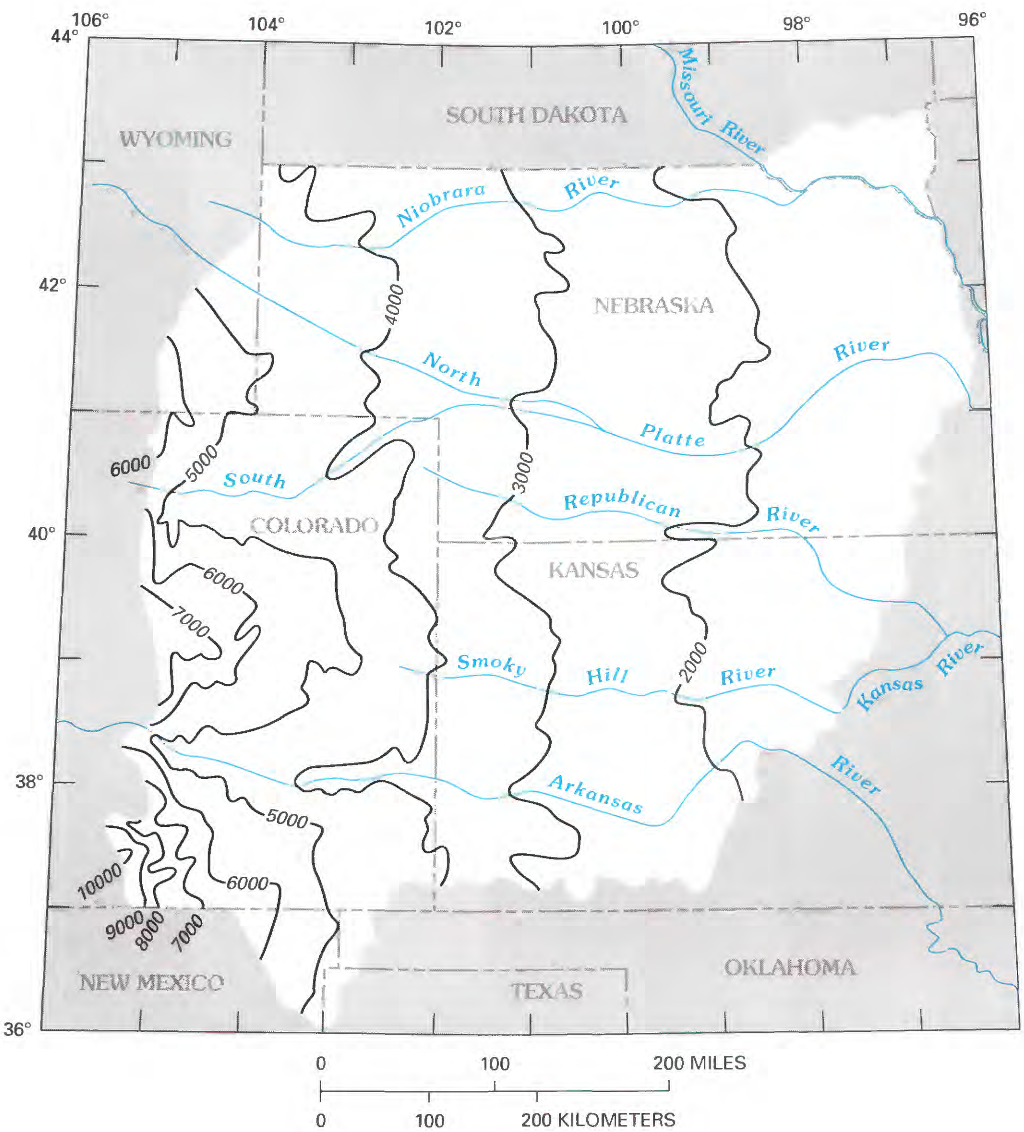
FIGURE 3.—Physiographic divisions of and adjacent to study area (Fenneman, 1946).

consists of stream-laid deposits of Cenozoic age and which yields large quantities of water. Where the High Plains aquifer yields sufficient amounts of water, there is little exploration for deeper sources of ground water. Consequently, lack of data over a large part of the study area has hindered evaluation of the Great Plains aquifer system.

The southeastern boundary of the study area, extending from east-central Nebraska to New Mexico, coincides with the limit of the Great Plains aquifer system. The remainder of the study-area boundary coincides with the CMRASA project boundary. The Great Plains aquifer system extends beyond the study area in several places (fig. 1): northeastern New Mexico, east-central Wyoming, all of southern South Dakota except the extreme eastern part, and northwestern Iowa.

PREVIOUS INVESTIGATIONS

The Dakota Sandstone and related sandstone have been of scientific and practical interest for more than



EXPLANATION

—*3000*— TOPOGRAPHIC CONTOUR—Shows altitude of land surface. Interval 1000 feet. Datum is sea level

FIGURE 4.—Altitude of land surface and location of major rivers.

a century. Much of the special attention arises from the water-yielding capability of these sandstones, particularly in parts of eastern North and South Dakota where flowing wells are common. Their significance as a source of water prompted many studies, which have been of great value to the current investigation. Most previous workers have referred to these rock units as the "Dakota aquifer," even though studies in different areas were not necessarily of the same stratigraphic unit. The name "Great Plains aquifer system" is derived from Fenneman's (1946) Great Plains province and is used in this report and related chapters of Professional Paper 1414 as a regional aquifer name to encompass the sandstone-shale sequence. Despite its internal complexity, the sequence is regionally distinct from overlying and underlying units.

Nearly all available geologic and hydrologic information in the study area describes either the shallowest areas of the aquifer system or the deep areas (Denver basin) that have been explored for oil and gas. In a large intermediate area that includes central Nebraska and northwestern Kansas, data pertaining to the Great Plains aquifer system are sparse.

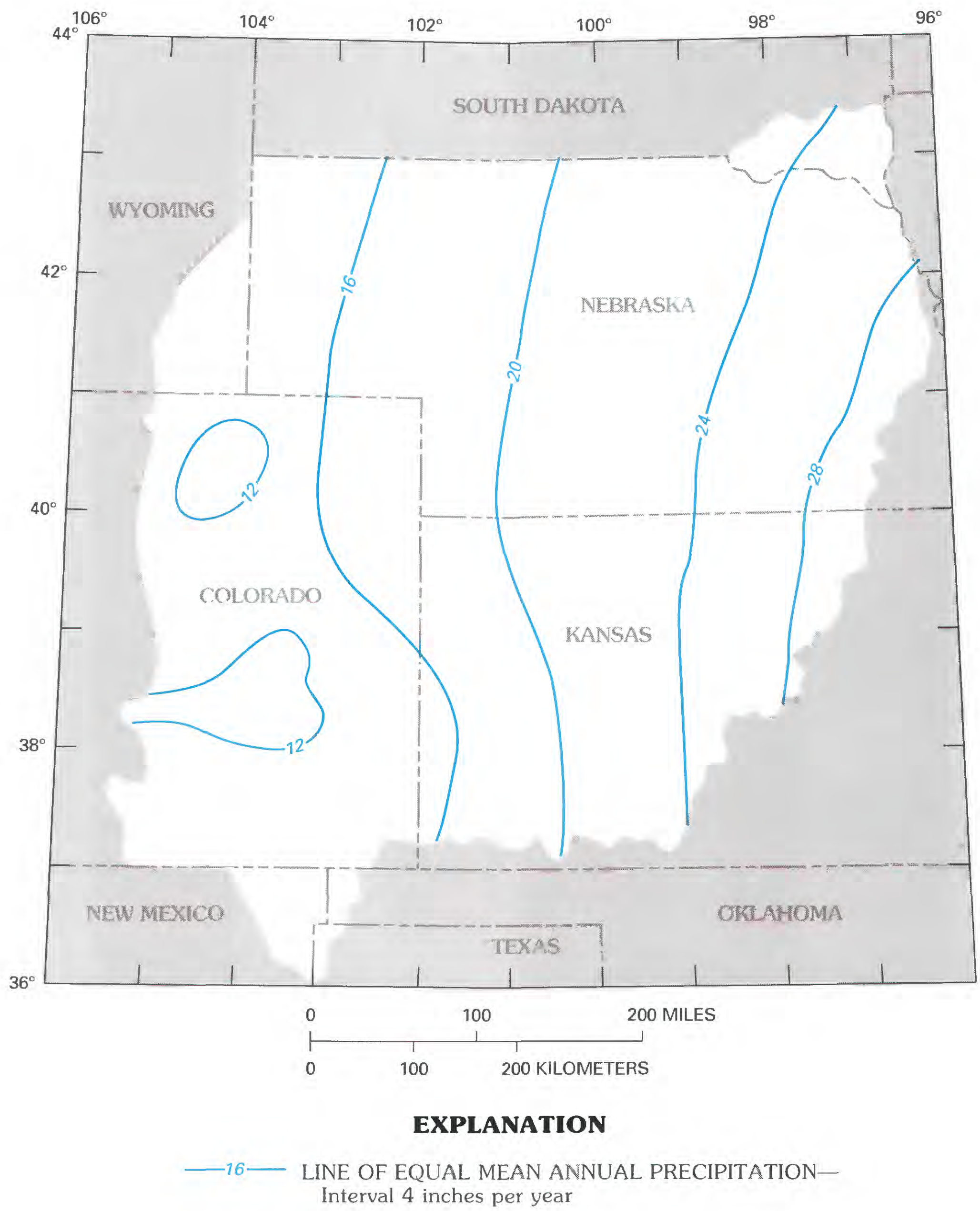


FIGURE 5.—Mean annual precipitation, 1951–80 (Hedman and Engel, 1989).

There are many published reports pertaining to the aquifer system. However, only relevant studies within or directly adjacent to the present study area are mentioned in the following paragraphs. Numerous studies of county-wide or more local scale are not cited. Moreover, extensive literature pertaining to geology, mainly originating within the petroleum industry, is not cited.

Pioneering studies of the aquifer system were made by Darton (1896, 1905, 1909, 1918). Darton (1905) described the "Dakota water horizon" as "the most widely extended and most useful in the Great Plains region." He offered his classic interpretation of easterly regional water movement through these strata. Darton also recognized an unknown rate of vertical leakage through the confining layers. The concept of simple artesian circulation as the primary mechanism operating within the system later came into question. Meinzer and Hard (1925) and Meinzer (1928) discussed the concept of volume elasticity

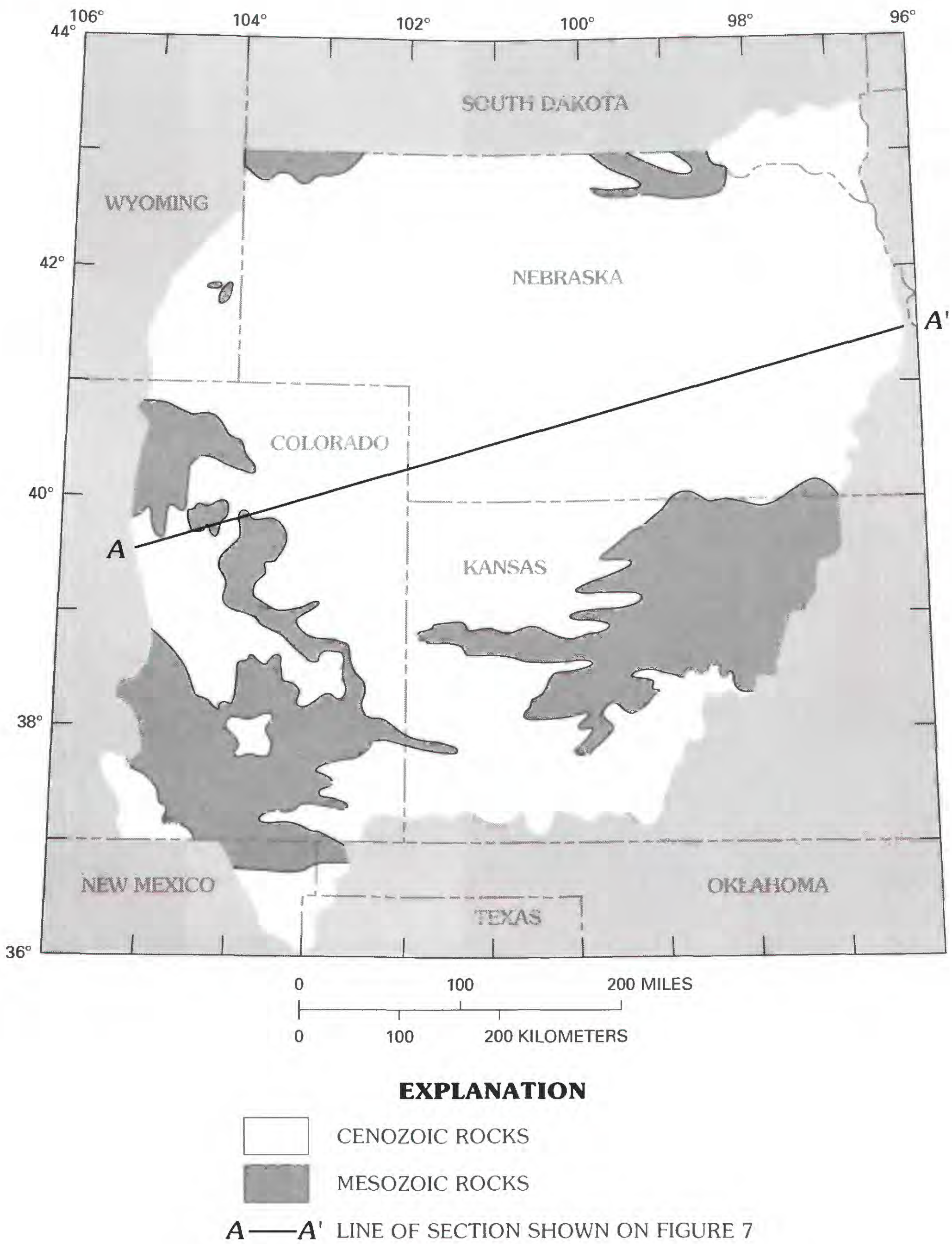


FIGURE 6.—Surficial distribution of major time-stratigraphic units.

whereby the aquifer undergoes compression to replace the volume of stored water that is discharged through wells. Russell (1928) submitted that lenticularity and other stratigraphic complexities prevent regional hydraulic continuity within the system. He described artesian pressure as developing from compaction of overlying sediments and attributed hydraulic-head variations to tilting of the strata. The "Dakota" thus became a focus for examination of some basic hydrologic concepts. Subsequent ideas of several investigators were concisely summarized by Bredehoeft and others (1983). The stratigraphic complexities of the Great Plains aquifer system have discouraged a conclusive, comprehensive interpretation of its regional hydrology (Helgesen and others, 1982; Leonard and others, 1983). At the same time, valid concepts within the interpretations of all investigators have contributed toward analysis of the system and appreciation for its obscurities.

Descriptive overviews of the aquifer system in various States in the study area were provided by Ellis (1984), McGovern (1984), Pearl (1984), and Stone (1984). Additional descriptions on a statewide or multicounty scale were presented by Keene and Bayne (1977), Gutentag and others (1981), Dealy and others (1984), Lawton and others (1984), Robson and Banta (1987), Watts (1989), and Geldon (1989). Water movement in the Denver basin has been of notable interest (Hubbert, 1953; Russell, 1961; Hoeger, 1968; Gibbons and Self, 1978; Ottman, 1984; Belitz, 1985; Robson and Banta, 1987).

Numerous studies have emphasized the hydrologic or hydrochemical significance of the interchange of water between the aquifer system and vertically adjacent rock units (Russell, 1961; Dyer and Goehring, 1965; Swenson, 1968; Schoon, 1971; Miller and Rahn, 1974; Keene and Bayne, 1977; Milly, 1978; Bredehoeft and others, 1983; Kolm and Peter, 1984, Neuzil and others, 1984; Belitz, 1985; Watts, 1989). Estimates of the flow and water budget of parts of the aquifer system using computer models have improved in recent years. Results of pertinent large-scale flow modeling

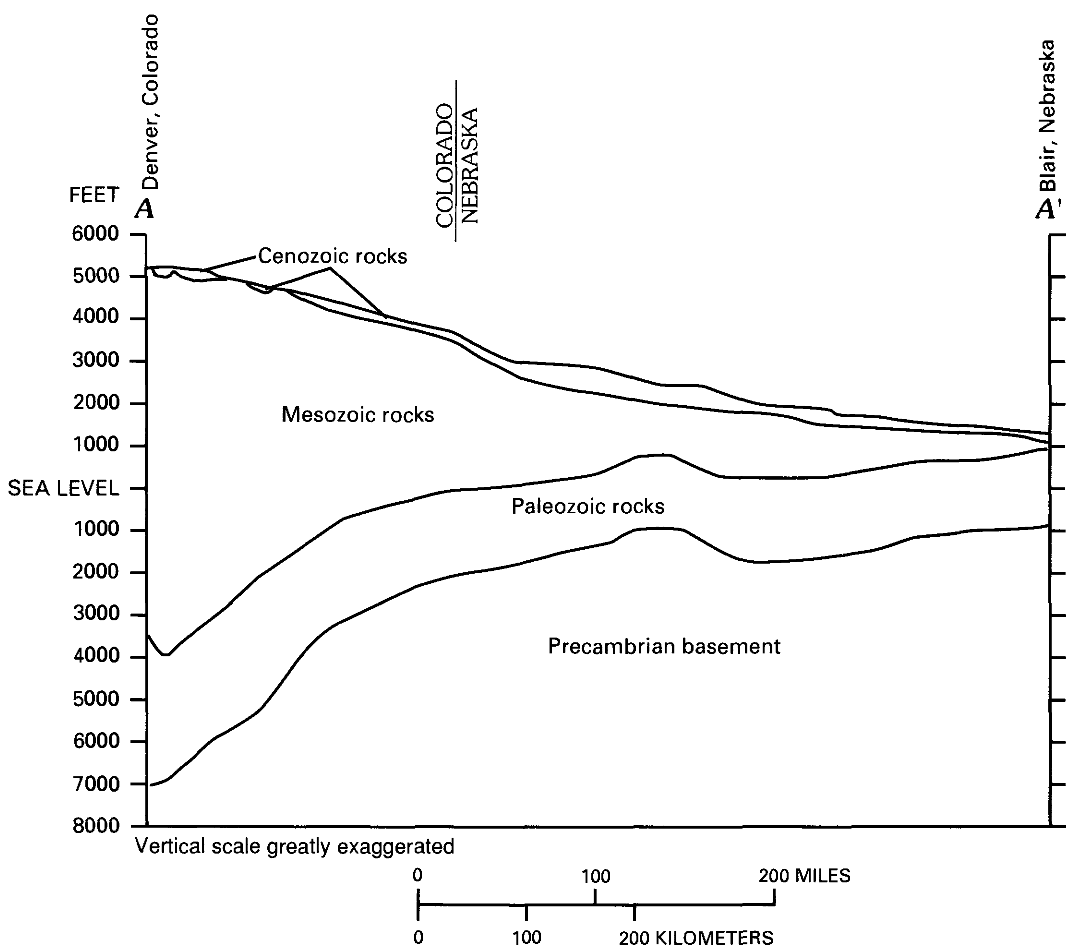


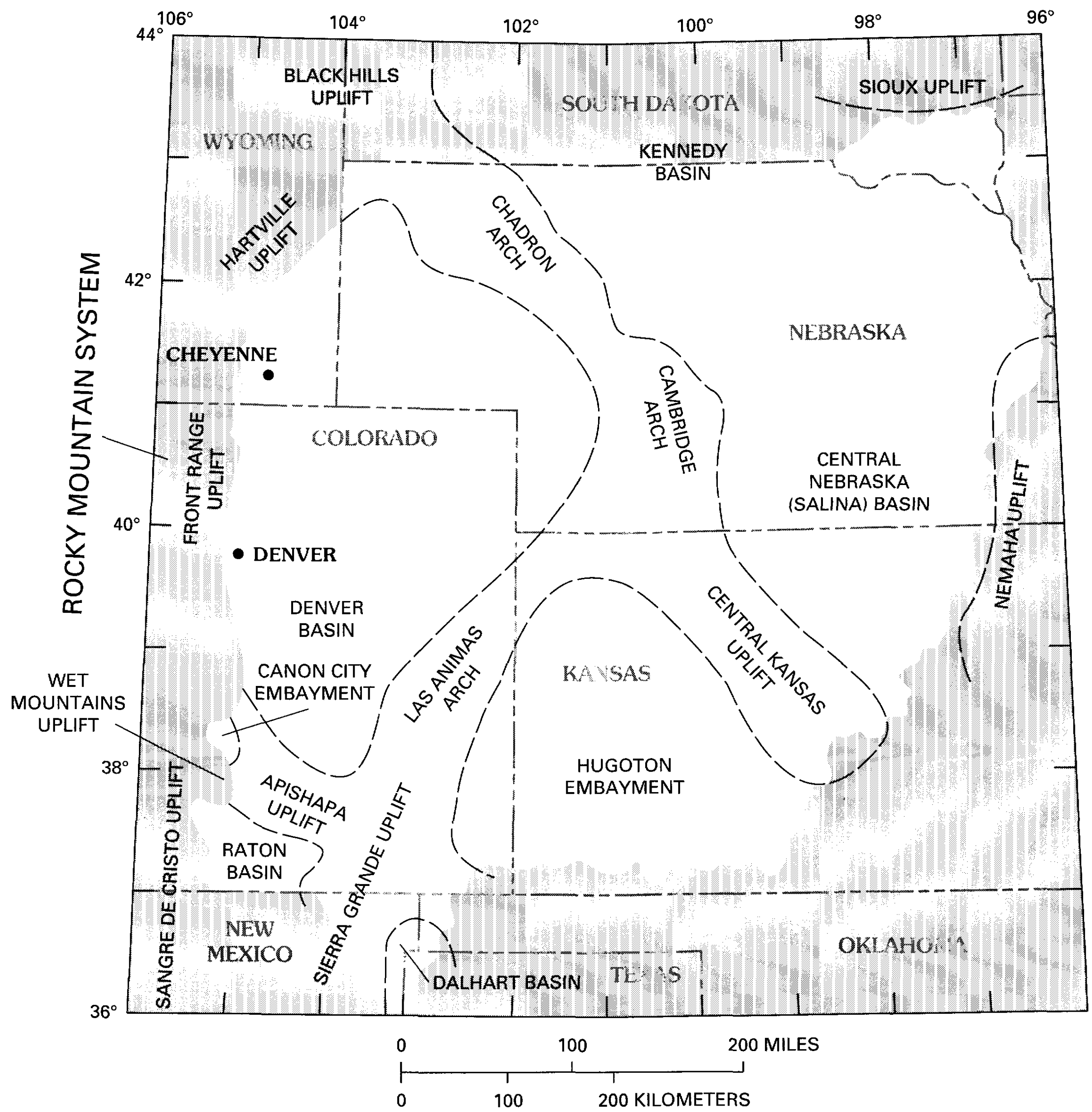
FIGURE 7.—Generalized section showing major time-stratigraphic units in study area. Location of section shown in figure 6.

of the aquifer system in South Dakota were reported by Milly (1978), Neuzil (1980), Bredehoeft and others (1983), and Case (1984). Belitz (1985) applied a flow model to an area corresponding with much of this study area.

Two other recent U.S. Geological Survey regional aquifer-system studies are relevant. The Northern Great Plains Regional Aquifer-System Analysis studied equivalent rock units laterally adjacent to and north of the study area (Anna, 1986). The High Plains Regional Aquifer-System Analysis evaluated the High Plains aquifer (Gutentag and others, 1984), which directly overlies the Great Plains aquifer system in some areas.

METHODS OF INVESTIGATION

This study mainly relied on existing data; very few new data were collected. Basic to the investigation was a delineation of the geologic framework, which required information on the extent and stratigraphic relations of pertinent rock units throughout the region.



EXPLANATION

——— APPROXIMATE BOUNDARY OF STRUCTURAL FEATURE

FIGURE 8.—Major structural features in study area and vicinity.

Data related to geology, hydrology, or petroleum exploration were assembled from many sources. Where data were abundant, representative data were selected. Data included the following:

1. Lithologic logs. Selected lithologic logs were obtained from State-agency files, petroleum-industry information services, and publications.

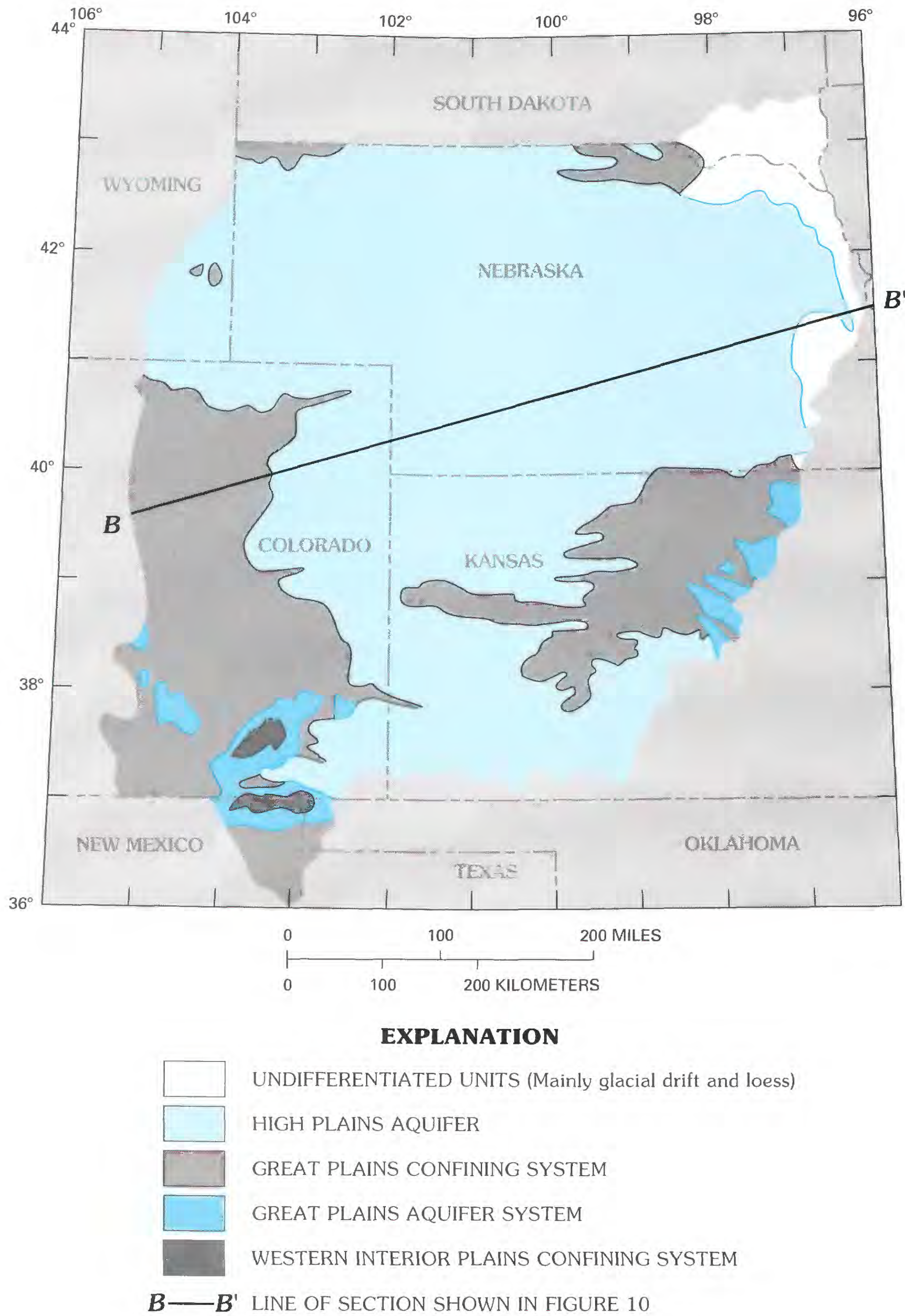


FIGURE 9.—Surficial distribution of regional geohydrologic units.

2. Geophysical logs. Selected geophysical logs were obtained from State-agency files, petroleum-industry information services, and publications.
3. Hydraulic-property data. Values of hydraulic conductivity and storage coefficient from pumping-test results were obtained from publications and U.S. Geological Survey files. Some hydraulic-conductivity values were estimated from reported specific-capacity data.
4. Water-level data. Records of water-level measurements in wells were obtained from publications and U.S. Geological Survey files.
5. Reservoir-parameter data. Values of reservoir pressure and intrinsic permeability were derived from selected oil-test records (results of drill-stem tests) or laboratory tests of cores. Such information was obtained primarily from petroleum-industry sources and State-agency files.
6. Hydrochemical data. Results of chemical analyses of water were selected from files of petroleum-industry information services, U.S. Geological Survey files, State-agency files, and published information.
7. Fluid withdrawal/injection data. Estimates were made based on data pertaining to water use and oil-and-gas production from State agencies and other sources.

Most storage, manipulation, and mapping of data was done by computer. Computer-generated contour maps greatly aided data synthesis and interpretation. Geologic and hydrologic interpretations presented in the plates of this report are based on thousands of data points, although only selected (data base) points are shown on the maps. Plates showing hydrochemical interpretations are based on several types of data. Interpretive mapping of basic data was also supplemented by published information.

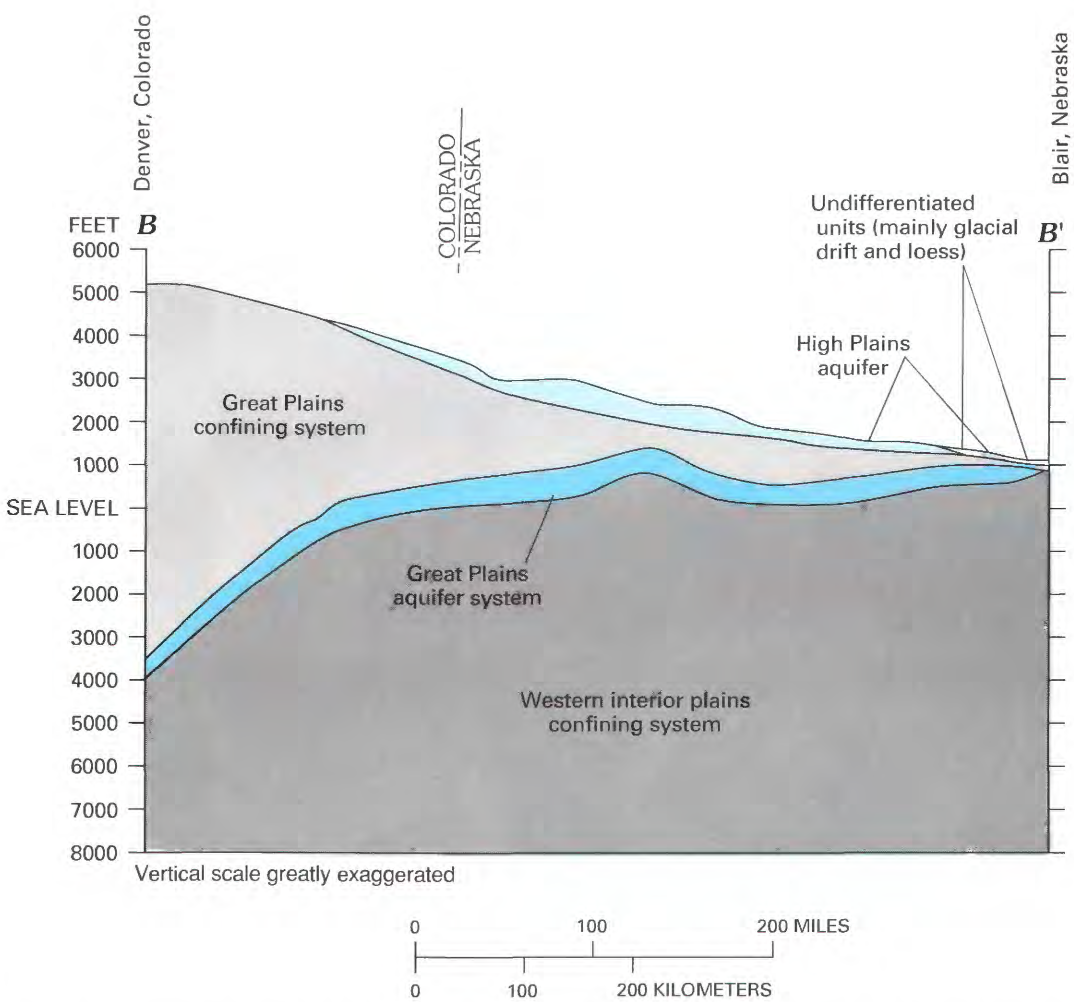


FIGURE 10.—Generalized section showing relations between regional geohydrologic units. Location of section shown in figure 9.

Most of the Great Plains aquifer system is not characterized by shallow, freshwater conditions with readily mappable hydraulic properties. Therefore, lithologic, geophysical, hydrochemical, and hydraulic information was considered collectively to identify relations useful for inferring hydrology over large areas with scarce data. These procedures are described as appropriate throughout the report.

Integrated interpretation of all types of information led to a conceptual flow model of the regional system. The conceptual model was tested and refined with the aid of a digital computer model of ground-water flow. Several auxiliary programs facilitated application of the model by properly preparing data and by arranging results for interpretation. The computer model is a representation of the regional flow system as currently understood and provides a basis for assessing water-resource development potential.

ACKNOWLEDGMENTS

This study relied on the assistance and cooperation of many individuals and organizations. In addition to published reports, unpublished information was supplied by many agencies, including the Colorado Oil and Gas Conservation Commission, the Kansas Department of Health and Environment, the Kansas State Board of Agriculture (Division of Water Resources), the Kansas Geological Survey, the University of Nebraska Conservation and Survey Division, the Nebraska Oil and Gas Conservation Commission, and the Wyoming Commissioner of Public Lands.

GEOHYDROLOGY

The extent, altitude, and thickness of the sandstone-shale sequence comprising the Great Plains aquifer system are described in this section. Geometry, boundaries, and internal physical character of the strata all affect the hydraulics and hydrodynamics of the aquifer system. The fluid system consists of water, oil, and gas, although hydrocarbons make up a very small part of the total fluid.

GEOHYDROLOGIC FRAMEWORK

The Great Plains aquifer system is composed mostly of sandstone and shale of Early Cretaceous age. The upper part of the strata in eastern areas is considered of Late Cretaceous age. Sedimentary facies changes and other heterogeneities have given rise to geologic names that vary considerably within the study area. Approximate stratigraphic correlations within the study area, as well as correspondence with geohydrologic units used in the report, are shown in figure 11. The aquifer system consists of the Apishapa aquifer, which is named for the Apishapa uplift (fig. 8) and is present over the western two-thirds of the study area; the overlying Apishapa confining unit of similar extent; and the overlying Maha aquifer, named for an Indian tribe that lived in the Missouri River valley near Omaha, Nebraska, which covers nearly all of the study area (figs. 12, 13). The Apishapa confining unit extends beyond the Apishapa aquifer in central Kansas. North of this area, the Apishapa and Maha aquifers merge where the Apishapa confining unit pinches out; eastward the aquifer system is considered to be composed solely of the Maha aquifer.

Details of the stratigraphy and structure reveal many irregularities and heterogeneities that are reflected not only in the stratigraphic terminology but also in the hydrology of the system. An appreciation for these complexities can begin with a consideration of the geologic history through which these strata were formed and changed.

GEOLOGIC HISTORY

Before the Lower Cretaceous strata of the Great Plains aquifer system were laid down, the study area was above sea level and undergoing erosion. The land surface consisted of various rock types whose ages ranged widely because the region had been tilted upward to the east and eroded to form an irregularly beveled surface. The age of rocks forming the land surface ranged from Jurassic in the western half of the study area to Precambrian in the extreme northeast. The pre-Cretaceous geologic history of the study area is summarized by Jorgensen and others (1992).

The Lower Cretaceous sedimentary rocks reflect a general marine transgression-regression-transgression sequence (Franks, 1975). A basal unit, the parent material of the Cheyenne Sandstone and equivalents, was formed of clastic material deposited on alluvial plains and in deltas and estuaries of a transgressing sea. Expansion of the sea resulted in marine clay deposition, which now forms the Kiowa Shale and equivalents. Seas encroaching from both the north and the south (Eicher, 1960; Haun and Kent, 1965; Young, 1970) are thought to have joined in the southern part of the study area and spread eastward. The sea is believed to have covered the entire study area before receding. Sediments, which would become the Dakota Sandstone and equivalents, were deposited partly during this regression, but regression was generally rapid enough to result in a disconformable

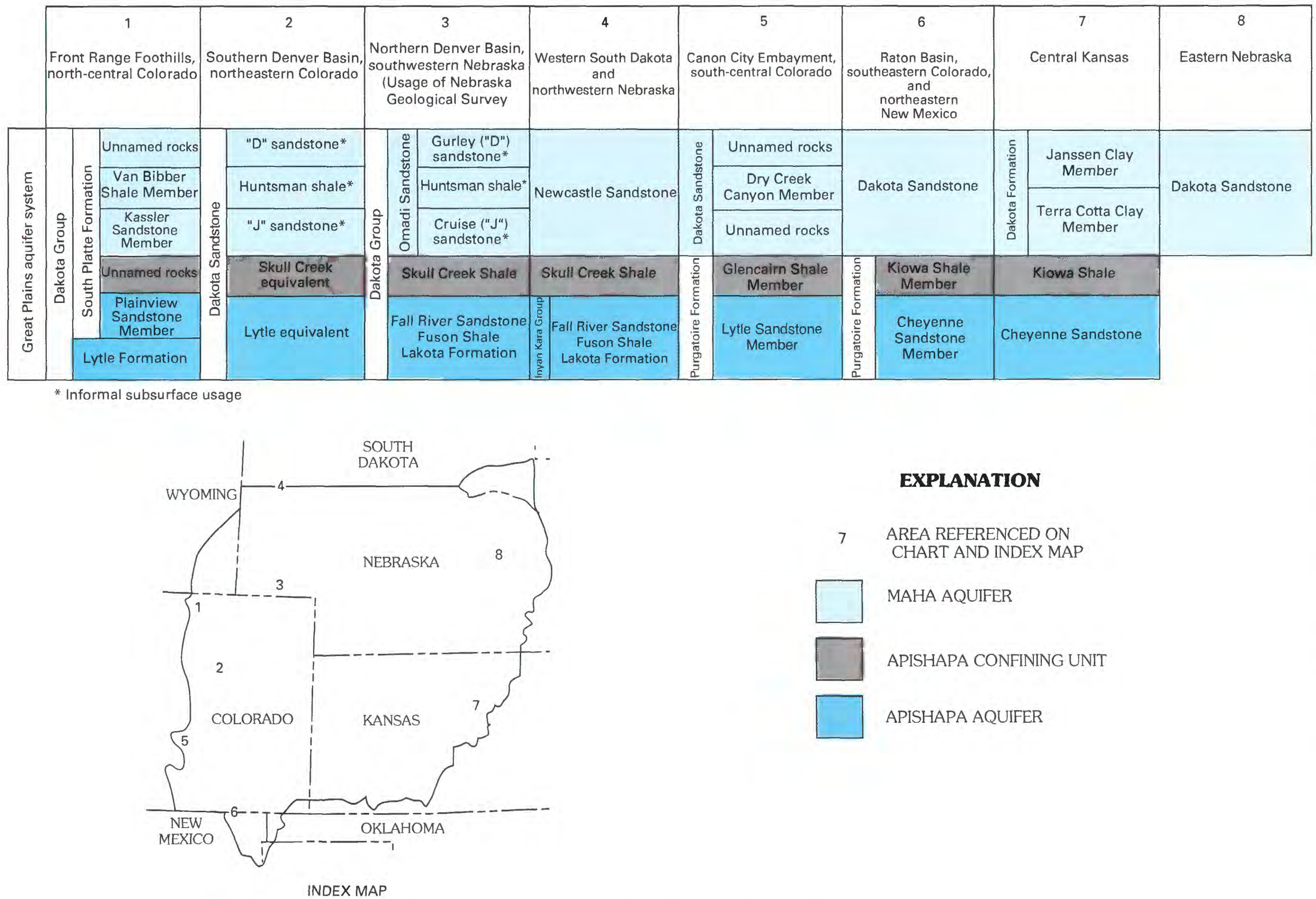


FIGURE 11.—Stratigraphic and geohydrologic units of Great Plains aquifer system.

contact between the Kiowa Shale and the Dakota Sandstone in part of the study area (Latta, 1948; Franks, 1975). Upper parts of the Dakota Sandstone were deposited during a subsequent marine transgression. Deposition of marine clay (to become the Graneros Shale and equivalents) followed, marking the top of the Great Plains aquifer system over most of the area.

Although the major stratigraphic units in this sequence are quite well defined regionally, local stratigraphy is typically variable, being a product of complex depositional and erosional environments. The

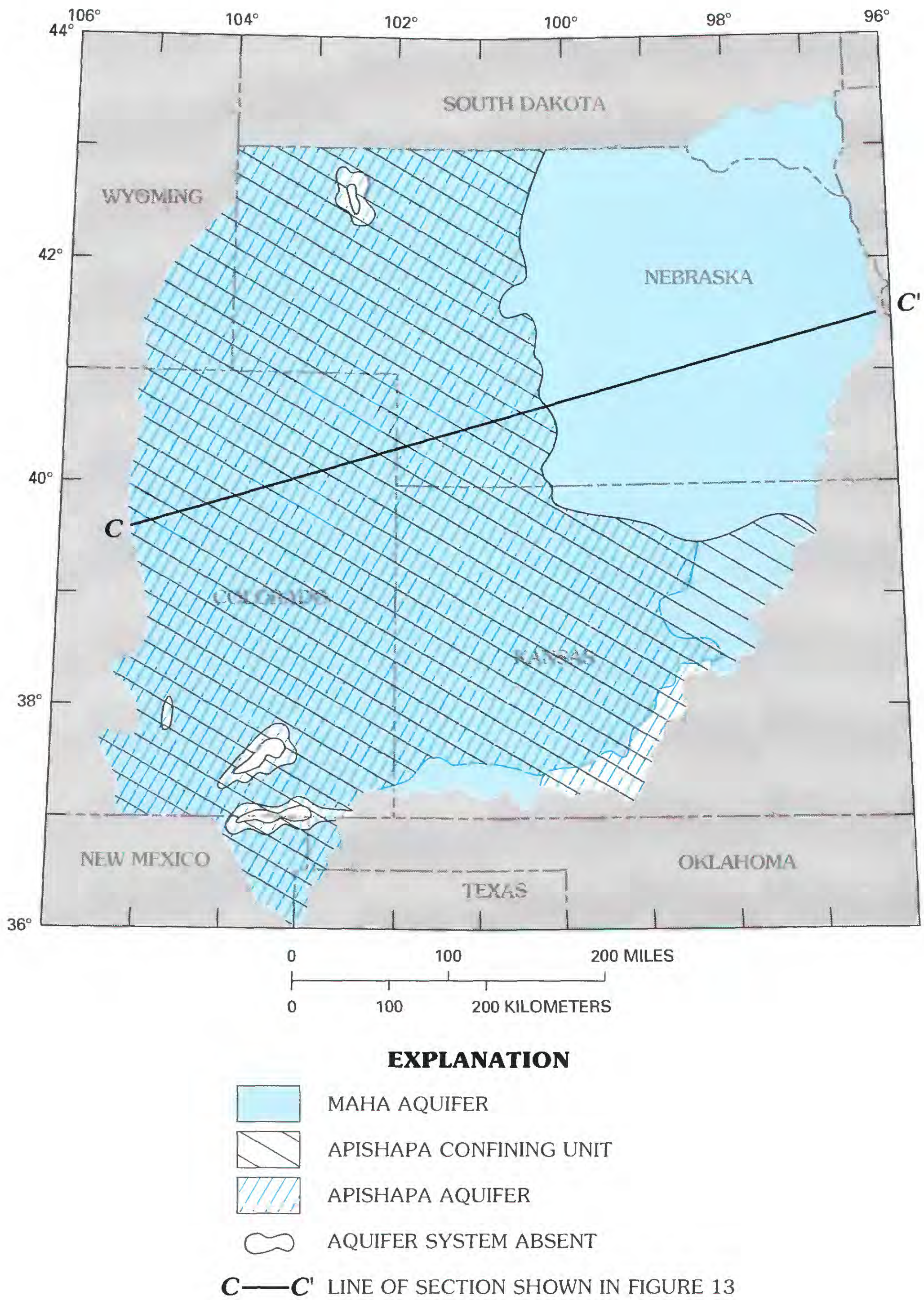


FIGURE 12.—Distribution of aquifers and confining units of Great Plains aquifer system.

thickness of the Cheyenne Sandstone varies considerably because of the relief of the pre-Cretaceous erosional surface (Merriam, 1963; Keene and Bayne, 1977). Transgressions and regressions usually included minor oscillations that led to intricate variations in the geometry and texture of the deposits. The rapidly changing character of most of the strata reflects conditions that shifted among marine, marginal marine, and nonmarine. Deltaic, shoreline, and alluvial sediments especially are characterized by lenticular, linear, or sinuous bodies. The low-lying landscape of central Kansas and southeastern Nebraska is thought to have been dominated by numerous small streams of low competency, resulting in clay-rich deposits (Franks, 1975; Karl, 1976). A mixture of tributary, braided, and distributary conditions provided the setting for development of complex local stratigraphy. Seemingly random occurrence of sandstone bodies in the western part of the study area (Bass, 1958) makes accurate reconstruction of the depositional environment difficult.

Deep burial in the western part of the study area promoted compaction and thermal diagenesis. The end of the Cretaceous Period is marked by the beginning of the Laramide orogeny, which uplifted the Rocky Mountain system and formed the adjacent Denver and Raton basins. Jointing of the rocks resulted from the tectonic stress. Large-displacement faults, which formed along the edges of the uplifts of the Rocky Mountain system, abruptly truncated the west sides of the study area. Dissolution and precipitation of minerals by heated ground water at depth affected the nature and distribution of cementation of the rocks. Oil migrated into the aquifer system from Upper Cretaceous source beds along the axis of the Denver basin (Clayton and Swetland, 1980). The area underwent alternating periods of deposition and erosion during the Tertiary Period. Unloading may have

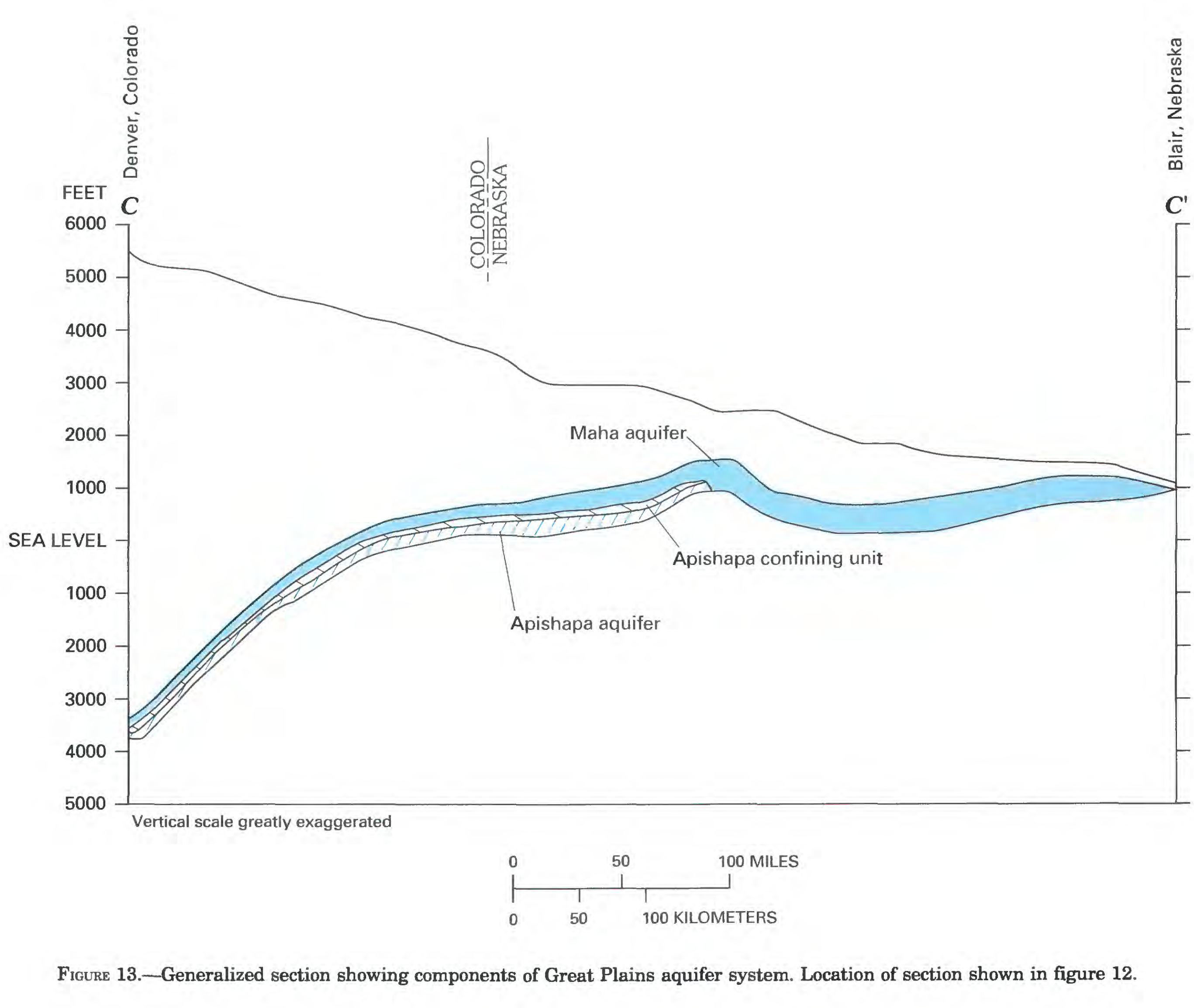


FIGURE 13.—Generalized section showing components of Great Plains aquifer system. Location of section shown in figure 12.

caused cementation of the sands by precipitation of minerals as a result of reduced overburden pressure. Since late Tertiary time, broad uplift and regional tilting to the east probably have caused only minor changes in the properties of the aquifer system.

STRATIGRAPHY

Correlation of stratigraphic units in the Great Plains aquifer system has gained the attention of many workers. Although there are some differences in interpretations, most workers are in general agreement. Some definition is lacking in the central part of the study area where subsurface control is sparse. Detailed geologic mapping has been done in some outcrop areas and in some areas with dense subsurface control (for example, Bass, 1958; Young, 1970; Franks, 1975; Karl, 1976; Clark, 1978; Geyer and Pritchett, 1978). Local stratigraphy is an important factor affecting local geohydrology and can vary substantially within short distances. Regional hydrology, however, depends on large-scale features of stratigraphy, particularly lithology and thickness, which are described in the following sections.

LITHOLOGY

Strata of the Great Plains aquifer system consist essentially of clastic sedimentary rocks ranging in texture from clay to conglomerate. Most are sandstone, siltstone, claystone, or shale. Some of the strata, particularly shale of terrestrial origin, are carbonaceous, with thin lignite beds. Ferruginous zones and iron-mineral concretions also have been reported. The following descriptions are summarized from many sources, including Bass (1958), Condra and Reed (1959), Merriam (1963), Weimer (1970), Young (1970), Franks (1975), Karl (1976), Lobmeyer and Weakly (1979), Brenner and others (1981), Munter and others (1983), Spinazola and Dealy (1983), Robson and Banta (1987), and Geldon (1989).

Rocks of the Apishapa aquifer, the lowest unit of the Great Plains aquifer system (figs. 11–13), consist mainly of light-colored fine- to coarse-grained sandstone. Conglomerate is usually present at the base of the unit but may occur in other intervals. Siltstone, claystone, and shale are commonly most abundant in the middle intervals. The sandstone is generally quartzose and poorly cemented in many areas. Although cementing material usually has not been reported, pyrite and calcite have been identified as cements in samples collected in Kansas. The percentage of the aquifer that is composed of sandstone (fig. 14) is hydrologically important because coarse-grained clastic rocks normally have large permeability. Figure 14 is derived mainly from geophysical logs and shows the percentage of total aquifer thickness that is composed of sandstone beds. Sandstone is the dominant rock type in most areas of the aquifer. This map identifies general areas of sandstone abundance but, because of local variability, should not be used to estimate sandstone percentage at a particular location.

The Apishapa confining unit (figs. 11–13) is made up mostly of gray to black shale, siltstone, and fine-grained sandstone. Minor amounts of limestone and bentonite have been observed. Calcite and iron minerals have been identified as sandstone-cementing agents in this confining unit in some outcrop areas. Some of the shale also has been reported as calcareous, and much of it is carbonaceous. The percentage of sandstone in this confining unit commonly increases upward, although distinct sandstone bodies have been reported throughout the unit. Delineation of the confining unit is arbitrary in areas of abundant sandstone; however, the sandstone is not as abundant as in the underlying and overlying aquifers.

Rocks of the Maha aquifer (figs. 11–13) commonly consist of fine- to coarse-grained quartzose sandstone, with complex interlayering of conglomerate, siltstone, claystone, and shale. Color is variable, and carbonaceous materials are present in many places. Degree of cementation varies, even locally, from well cemented to poorly cemented. In eastern outcrop areas, iron minerals, calcite, and occasionally silica are cementing agents. In the Denver basin, silica and argillaceous materials are the predominant cementing agents. Sandstone percentage (fig. 15) tends to be greatest in the southwestern, central, and northeastern parts of the study area. The small sandstone percentage in the northwestern part of the study area reflects increasing prevalence of marine shale in that direction. The small sandstone percentage in central Kansas resulted from a low-lying, low-energy coastal-plain depositional environment that produced a predominance of clay rocks. It should be noted again that local stratigraphic complexities may supplant apparent regional trends at any specific location.

THICKNESS

The total thickness of the Great Plains aquifer system ranges from 200 to 800 feet over most of the study area (fig. 16). It is thickest in parts of north-central Nebraska and gradually thins to the west, south, and east from that area. Progressive thinning near the eastern and southern edges of the aquifer system in Nebraska and Kansas has resulted from erosion. In these areas, the aquifer system occurs at or near land surface, and thickness contours are partially shaped by recent stream erosion. Truncation of the rocks along the western edge of the study area and along the Purgatoire and Cimarron Rivers (southwestern part of area) is generally abrupt. Consequently, thickness contours in these areas (fig. 16) end abruptly against lines that represent the truncated edges.

The thickness of the Great Plains aquifer system (fig. 16) is the sum of the thicknesses of the Maha and Apishapa aquifers and the Apishapa confining unit. Figure 16, as well as each of the thickness maps for the individual components of the aquifer system (pls. 1–3), is intended to show regional trends and does not show local variations. The thickness of the Apishapa aquifer, in particular, commonly shows

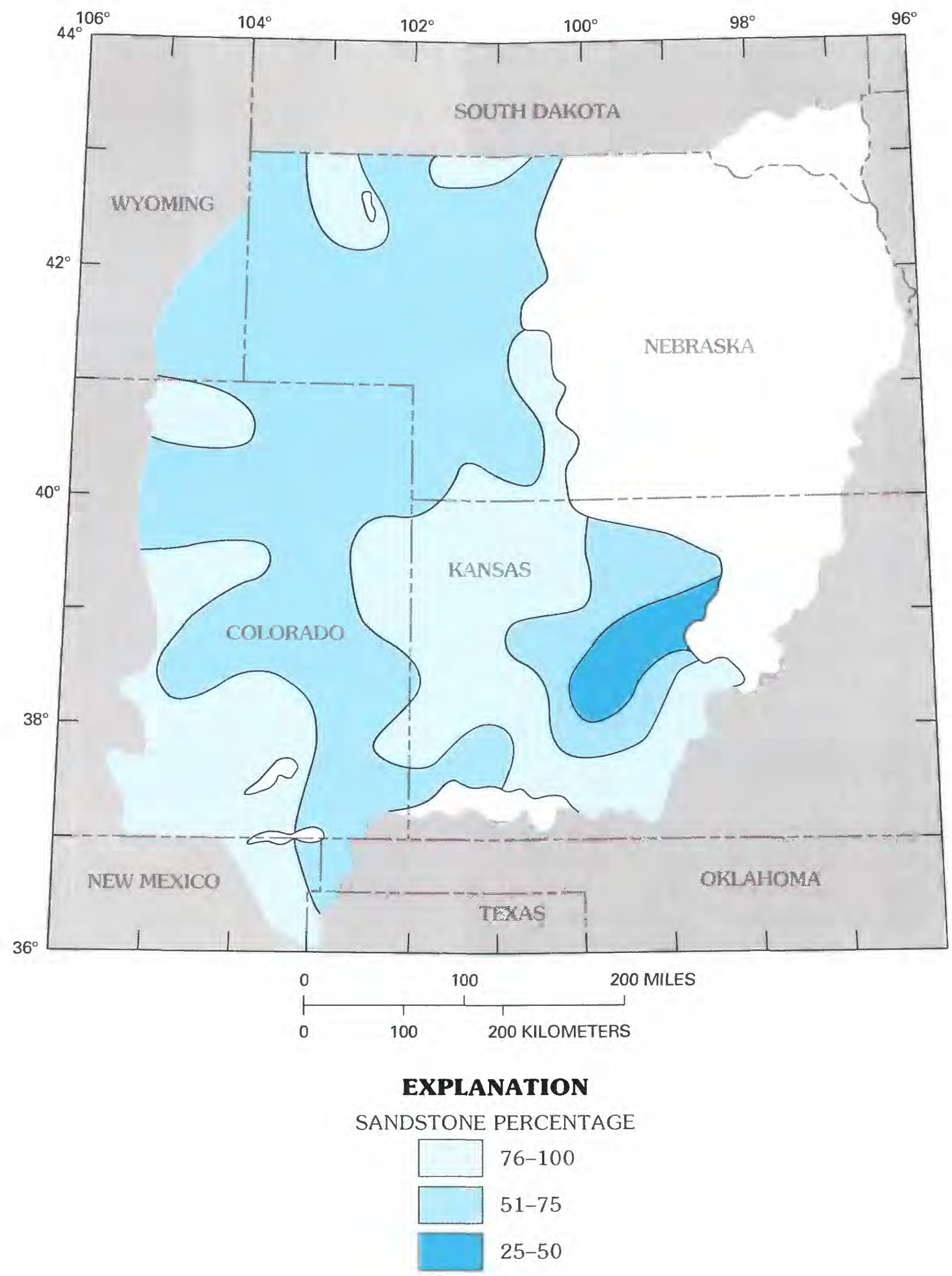


FIGURE 14.—Percentage of Apishapa aquifer consisting of sandstone beds.

local differences from the regional interpretation because of the irregular erosional surface upon which those sediments were laid. The limit of the Apishapa confining unit in Nebraska and northern Kansas (pl. 2) is not precisely mapped, although a gradual thinning toward that limit is evident in most places. Beyond (generally east of) this limit, the entire thickness of the aquifer system is assigned to the Maha aquifer, and an abrupt increase in thickness is shown for that unit (pl. 3).

STRUCTURE

The regional structure of the aquifer system is dominated by the basinal features in the western

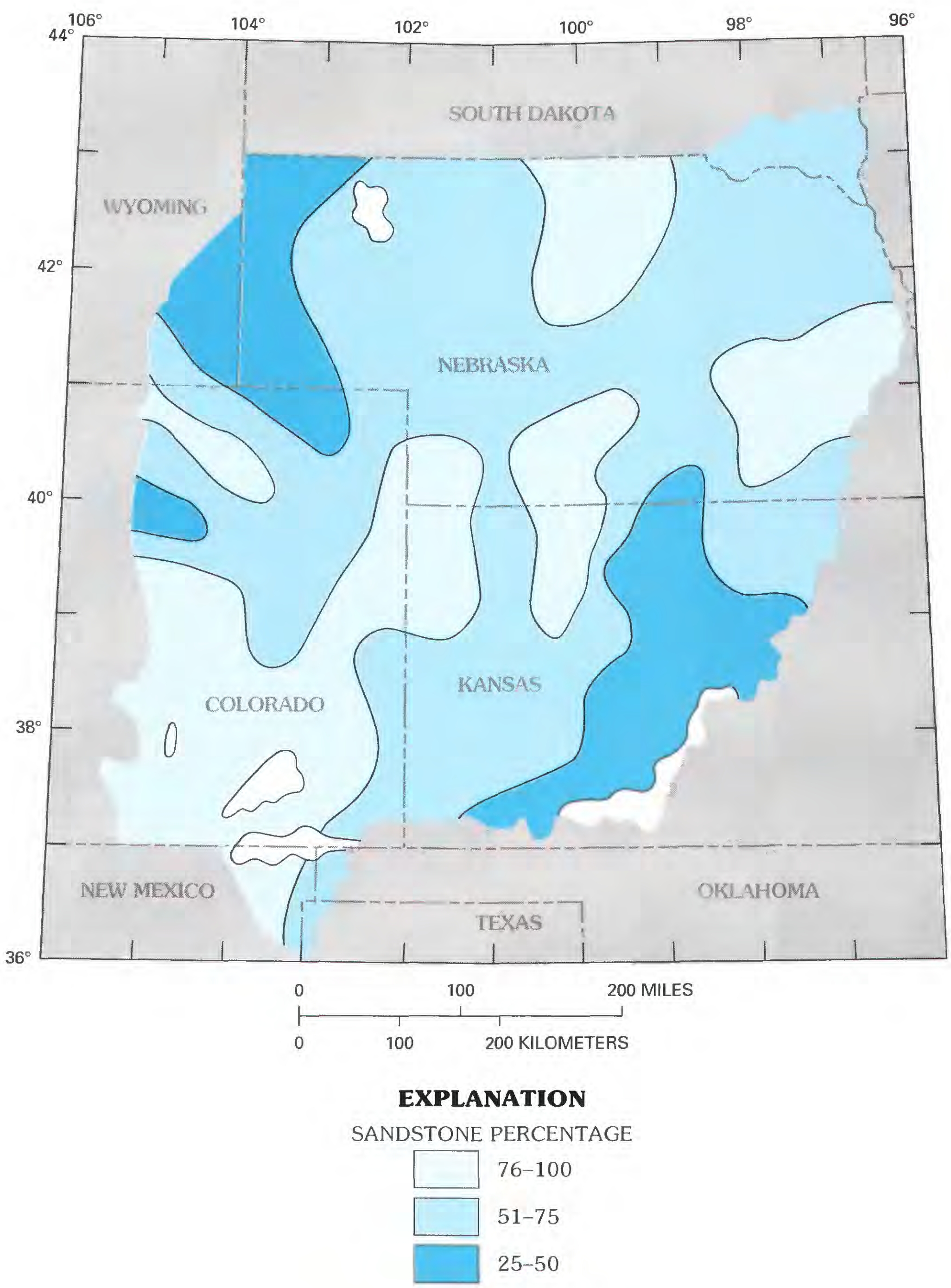
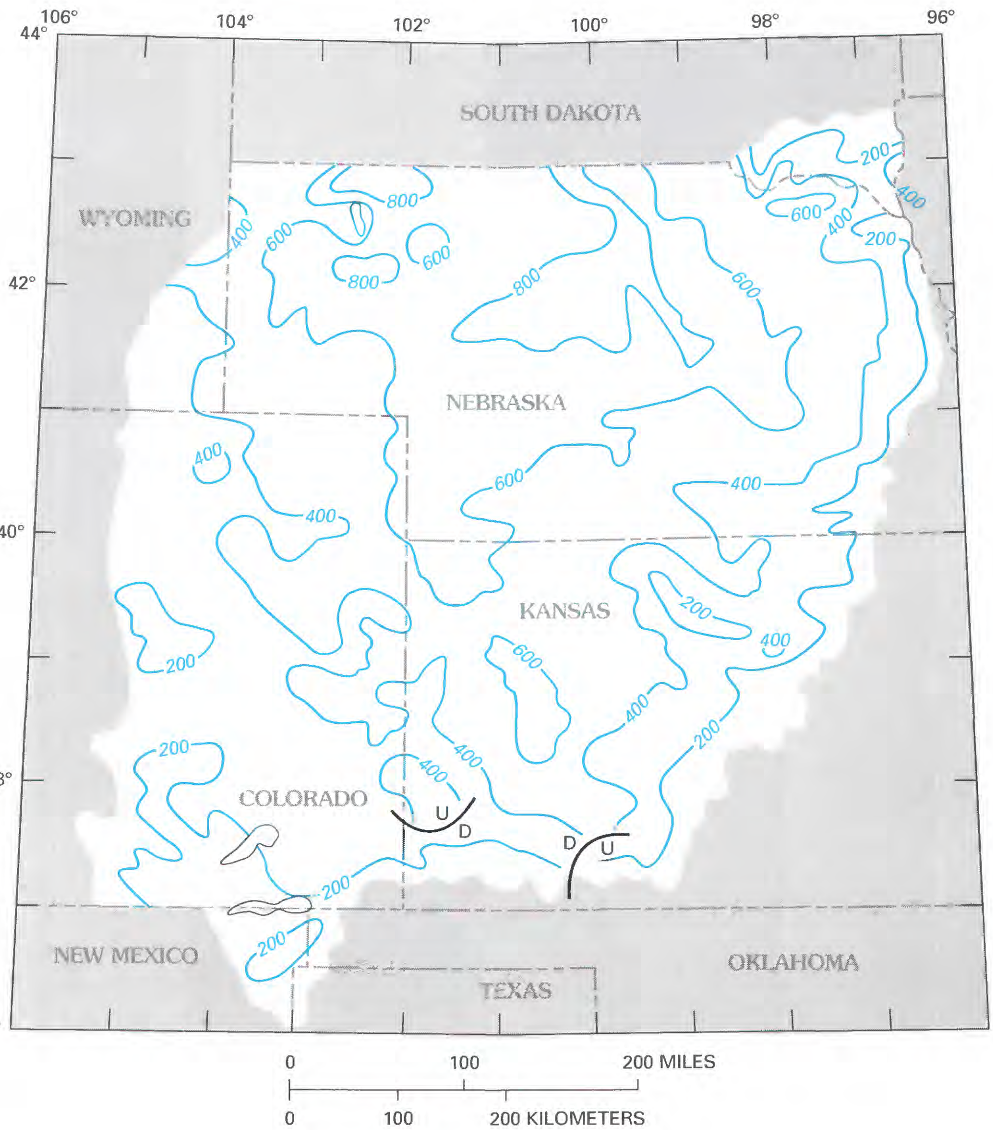


FIGURE 15.—Percentage of Maha aquifer consisting of sandstone beds.

part of the study area (pl. 4; fig. 8). Two structural lows exist along the axis of the Denver basin, one under Denver, Colorado, and the other under Cheyenne, Wyoming. The Raton basin is centered under Huerfano County, Colorado. A smaller structural low north of the Raton basin underlying Fremont County, Colorado, is the Canon City embayment. The Apishapa uplift forms the structurally high area between the Denver and Raton basins. Broad structural highs bound the basins on the east; from south to north, these are the Sierra Grande uplift and the Los Animas, Cambridge, and Chadron arches. Structural features east of this series of arches affect strata deeper than the Great Plains aquifer system and do not affect rocks of the aquifer system itself, which are nearly flat lying. Postdepositional



EXPLANATION

400 — LINE OF EQUAL THICKNESS OF GREAT PLAINS AQUIFER SYSTEM—Interval 200 feet

AQUIFER SYSTEM ABSENT

U/D — FAULT—U, upthrown side; D, downthrown side

FIGURE 16.—Thickness of Great Plains aquifer system.

uplifting along the Sierra Grande uplift and the Chadron arch resulted in erosion of the strata of the aquifer system near the Colorado-New Mexico-Oklahoma State lines and in Sheridan County, Nebraska. The top of the aquifer system is regionally smooth except near the eastern and southern eroded edges and in faulted areas.

High-angle faults with large offsets form much of the western boundary of the basins and hence the boundary of the study area. Most of the movement along these and associated smaller faults just inside the western boundary (pl. 4) occurred during the Laramide orogeny. Faulting in southwestern Kansas was caused by dissolution of Permian evaporite rocks, causing subsidence of overlying strata to form a grabenlike feature between the two faults (Gutentag and others, 1981). Most faults within the study area probably do not significantly disrupt the regional continuity of the aquifer system, although some may cause large lateral displacement locally (Spinazola and Dealy, 1983; Banta, 1985).

VERTICALLY ADJACENT UNITS

The distribution and character of underlying and overlying rock units are pertinent to the Great Plains aquifer system insofar as they form hydrologic boundaries to the system. The vertical sequence of regional geohydrologic units is shown in table 1, but none of the units except the basement confining unit extend across the entire study area. In most areas, vertically adjacent units act to confine the aquifer system both above and below, but exceptions to this condition are hydrologically significant.

UNDERLYING UNITS

The aquifer system is directly underlain by one of three regional geohydrologic units, depending on location (fig. 17). In the extreme northeastern part of the study area, the system is directly underlain by the basement confining unit or the Western Interior Plains aquifer system. In the remainder of the study area, the Great Plains aquifer system is directly underlain by the Western Interior Plains confining unit.

The basement confining unit (igneous or metamorphic rocks) is nearly impermeable, except where weathered or fractured. The Western Interior Plains aquifer system is more permeable than the basement confining unit but has slight permeability in the area of subcrop (northeastern Nebraska).

In the area where the Western Interior Plains confining system directly underlies the Great Plains aquifer system, several areas having significant geohydrologic characteristics are delineated (fig. 17). In most of eastern Nebraska and Kansas, strata of Pennsylvanian and Permian age underlie the aquifer system. These strata have been tilted and eroded so that progressively younger rocks subcrop from northeast to southwest. The Pennsylvanian sequence consists of thin-bedded shale, limestone, sandstone, and coal. The Permian sequence contains shale, sandstone, limestone, and evaporite deposits (halite, gypsum, and anhydrite). Jurassic rocks directly underlie the aquifer system in most of the western two-thirds of the area. These rocks consist mainly of the slightly permeable shale- and siltstone-rich Morrison Formation. This formation is absent in the tristate area of Colorado-Kansas-Oklahoma, where the Entrada Sandstone or sandstone of the Dockum Group directly underlies the Great Plains aquifer system; these sandstone units form a somewhat more permeable lower boundary to the aquifer system. Despite the diverse rock types underlying the Great Plains aquifer system, they collectively act to restrict ground-water flow vertically. Two areas of relatively greater permeability are extensive enough to warrant special consideration in defining regional geohydrology; these are the subcrop areas of the Cedar Hills Sandstone of the Nippewalla Group in central Kansas and the Entrada Sandstone and Dockum Group in the Colorado-Kansas-Oklahoma tristate area (fig. 17).

Evaporite deposits (halite, gypsum, or anhydrite) are also of special hydrologic interest because they are nearly impermeable and because their dissolution can profoundly affect water quality. Evaporite deposits constitute several separate stratigraphic units, interbedded with other strata, in the middle to upper parts of the Permian rock section. The major units of interest are within the Nippewalla and Sumner Groups. Although the area of direct contact between the evaporite deposits and the overlying Great Plains aquifer system is relatively small (generally just east of the Cedar Hills Sandstone subcrop area in central Kansas), the large areal extent of the evaporite deposits (fig. 17) and the fact that they usually occur within a few hundred feet below the aquifer system make them a regionally significant restrictive element for vertical ground-water flow.

OVERLYING UNITS

The Great Plains aquifer system is overlain directly by the Great Plains confining system in more than 90 percent of the study area (fig. 18). Most of this confining system consists of very slightly permeable units, including the Graneros Shale, the most extensive unit that directly overlies the aquifer system, or its equivalent. In a small area of northwestern Nebraska, uplift, erosion, and renewed deposition has left fine-grained Tertiary sediments immediately over the Great Plains aquifer system (DeGraw, 1969).

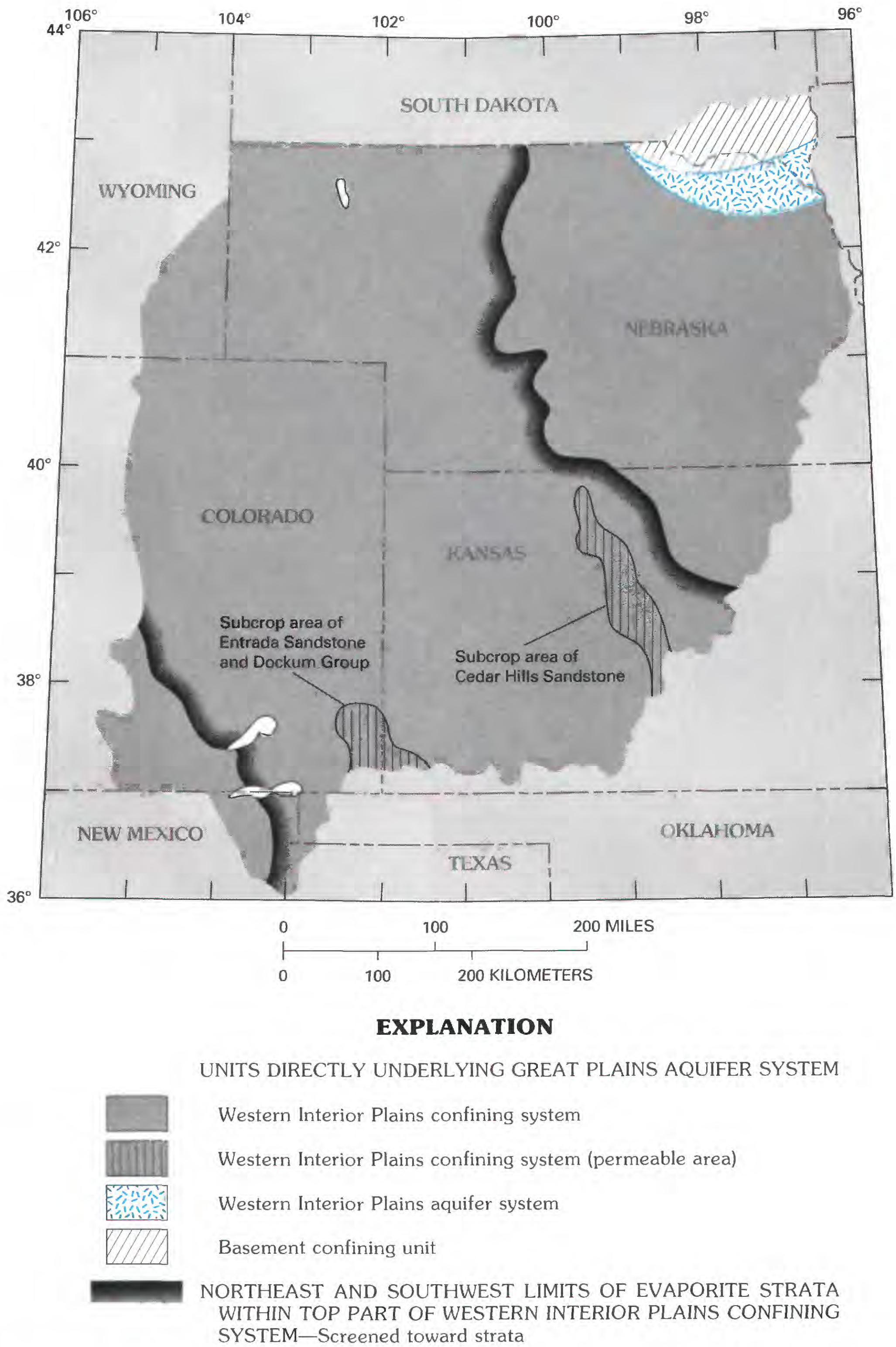


FIGURE 17.—Geohydrologic units directly underlying Great Plains aquifer system and extent of underlying evaporite deposits.

The Great Plains confining system is absent along much of the southern and eastern edges of the study area. In these areas, the High Plains aquifer (Gutentag and others, 1984) or undifferentiated Quaternary deposits (described below) directly overlie the Great Plains aquifer system. The High Plains aquifer contains permeable sand and gravel, affording effective hydraulic connection at the contact.

Along the eastern edge of the study area in Nebraska (fig. 18), the aquifer system is directly overlain by Quaternary deposits consisting of glacial drift or interglacial or postglacial sediments. The drift consists of till, sand, and gravel resulting from several ice advances from the northeast. Loess occurs between drift sheets and at land surface in some areas; it probably lies directly on the Great Plains aquifer system locally. Alluvium directly overlies the aquifer system along a reach of the Missouri River forming the northeastern boundary of Nebraska. Similar conditions along smaller streams, not mapped, occur in and near outcrop areas elsewhere in the study area. The different types of Quaternary deposits exhibit varying degrees of hydraulic connection with the underlying Great Plains aquifer system. The alluvium along the Missouri River is the only part of the undifferentiated Quaternary deposits delineated in this study that provide a particularly effective connection over a large area.

HYDRAULICS

Most data pertaining to hydraulic properties and heads were obtained from the Maha aquifer. However, the sparse data available for the Apishapa aquifer do not suggest significant differences between the aquifers. The following discussion, therefore, refers to the aquifer system as a whole, except as noted. Regionally, distributions of hydraulic properties and heads adequately characterize both aquifers.

STORAGE PROPERTIES

Borehole-geophysical logs are the main source of porosity data for this study. Neutron, density, and sonic logs measure properties of the rocks that can be related to a calibrated porosity scale. Porosity data were also obtained from oil-industry literature (Finch and others, 1955; Parker, 1962); these values are laboratory-determined and tend to slightly exceed values derived from logs, probably because they apply to less-representative, oil-bearing zones.

Regional trends in sandstone porosity for the aquifer system (fig. 19) indicate an inverse correlation with depth of burial. Porosity decreases with increased depth of burial westward into the Denver and Raton basins. The relation, also shown graphically for data derived from geophysical logs (fig. 20), suggests that the effect of compaction and diagenetic effects due to elevated temperatures with depth impart a regionally mappable trend that transcends local variations in such factors as texture, degree of cementation, and jointing. Scatter on the graph is probably attributable to the variable effects of these factors. Very little information on porosity is available east of the 30-percent contour in figure 19; however, the regional value probably remains at about 30 percent. A correlation between burial depth and porosity generally is well recognized (Athy, 1930; Schmoker and Halley, 1982; Baldwin and Butler, 1985) and also has been noted for this aquifer system by Belitz (1985) and Higley and Gautier (1986).

Storage coefficient is important to aquifer-system development (withdrawals or injections). In areas where the system is unconfined, in and near outcrop areas, storage coefficient is nearly equal to specific yield. Specific yields determined from aquifer tests in Kansas have been as large as 15 to 20 percent (Keene and Bayne, 1977). Robson and Banta (1987) reported values of about 10 percent in Colorado. In the confined areas, storage coefficient is small because water is derived from storage by compression of the aquifer and expansion of the water (Meinzer and Hard, 1925; Swenson, 1968; Lohman, 1972).

Specific storage (storage coefficient per unit thickness) of confined areas, S_s, may be expressed as

$$S_s=\gamma_w(n/E_w+C/E_k) \quad [l^{-1}] \tag{1}$$

where γ_w is specific weight of water $[fl^{-3}]$; n is porosity [dimensionless]; E_w is bulk modulus of elasticity of water $[fl^{-2}]$; E_k is bulk modulus of elasticity of the solid skeleton of the aquifer $[fl^{-2}]$; and C is a dimensionless ratio dependent on the nature of the aquifer material. Applying this relation to the Great Plains aquifer system, a representative value of specific storage is estimated to be 9.5×10^{-7} per foot of aquifer thickness. The largest potential source of error in this estimate is the effect of gas and oil, which is not included in equation 1 but which forms a part of the fluid system in the Denver basin.

Regionalized porosity and total saturated thickness are used to estimate the volume of water stored in the aquifer system in the study area (table 2). Computations were made using mapped porosity and thickness data, thereby enabling incorporation of areal trends in these parameters. Total thickness of the aquifer, including the shale component, was used. Shale has greater original porosity than sandstone, but geophysical logs indicate that the observed values are comparable to that of sandstone. Presumably, this has resulted from compaction of the shale. The aquifer system contains about 12 billion acre-feet of water within the study area.

The volume of drainable water is significantly less than the volume in storage (table 2). This estimated volume is based on assumptions that essentially no water drains from shale because of its fine grain size and that one-half of the water stored in sandstone cannot drain because of cementation. Sandstone is estimated to be about 50 percent of the aquifer-system thickness. Therefore, drainable volume is estimated to be about 3 billion acre-feet.

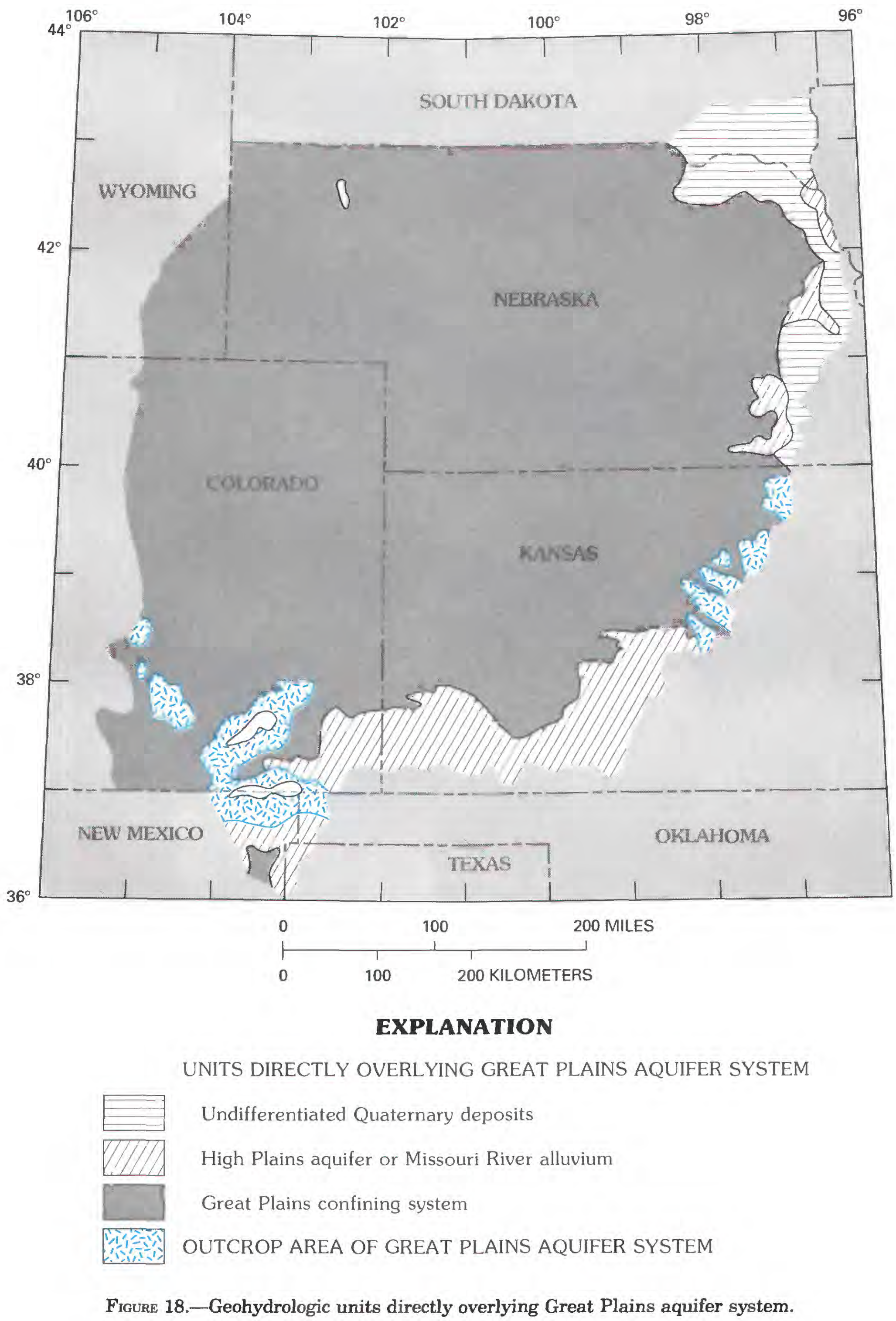


FIGURE 18.—Geohydrologic units directly overlying Great Plains aquifer system.

TRANSMISSIVE PROPERTIES

Transmissive properties relate to the ease of fluid moving through the aquifer system. Because lateral flow normally predominates over vertical flow in stratified rocks, most of this discussion relates to transmissive properties in the lateral direction. Properties characterizing the vertical direction are briefly discussed at the end of this section. The basic property is intrinsic permeability, which is characteristic of the rock alone and is independent of the properties of fluids in the rock. Permeability values listed in oil-industry sources are reported as intrinsic permeability.

Given the regional effect of depth of burial on porosity, it was expected that the depth factor would also be useful in estimating regionalized intrinsic permeability. However, unlike porosity, intrinsic permeability cannot be obtained readily from geophysical

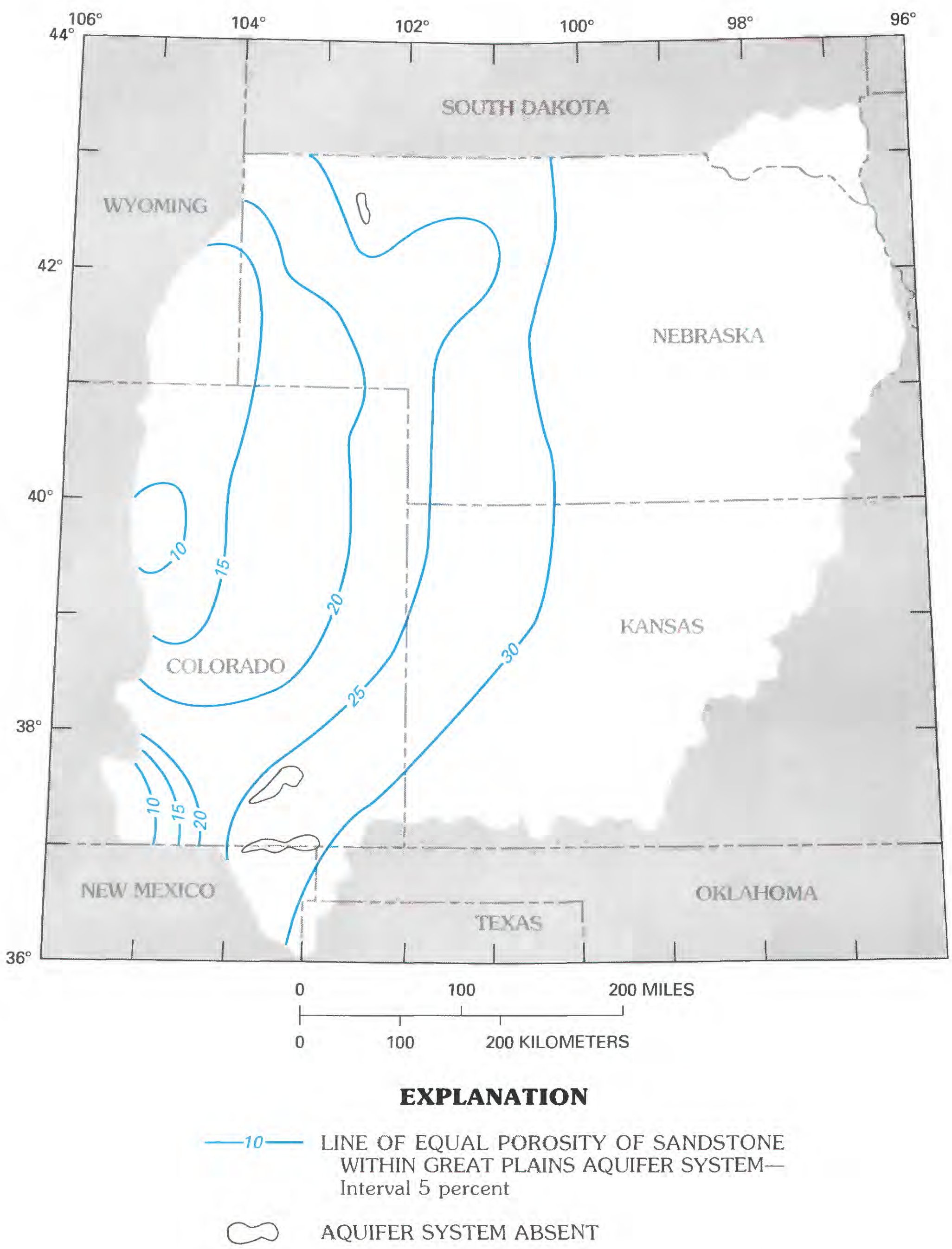


FIGURE 19.—Regionalized porosity of sandstone within Great Plains aquifer system.

logs. Thus, values of intrinsic permeability of sandstone were estimated using an empirically derived relation (Jorgensen, 1989)

$$k=(1.93\times10^{-9})(P^{1.10}) \tag{2}$$

where k is intrinsic permeability [ft^2] and

$$P=n^{m+3}/(1-n)^2 \tag{3}$$

where n is porosity [dimensionless] and m is cementation factor [dimensionless]. Cementation factor, which is related to tortuosity, is a commonly used term in oil-industry literature and was estimated from correlating porosity and bulk resistivity from geophysical-log data. Mapping of cementation factor revealed no clear trends but was used to provide reasonable values for specific areas. Shale content was accounted for by assuming that the permeability of shale was everywhere four orders of magnitude less than the permeability of sandstone at the same location, and a lithology-weighted permeability was calculated. Because of the much smaller permeability of the shale, porosity is of much greater significance in the calculation than the lithology consideration.

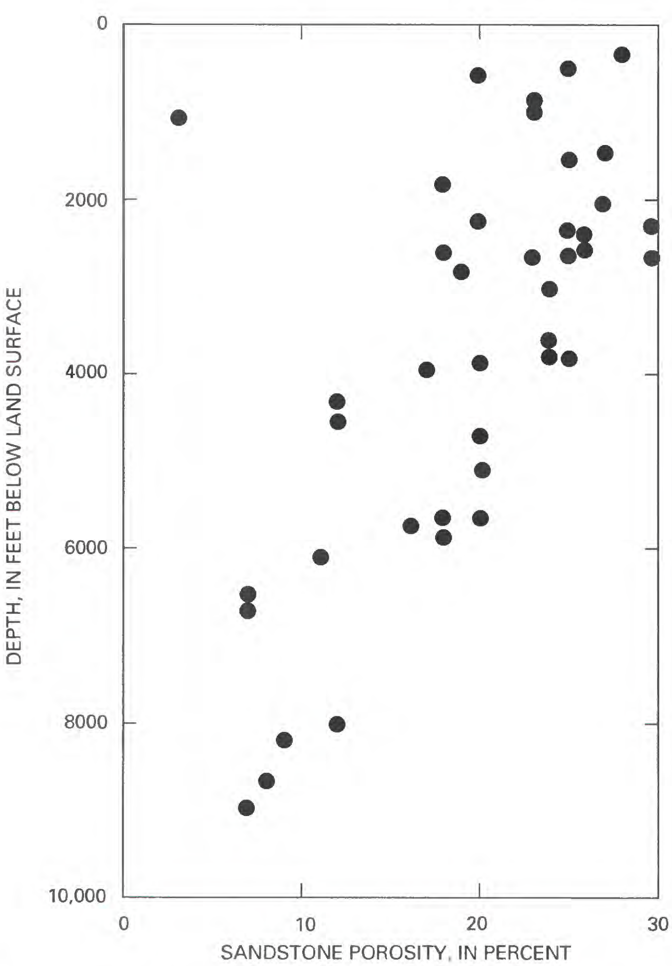


Figure 20.—Relation between depth and porosity of sandstone, as determined from geophysical logs, in Great Plains aquifer system.

Table 2.—*Volume of water stored in the Great Plains aquifer system in the study area*

[Values in millions of acre-feet]

State	Water in storage	Drainable water in storage
Colorado	1,553	388
Kansas	2,717	679
Nebraska	7,035	1,759
New Mexico	54	14
Oklahoma	9	2
South Dakota	190	48
Wyoming	244	61
Total	11,802	2,951

The resulting distribution of lithology-weighted intrinsic permeability (fig. 21) shows a decrease of several orders of magnitude across the study area from east to west. Most field-determined values of intrinsic permeability are in general agreement with these regional estimates. However, deviations are large at many locations in the Denver basin, reflecting the presence of stratigraphic traps in which petroleum has accumulated. Intrinsic-permeability values from laboratory tests of cores collected from western Nebraska tend to be one to two orders of magnitude smaller than these regionalized values. This difference is consistent with results of Neuzil (1980) and Bredehoeft and others (1983) for Upper Cretaceous shale in South Dakota and probably reflects the general absence of fractures in small samples such as cores. As a result of stratigraphic complexity, intrinsic permeability is quite variable within short distances; therefore, figure 21 should not be used to estimate local values of intrinsic permeability.

Ground-water flow is affected by hydraulic conductivity rather than intrinsic permeability. These terms are related by

$$K=k\rho g/\mu \tag{4}$$

where K is hydraulic conductivity [lt^{-1}], ρ is fluid density [ml^{-3}], g is acceleration of gravity [lt^{-2}], and μ is dynamic viscosity [$ml^{-1}t^{-1}$]. Procedures described by Weiss (1982a, b) were used to determine water density and viscosity for use in calculating the hydraulic conductivity as shown in figure 22. The maximum calculated hydraulic conductivity is about double the hydraulic conductivity of freshwater at 60 °F. Therefore, density and viscosity variations are of relatively small consequence considering that hydraulic conductivity varies by orders of magnitude.

Assuming that the estimated regional hydraulic-conductivity distribution applies to both the Maha and Apishapa aquifers, then the transmissivity distribution of each aquifer (figs. 23, 24) is obtained by multiplying by the appropriate aquifer thickness.

Vertical hydraulic conductivity is a primary factor affecting water movement between underlying and overlying rock units. Very few data exist on vertical hydraulic conductivity in the study area. However, vertical hydraulic conductivity of sandstone is commonly on the order of 0.1 to 0.01 times that of lateral hydraulic conductivity.

HYDRAULIC HEAD

Distribution of hydraulic head in the aquifer system is a product of many factors, including hydraulic

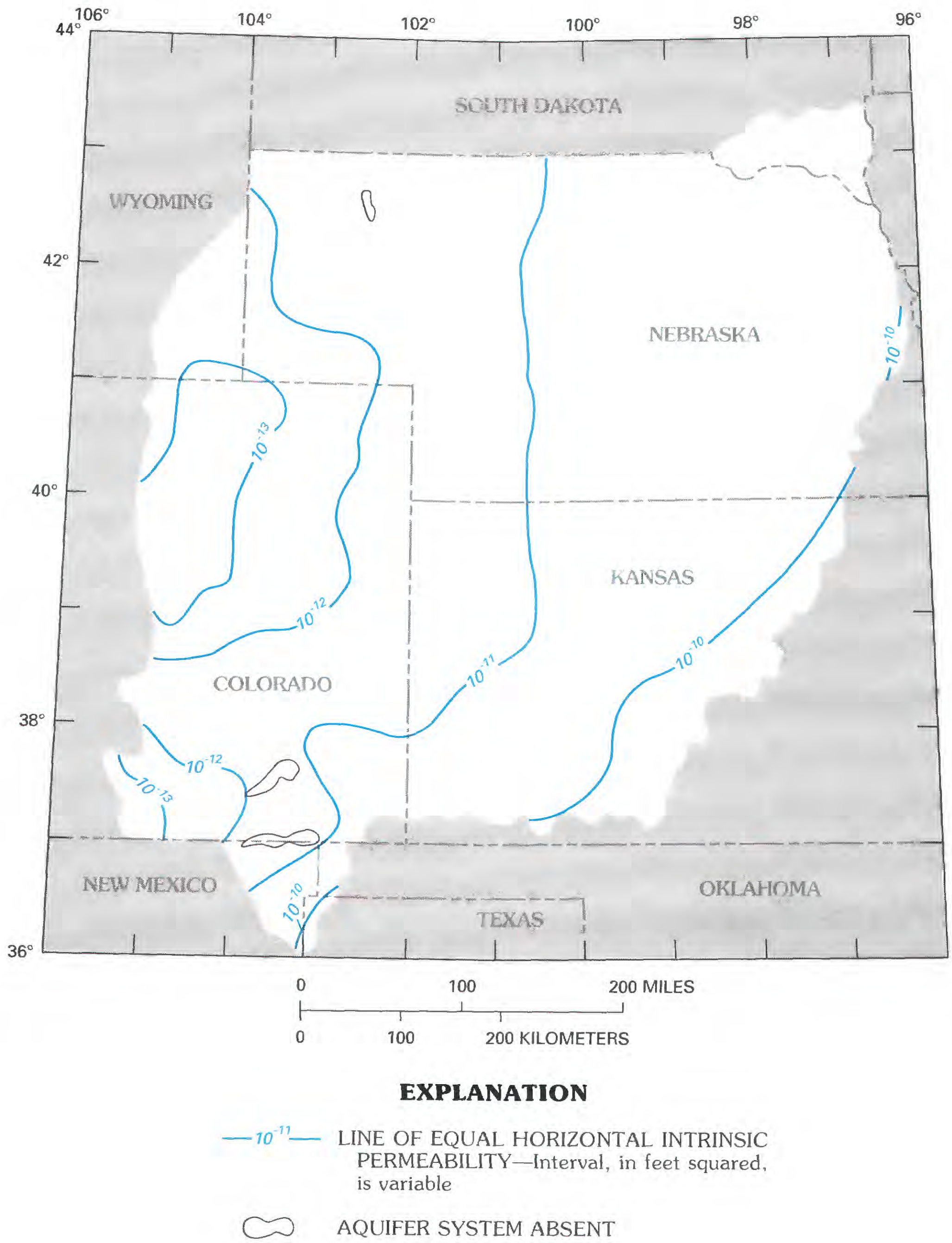


FIGURE 21.—Regionalized intrinsic permeability of Great Plains aquifer system.

properties, boundary conditions, and recharge and discharge distributions. Fluid density also is considered in aquifers containing fluids with salinity or temperature that is different from that of shallow water. Dahlberg (1982) discussed pressure and hydraulic-head conditions for various subsurface fluids, illustrating the complexities that may prevail in such locations as the Denver basin. Oil and gas occupy only a very small proportion of the aquifer system, and drill-stem-test data used for this study were selected from tests that obtained saline water as a major part of the recovered fluid, so that pressure data would be representative of the saline-water part of the system.

The effect of variable water density on interpretations of ground-water flow can be significant (Hubbert, 1940; Jorgensen and others, 1982). A map of equivalent freshwater head was prepared for the Great Plains aquifer system on the basis of known or estimated fluid densities (pl. 5). The maximum hy-

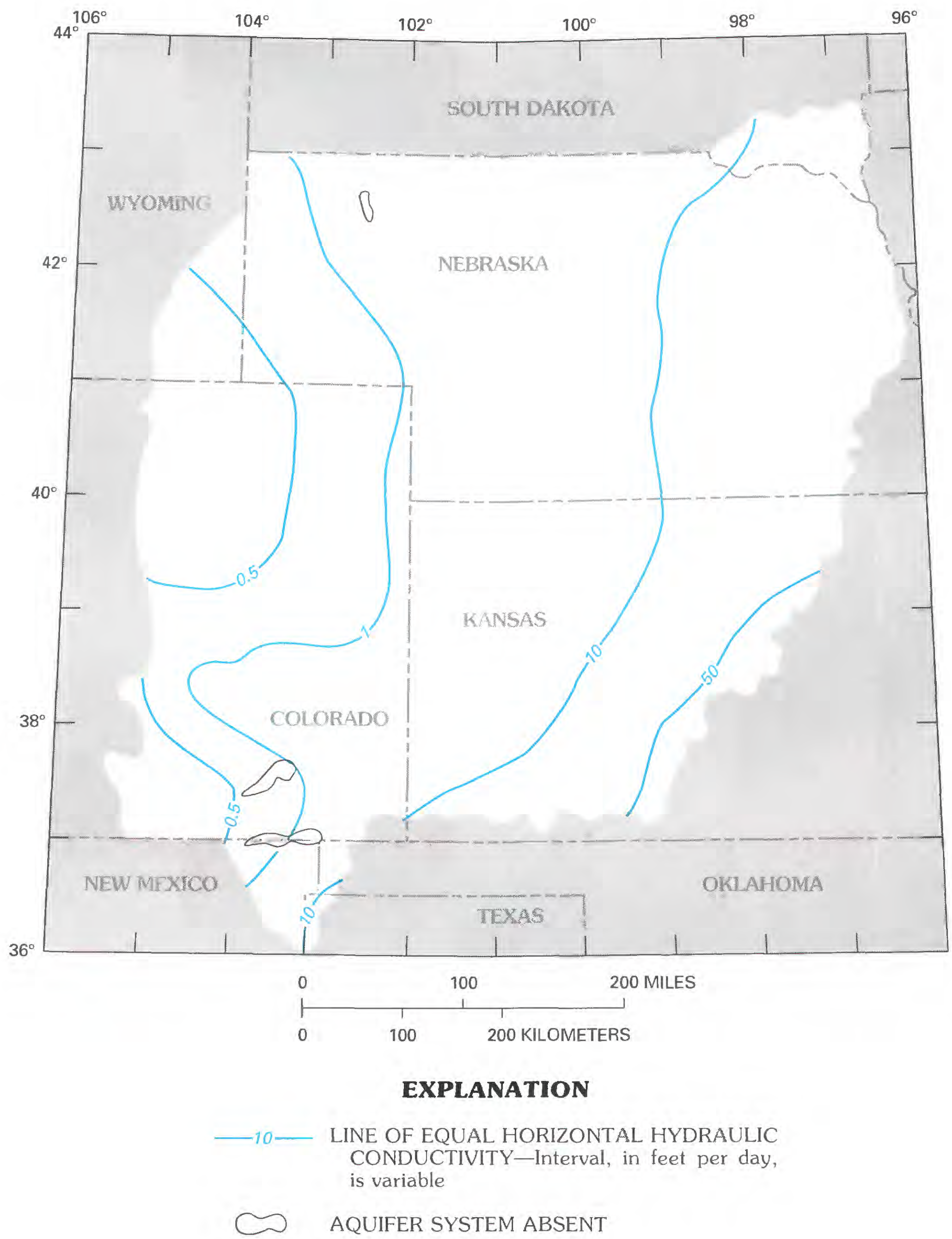


FIGURE 22.—Regionalized hydraulic conductivity of Great Plains aquifer system.

draulic-head adjustment for salinity at any location is about 100 feet, and throughout most of the area it is much less. This adjustment is small relative to the regional range in hydraulic head. Furthermore, because of typically small hydraulic conductivity, the effect of head adjustment on flow rates is insignificant. The equivalent freshwater-head distribution thus is presumed to approximately represent the potentiometric surface that defines regional flow.

Water in most of the Great Plains aquifer system is confined. Confined hydrostatic heads generally are expected to be close to water-table altitudes (a regionalized water-table map of the study area is shown in figure 25). However, underpressured conditions (small confined heads) prevail in the Great Plains aquifer system, as illustrated by figure 26, which shows the difference between water-table altitudes and the confined heads of the aquifer system.

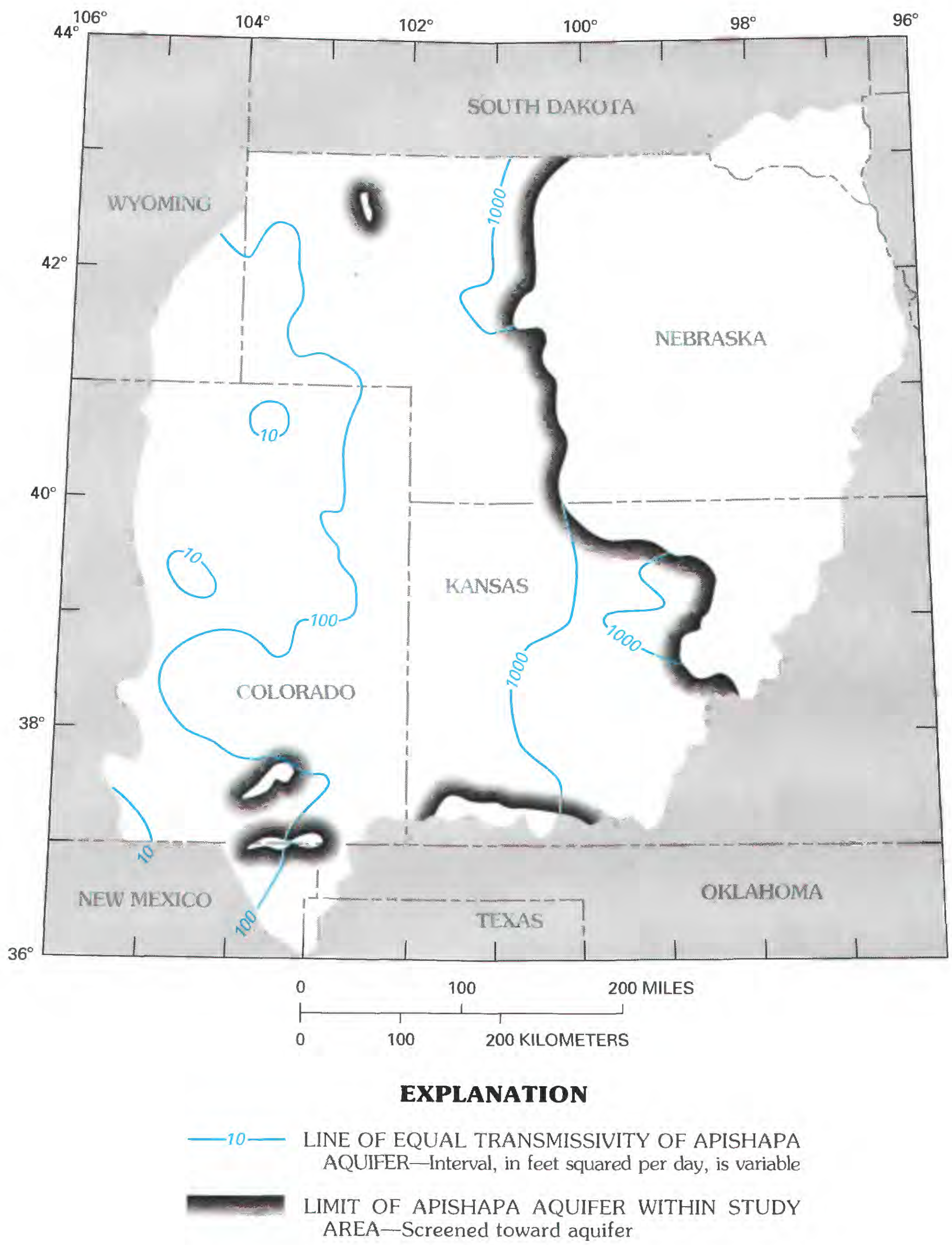


FIGURE 23.—Regionalized transmissivity of Apishapa aquifer.

The underpressured condition was not discussed by Darton (1905) because no data were available at that time for a large area of Nebraska, northern Kansas, and northern Colorado. Collection of relatively recent data has enabled identification of this condition (Russell, 1961; Hoeger, 1968; Helgesen and others, 1982; Ottman, 1984; Belitz, 1985). The amount of underpressuring generally is related to geologic structures. In two areas near the axis of the Denver basin, the difference between the water-table altitudes and confined heads exceeds 2,500 feet.

Unconfined conditions in the Great Plains aquifer system occur in and near areas where it is exposed (figs. 18, 26), some of which are not shown at the small map scale. An unconfined condition also is present, but not shown at this map scale, in a small area of northwestern Nebraska and is discussed later.

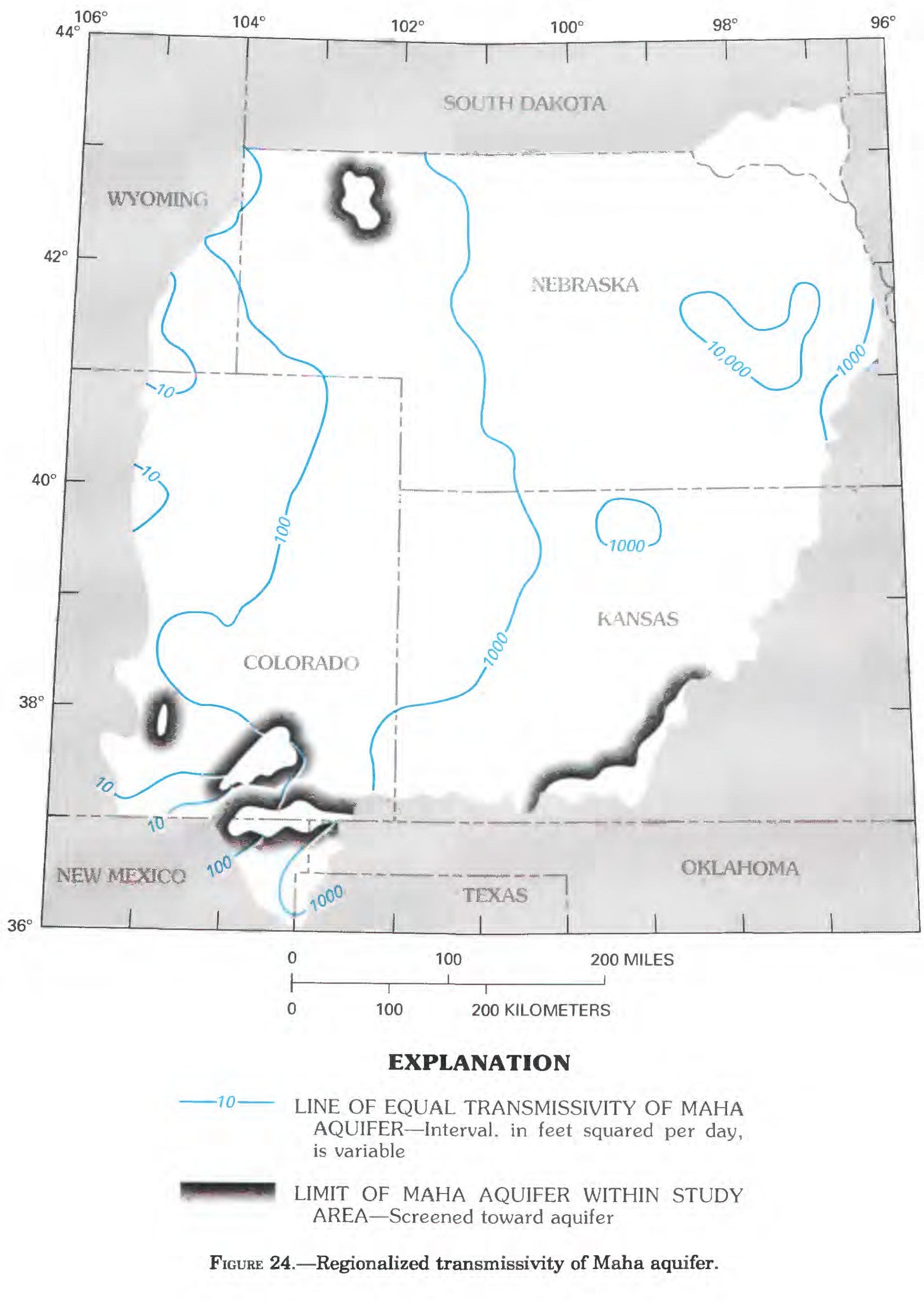
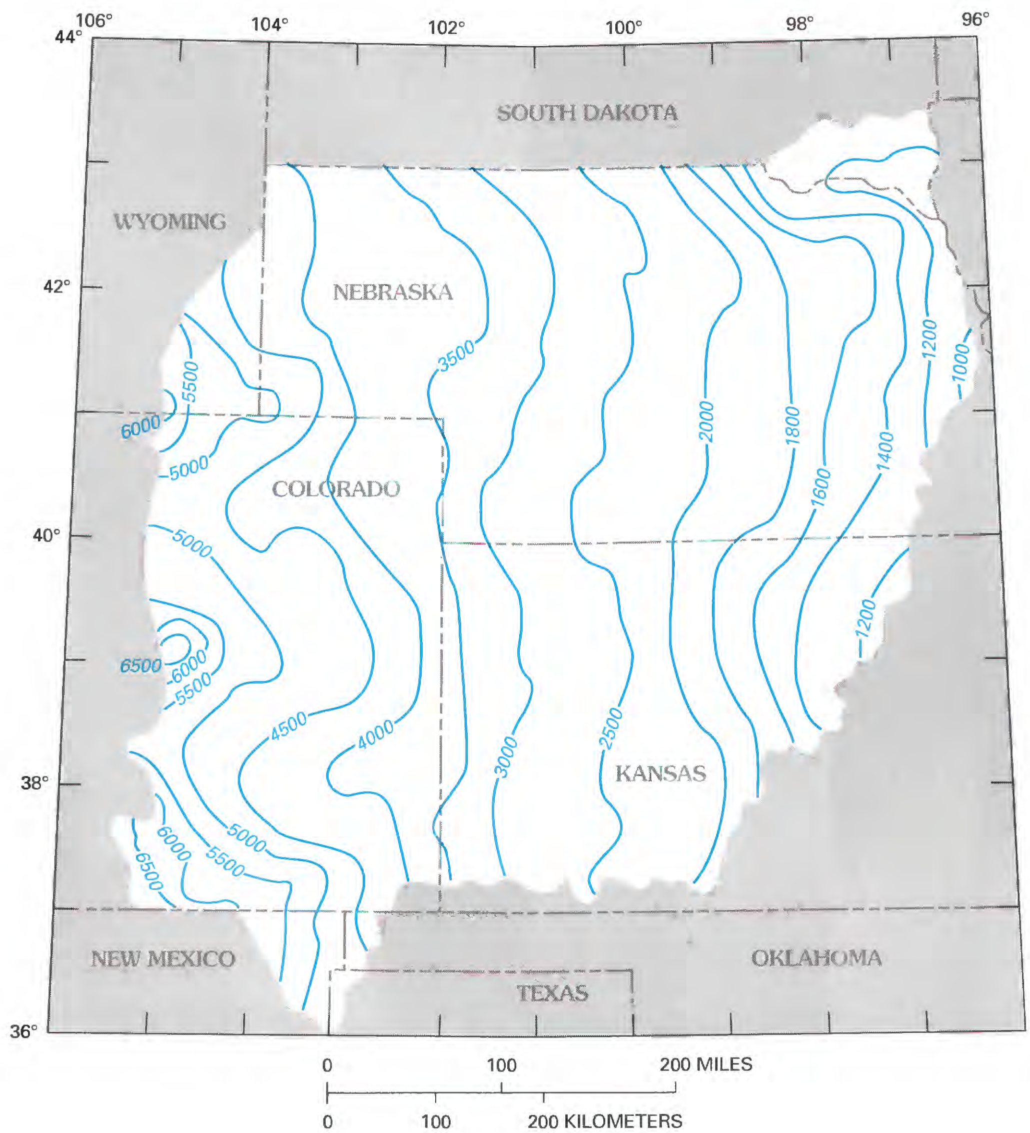


FIGURE 24.—Regionalized transmissivity of Maha aquifer.

The equivalent freshwater-head distribution in plate 5 is assumed to represent regional predevelopment conditions in the Great Plains aquifer system. Distribution and rates of fluid withdrawals are described later, in the section entitled "Present Development." Freshwater pumpage has caused head declines in places, but these declines have not been well documented, and they are small at the scale and contour interval shown in plate 5. Head declines due to withdrawal of saline water associated with oil and gas development in the Denver basin also are undocumented but probably are significant. The area of particularly small and variable hydraulic-head values generally coincides with the area of oil-and-gas development; furthermore, the computer flow model (discussed later) simulates reasonable magnitudes of head decline in this area in response to estimated withdrawals. Equivalent freshwater heads mapped in northern Colorado, western Nebraska, and southeastern Wyoming (pl. 5) are inferred predevelopment heads, which do not agree with present heads. The inferred contours are smoothed projections of contours that enter the oil-and-gas development area. The inferred predevelopment potentiometric surface



EXPLANATION

—2000— WATER-TABLE CONTOUR—Shows altitude of water table. Intervals 200 and 500 feet. Datum is sea level

FIGURE 25.—Altitude of water table in study area.

is as much as several hundred feet higher than the present heads. Present heads are quite variable, even within short distances. This variability may be attributable partly to oil-and-gas development. However, Robson and Banta (1987) noted that complex hydraulic conditions might be associated with the lithologic heterogeneity of this aquifer system. Generation and trapping of gas may have resulted in local pressure anomalies. Furthermore, problems and inaccuracies of drill-stem tests and their analyses con-

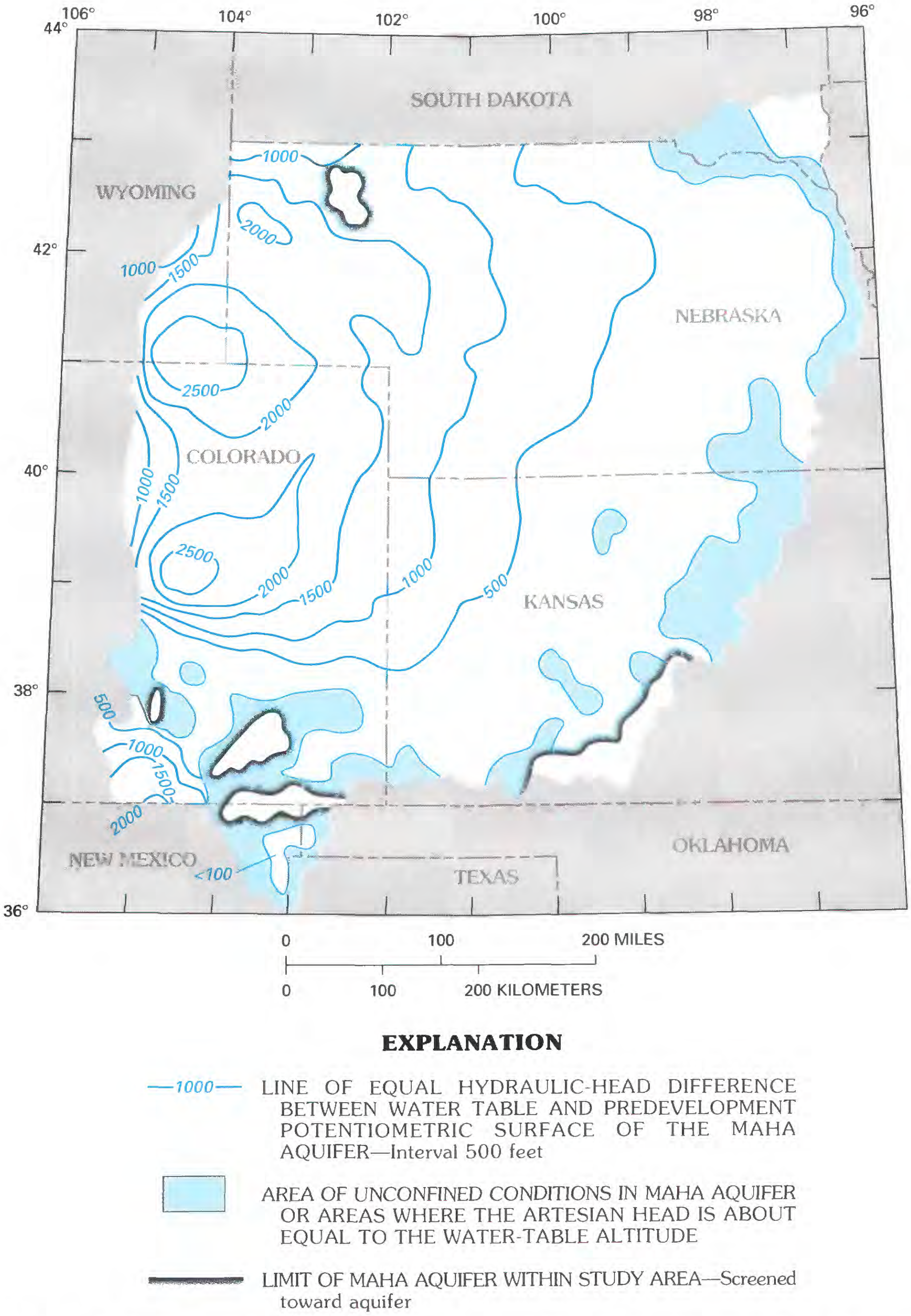


FIGURE 26.—Difference in hydraulic head between water table and potentiometric surface of Maha aquifer for predevelopment conditions.

tribute an unknown variability to the data. Detailed study of small areas could contribute to a better understanding of the complex relations that appear to exist among lithologic and hydraulic properties, hydraulic head, water quality, and oil-and-gas development in the Denver basin.

HYDROCHEMISTRY

The natural chemical composition of ground water is the result of time-, temperature-, and pressure-dependent reactions among dissolved constituents in the water and minerals in the rock and soil. Therefore, the chemistry of a sample of ground water is a product of any or all of the following factors: chemistry of the water entrapped in the interstices of sedimentary rocks during deposition; changes accompanying diagenesis; the lithology and structure of the soil or rock through which it has passed; the rate of flow and position along a flow path; and interchange with water from the surface or from adjacent rock units.

The principal objective of the hydrochemical studies described herein is to relate the regional distribution of the major ions in ground water in the Great Plains aquifer system to its geohydrology. The results also serve as a basis for evaluating the chemical quality of the ground water for use.

Because trends in water chemistry in a continuous porous medium generally are systematic and somewhat predictable, they can be used to aid in the definition of conceptual models of the flow system. Similarities in water chemistry over wide areas are considered evidence of similar geohydrologic origin. Conversely, major changes or discontinuities in water quality may reflect significant geologic and hydrologic features, such as faults, changes in mineralogy or hydraulic conductivity of the aquifer, or interchange with water from adjacent rock units. The density of water increases as its dissolved-solids content increases; therefore, large concentrations of dissolved solids can have a significant effect on the hydrodynamics of a variable-density system.

PROCESSING AND MAPPING OF DATA

Concentrations of dissolved solids and chloride, hydrochemical facies (chemical water types), and ratios of the concentrations of sodium to chloride in the Great Plains aquifer system are shown on plates 6–10. The illustrations are based principally on data selected from more than 4,000 water analyses and associated data on location and depth.

The principal sources of data for plates 6–10 were WATSTORE (National Water Data Storage and Retrieval System, U.S. Geological Survey), PDS (Petroleum Data System of North America, University of Oklahoma), and NURE (National Uranium Resource Evaluation Program, U.S. Department of Energy). Published and unpublished information from various sources also was used. Most of the chemical data available were for samples reportedly from the Maha aquifer. However, because the boundaries of individual sandstone bodies in the aquifer system are irregular and poorly defined over large areas, some samples appear, based on reported sampling depth, to have been collected from geohydrologic units vertically adjacent to the Maha aquifer. Furthermore, some wells were open to more than one rock unit. Data were used only if reported locations and depth, as well as continuity with adjacent samples, indicated that the sample probably was obtained from within the Great Plains aquifer system.

The WATSTORE and NURE data describe water collected chiefly from relatively shallow domestic, municipal, and irrigation wells yielding freshwater from depths less than 1,000 feet. Most of these wells are located in a relatively narrow band along the eastern and southern edges of the area where the water is most subject to local recharge and surface contamination. The PDS data, principally from oil fields or exploratory wells, generally describe saline water or brine associated with oil and gas at depths between about 3,000 and 9,000 feet in the western part of the study area. Data from intermediate depths (1,000 to 3,000 feet) are sparse.

Most of the chemical data available for the Great Plains aquifer system represent water samples that were collected and analyzed for purposes other than hydrochemical studies. Minimal new data were collected as part of this study, and few of the data probably represent in-situ equilibrium with minerals in the aquifer. Although the chemical data are not adequate to simulate the chemical evolution of water along flow paths, most of the data are useful for general description and interpretation of regional trends.

The central part of the area, where adequate supplies of freshwater commonly can be obtained from the surficial High Plains aquifer, has nearly no hydrochemical data for the Great Plains aquifer system. Concentrations of dissolved solids in this area were estimated from geophysical logs of exploratory wells drilled through the aquifer system to test deeper formations. Those estimates, along with dissolved-solids concentrations determined from laboratory analyses and regressions with chloride, resistivity, or specific conductance, were used to describe regional trends in dissolved solids (pl. 6).

Large lateral and vertical variations in the concentrations of major ions necessitated selection of chemical analyses of water samples that presumably represent conditions over broad areas. Differences of more than an order of magnitude in chemical values in samples from closely adjacent wells are common. Significant differences also are reported for samples collected at different depths and times from the same well. Concentrations of dissolved solids estimated from geophysical logs commonly increased with depth and differed widely from those determined by laboratory analysis of samples from nearby wells.

Part of the variability can be ascribed to faulty sampling and analytical techniques or to oil-field activities, including brine disposal, repressurization, and induced migration accompanying withdrawals of fluid. Because chemical changes (particularly in the concentrations of conservative ions) normally represent mass transfer, they are less likely to represent localized transient conditions than are changes in pressure. Therefore, when combined with the accompanying large variations in pressure and hydraulic conductivity, the chemical variations support the evidence of natural heterogeneity of the aquifer system.

In the oil-field areas, most of the samples appear to consist of water from reservoirs having poor hydraulic interconnection. Hydrocarbons can alter the hydraulic properties of the rock as well as react with it or with ionic constituents in the water. However, it is assumed, as stated by Tóth (1980), that hydraulic continuity is maintained across even the least permeable elements.

Preliminary mapping of dissolved solids showed that selection of regionally representative analyses was very subjective, but that the configuration of the contours indicate apparent regional trends. Computer programs were developed (J. Baird and F. Sherman, U.S. Geological Survey, written commun., 1984) to select, for mapping, the analyses having median concentrations of chloride and dissolved solids at median depth within quadrangles (normally 5 minutes of latitude and longitude). Median, rather than mean, values were used because the median values are less affected by skewed values.

In a balanced chemical analysis, the sums of the concentrations (expressed in milliequivalents per liter) of cations and of anions (positively and negatively charged ions, respectively) are approximately equal. For most of the analyses selected for use, the difference between those sums was less than 10 percent. Plates 6–9 are based on data representing 5-minute quadrangles; for clarity, only the data values representing 15-minute quadrangles are shown.

DISSOLVED SOLIDS AND MAJOR CONSTITUENTS

The dissolved-solids concentration is useful for classification of water and as a general measure of its chemical quality. The concentration of dissolved solids in ground water from the Great Plains aquifer system ranges from 500 milligrams per liter (mg/L) or less in the eastern and southern outcrop areas to about 140,000 mg/L in oil-field areas in the Denver basin (pl. 6). According to various classifications used by the U.S. Geological Survey (for example, Winslow and Kister, 1956), freshwater is defined as containing less than 1,000 mg/L, and brine as containing more than 35,000 mg/L of dissolved solids, the approximate concentration in seawater. Water containing intermediate concentrations of dissolved solids are classified as saline, although saline water containing less than 10,000 mg/L (characteristic of much of the Great Plains aquifer system) may be classified as brackish.

In general, the concentration of dissolved solids commonly increases downgradient from recharge areas as minerals are dissolved or as meteoric water mixes with more concentrated connate water; therefore, dissolved-solids maps may be used for interpretation of the ground-water flow system. However, within the study area, the largest concentrations of dissolved solids in the aquifer system generally occur in the Denver basin, and the smallest concentrations occur downgradient along the eastern edge of the study area. The significance of this deviation from normal conditions is addressed later in the section entitled "Regional Ground-Water Flow System."

The value of dissolved-solids maps as a measure of water quality or as an interpretive tool is enhanced when the distribution of the ionic components is known. The concept of water type, or hydrochemical facies (Back, 1960), in which the relative composition of the water is described in terms of the principal ions (pl. 7), is used herein to provide additional information on the probable source and flow path of the water in the aquifer system.

The concentrations (expressed in milliequivalents per liter) of each of the ions can be expressed as percentages of total cations and anions. As used herein, the principal ion refers to the cation or anion that composes more than 50 percent of the total cations and anions. If no cation or anion exceeds 50 percent, the water is classified as mixed cation and anion. Plate 7 shows broad areas of sodium chloride, sodium bicarbonate, calcium sulfate, and calcium bicarbonate type water. Areas of sodium bicarbonate, sodium sulfate, and mixed water probably result from mixing or natural softening by ion exchange. In general, the hydrochemical facies show less spatial variability than do the associated concentrations of individual ions.

As described above, the aquifer system consists principally of sandstone, siltstone, and shale. These rocks are composed principally of relatively insoluble minerals, including quartz (SiO_2), feldspar ($K\text{-}NaAlSi_3O_8$, $CaAlSi_2O_8$), and clay minerals, mainly complex aluminosilicates formed largely by degradation of the feldspars. Although relatively insoluble, many of the clay minerals are reactive, are capable of participating in ion-exchange reactions, or form membranes capable of selective filtration of individual ions. Ion-exchange reactions probably affect the water type, but dissolution of the relatively insoluble minerals in the system probably does not appreciably increase the dissolved-solids concentration.

The soluble evaporite minerals rock salt or halite (NaCl), gypsum ($CaSO_4 \cdot nH_2O$), and anhydrite ($CaSO_4$) are generally absent from the Great Plains aquifer system but are present in some overlying or underlying rock units. Therefore, the widespread occurrence of sodium chloride or calcium sulfate type water containing more than 2,000 mg/L dissolved solids suggests sources and processes other than dissolution of minerals within the aquifer system.

Because the sediments of the aquifer system were deposited in a terrestrial to marine environment, the chemical composition of unaltered connate water would range between the compositions of meteoric water and seawater. Water in the Cretaceous sea probably was a sodium chloride type similar to modern seawater; therefore, the sodium chloride type water (pl. 7) probably represents mixing of residual estuarine water or seawater with recharge water, or leakage of salty water from adjacent strata, depending on vertical hydraulic-head relations.

Chloride (pl. 8) is a useful major ion to aid in the interpretation of the flow system. It is the principal ion component of seawater, most oil-field brine, and other deep formation water. At the temperatures and pressures occurring in the Great Plains aquifer system, chloride tends to be conservative. That is, unlike most of the other major ions, it does not precipitate from solution nor does it react appreciably with minerals as it migrates along the flow paths. Because chloride-rich minerals are not common in the aquifer system, large concentrations, particularly those exceeding 19,000 mg/L (the approximate concentration of chloride in seawater), normally can be ascribed to entrapped or altered seawater, to migration of saline water from vertically adjacent salt-bearing units, to oil-field-brine contamination, or ion filtration. Conversely, smaller concentrations reflect nonmarine conditions of deposition or dilution with meteoric water.

Ratios of the major ions (in milliequivalents per liter) provide additional information useful for distinguishing between different sources of salinity. Although ratios from different sources may overlap (Whittemore and others, 1981), they can be used to strengthen or weaken the interpretations based on associated data. Certain trace constituents and stable isotopes might provide more information describing the sources of saline water and flow patterns; however, the distribution of data describing those constituents is inadequate for regional interpretation.

The milliequivalent ratio of concentrations of sodium to chloride (Na:Cl) (pl. 9) is particularly useful for determining the probable sources of large concentrations of chloride (Leonard, 1964). If the source of chloride is dissolution of rock salt, the Na:Cl ratio should be about 1.0. If the water was derived from relatively unaltered seawater, the value would be about 0.85. The Na:Cl ratio for oil-field brines from older formations in the study area characteristically is about 0.80. Ratios larger than 1.0 probably represent either dilution of chloride or increased sodium concentrations produced by cation-exchange reactions. The extensive areas of Na:Cl ratios larger than 1.0, shown on plate 9, probably have resulted from a combination of saline-water dilution and cation-exchange reaction.

PRESENT DEVELOPMENT

The Great Plains aquifer system has been developed during the past several decades to provide freshwater and oil-and-gas supplies. The areas of development (fig. 27) are regionally distinct; most of the freshwater is withdrawn where the aquifer system is shallower than about 1,000 feet, and oil-and-gas production is in the Denver basin from depths exceeding 3,000 feet. Saline water also is withdrawn in association with petroleum production, but much of that withdrawn is reinjected into the aquifer system. The distribution and rates of all fluid withdrawals and injections have been poorly documented in most areas. The history of these developments, reconstructed to the degree possible, is discussed in the following paragraphs. Estimates are made on a temporal basis by decade (an average rate assumed to be representative of each 10-year period), on an areal basis by county, and on a source basis by aquifer (either Maha or Apishapa aquifer).

FRESHWATER

Withdrawals of freshwater from the aquifer system are concentrated mainly along the southern and eastern margins of the study area (fig. 27). The largest withdrawals are in parts of the Great Plains aquifer system where it is directly overlain by the High Plains aquifer in southwestern Kansas and southeastern Colorado. A summary of estimated freshwater pumpage by State and decade (fig. 28) shows that ground-water development of the Great Plains aquifer system has increased steadily through the past several decades. Pumpage was estimated because little of the actual pumpage is reported. Methods of estimation varied from state to state depending on the type of information available. Pumpage estimates for much of the large-scale development (mainly for irrigation) were derived from well-permit records. Pumpage for domestic and stock use mainly was estimated from census data and assumed average consumption rates.

Average freshwater pumpage from the aquifer system for the 1970's is estimated to be on the order of 850 ft^3/s (615,000 acre-ft per year) (fig. 28). The major use of freshwater is for irrigation. Public supply is a significant use, whereas industrial use is relatively

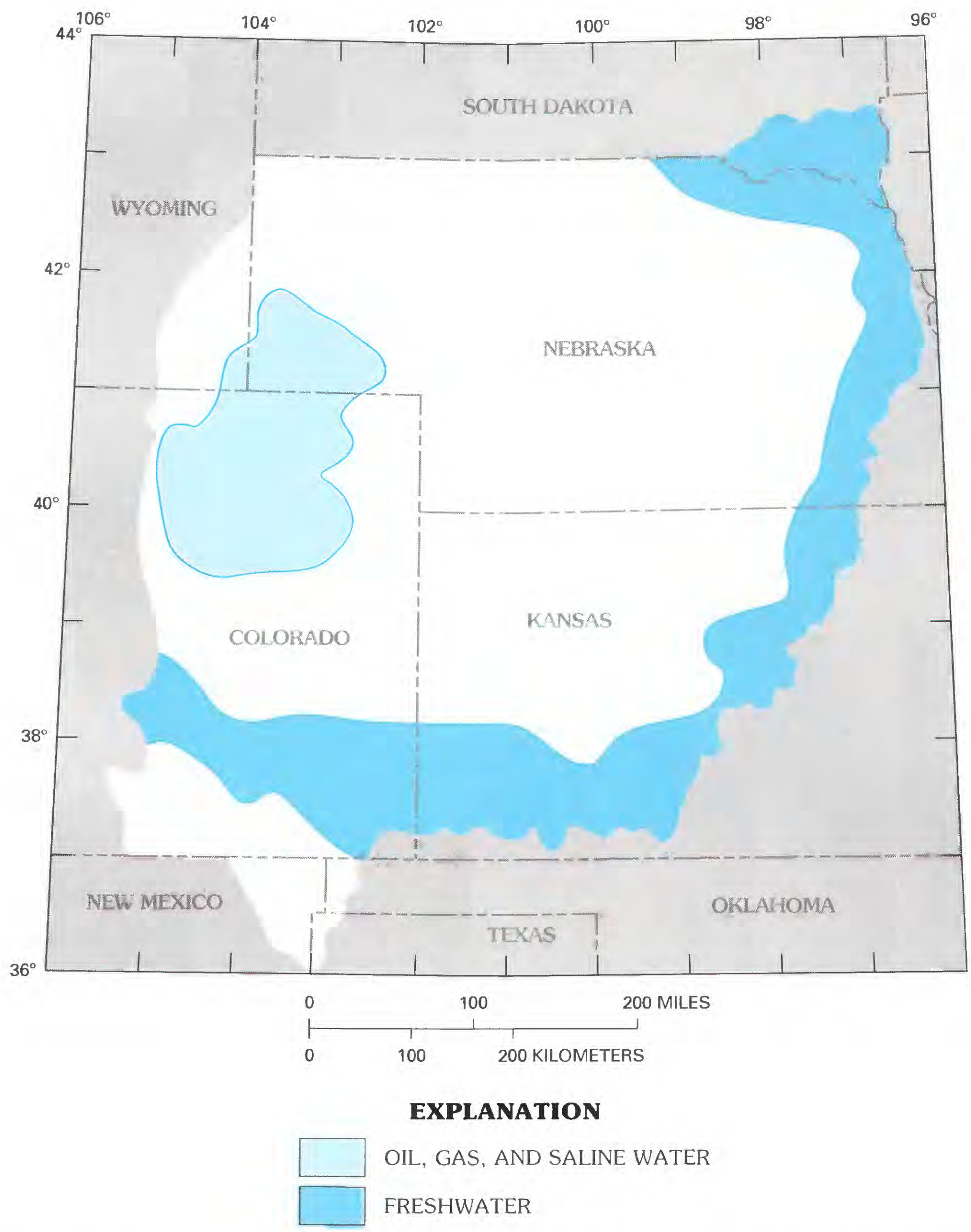


FIGURE 27.—Major areas of withdrawal of freshwater and oil and gas from Great Plains aquifer system.

minor. Withdrawals for domestic and stock supplies are made through many individual wells but are a relatively small part of the total amount withdrawn.

Publications and files containing water-use data rarely specify the source (aquifer) of pumped ground water. This problem is significant particularly for southwestern Kansas and southeastern Colorado, where a common practice of well construction is to screen both the High Plains aquifer and the Great Plains aquifer system. A recent estimate of 1985 withdrawal rates from the Great Plains aquifer system in Kansas (Baker and Kenny, 1990) is only about one-half of the rate used for Kansas in this study. This discrepancy probably exemplifies the crudeness of the earlier water-use estimates.

OIL AND GAS

Nearly all oil and gas from the aquifer system is produced from the Denver basin in northeastern Colorado and the southern part of the Nebraska panhandle. Essentially all oil-and-gas production is reportedly from the top part of the system (Maha aquifer).

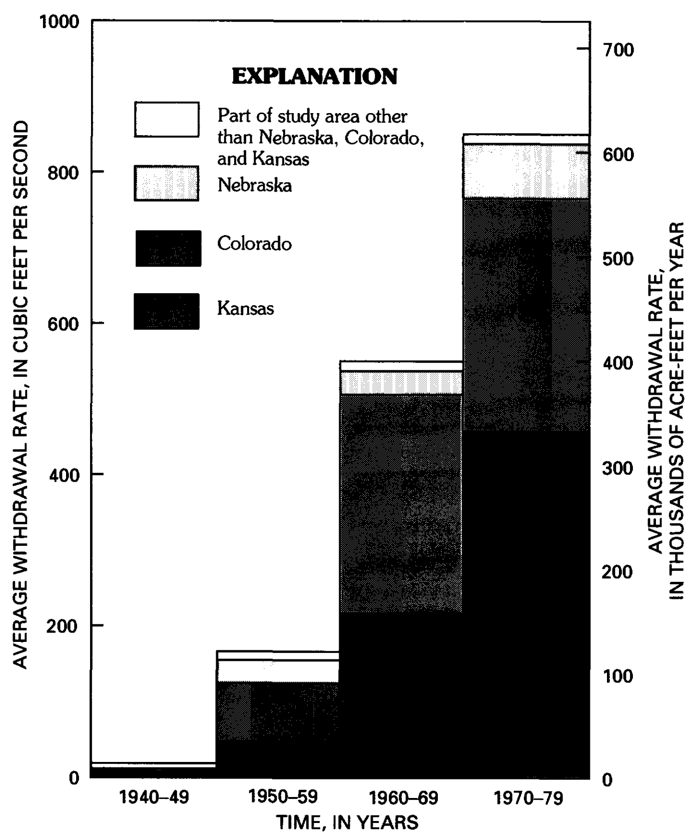


FIGURE 28.—Estimated freshwater withdrawal rate from Great Plains aquifer system, 1940–79.

Only small quantities of oil and gas were produced before 1950, and production peaked in the 1960's (fig. 29). The average withdrawal rate from the aquifer system during the 1970's is estimated to be about 3 ft^3/s. As is the case with freshwater-withdrawal data, no single source of information provides complete records of petroleum production. Sources of data that were consulted include State-agency publications and files, International Oil Scouts Association (1977), and a computerized data base (Petroleum Data System of North America).

Estimates of oil-and-gas withdrawals (fig. 29) are presented in terms of equivalent water volumes, by accounting for the densities of oil and gas as follows:

$$V_{eq}=M_{og}/d_w=(d_o/d_w)V_o+(d_g/d_w)V_g \qquad (5)$$

where

V_{eq} is equivalent volume of water $[l^3]$,
M_{og} is mass of oil and gas $[m]$,
d_w, d_o, and d_g are densities of water, oil, and gas, respectively $[ml^{-3}]$, and
V_o and V_g are volumes of oil and gas, respectively $[l^3]$. Average densities, relative to water, of 0.87 for oil and 0.001 for gas were assumed.

SALINE WATER

Saline water, "oil-field brine," is pumped in association with oil, typically at rates that exceed the rates of oil production. Unfortunately, records of saline-water pumpage in most of the area are inaccurate. Other factors also make the estimates of withdrawals difficult: (1) water-to-oil production ratios vary spatially and temporally, depending on reservoir conditions,

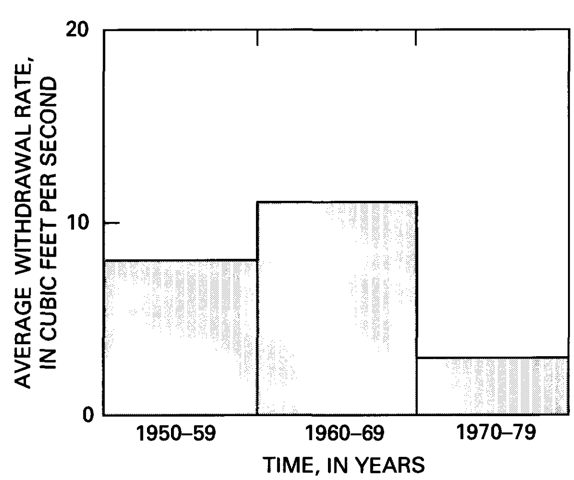


FIGURE 29.—Estimated oil and gas withdrawal rate from Great Plains aquifer system (in terms of equivalent water volume), 1950–79.

development and production procedures, and prevailing economic constraints; (2) the practice of injecting saline water back into the aquifer for disposal has increased in recent years; (3) water injection for maintaining reservoir pressure also has increased recently; and (4) the aquifer system has been used, in a few places, as a source of water for pressure-maintenance operations in deeper oil-producing zones.

Estimates of saline-water withdrawals are important; however, the accuracy of estimates is debatable due to these complexities. A water-to-oil ratio of 2:1 is assumed for the 1950's estimates, and a ratio of 4:1 is assumed for the 1960's and 1970's estimates. The lack of increase in water-to-oil ratio for the 1970's is appropriate if the increase that normally occurs through time is offset by injection of saline water into the aquifer. Based on these assumptions, the average withdrawal rate of saline water from the aquifer system during the 1970's was about 12 ft^3/s.

REGIONAL GROUND-WATER FLOW SYSTEM

An understanding of ground-water flow in the Great Plains aquifer system is needed to evaluate the potential of the resource for use. Recharge, discharge, and flow are important factors relating to water-yielding capability, spatial and temporal variation of water quality, and response of the system to fluid withdrawal or injection. The flow system is described in the terms of conceptual and computer models.

CONCEPT OF PREDEVELOPMENT FLOW

A conceptual model of flow through the aquifer system must consider numerous factors, including topography, geometry and lithology of the system, hydraulic properties, hydraulic-head distribution, hydrochemistry, nature of aquifer-outcrop areas, surface- and ground-water relations, and characteristics of overlying and underlying rock units.

The concepts of recharge and discharge will be considered first, followed by a description of regional flow through the aquifer system. An aquifer system, even under natural conditions, is never in an absolute state of equilibrium (steady state). The flow system is continually adjusting (quasi-steady state) to temporal variations of recharge and discharge. Extreme climatic conditions certainly have influenced ground-water conditions through time. However, estimates of long-term average recharge and discharge can represent the approximate state of equilibrium of the aquifer system. This section discusses the steady-state conditions of the aquifer system before development.

RECHARGE

All natural recharge originates as precipitation, but the routes by which water enters the aquifer system vary considerably within the study area. Recharge occurs by direct infiltration of rainfall in outcrop areas, by leakage downward through overlying strata, by leakage upward through underlying strata, by lateral boundary flow from outside the study area, or by seepage through streambeds.

DIRECT INFILTRATION IN OUTCROP AREAS

Recharge directly to the aquifer system from precipitation takes place where strata composing the system are exposed (fig. 30). Outcrops are a small part of the system areally (less than 5 percent), but hydrologically they are significant because of relatively rapid rates of recharge. For purposes of estimating natural recharge rates, outcrop areas are classified as flat outcrop areas or hogback outcrop areas (fig. 30). Recharge approximations for flat outcrop areas are taken from model results of Dugan and Peckenpaugh (1985) that include estimations of regional ground-water recharge for much of the CM-RASA project area, based on climate, soils, and land-use data. Application of these results to hogback areas (steeply dipping erosion-resistant ridges) is questionable. Because of complicating effects, such as steep local topographic relief, estimates of recharge in the hogback areas are difficult if not impossible. An approximation is taken that recharge rates in the hogback areas are assumed to be equal to the lateral flow in the aquifer system away from those areas. The recharge rate, Q, is estimated by Darcy's equation

$$Q=KA(dh/dl) \quad [l^3t^{-1}] \tag{6}$$

where K is hydraulic conductivity $[lt^{-1}]$, A is cross-sectional area of flow $[l^2]$, and dh/dl is hydraulic gradient [dimensionless] near the hogback areas.

Three large areas of flat outcrop are referred to herein as the central Kansas, Purgatoire-Cimarron, and Pueblo areas (fig. 30). The central Kansas outcrop area extends from Washington County to Rice County, Kansas, along the eastern edge of the aquifer system. Alluvium and loess deposits cover the aquifer system along several southeasterly flowing streams, but broad outcrops of the Maha aquifer and the Apishapa confining unit occur in the interfluves (divide areas between streams). Parts of these outcrop areas receive recharge that moves only short distances, then discharges locally to small streams. Small parts of the outcrop areas probably receive recharge that moves greater distances to major streams (Republican, Solomon, Saline, or Smoky Hill Rivers) or leaks downward to the regional system. Application of recharge rates from Dugan and Peckenpaugh (1985) over those parts of the outcrop that are assumed to contribute to the regional system results in a long-term average recharge rate of about 10 ft^3/s in the central Kansas outcrop area.

The Purgatoire-Cimarron outcrop area is associated with erosion along the Purgatoire and Cimarron Rivers and tributaries in southeastern Colorado, northeastern New Mexico, and extreme western Oklahoma. The valleys are relatively narrow and deeply incised, but broad areas adjacent to the valleys

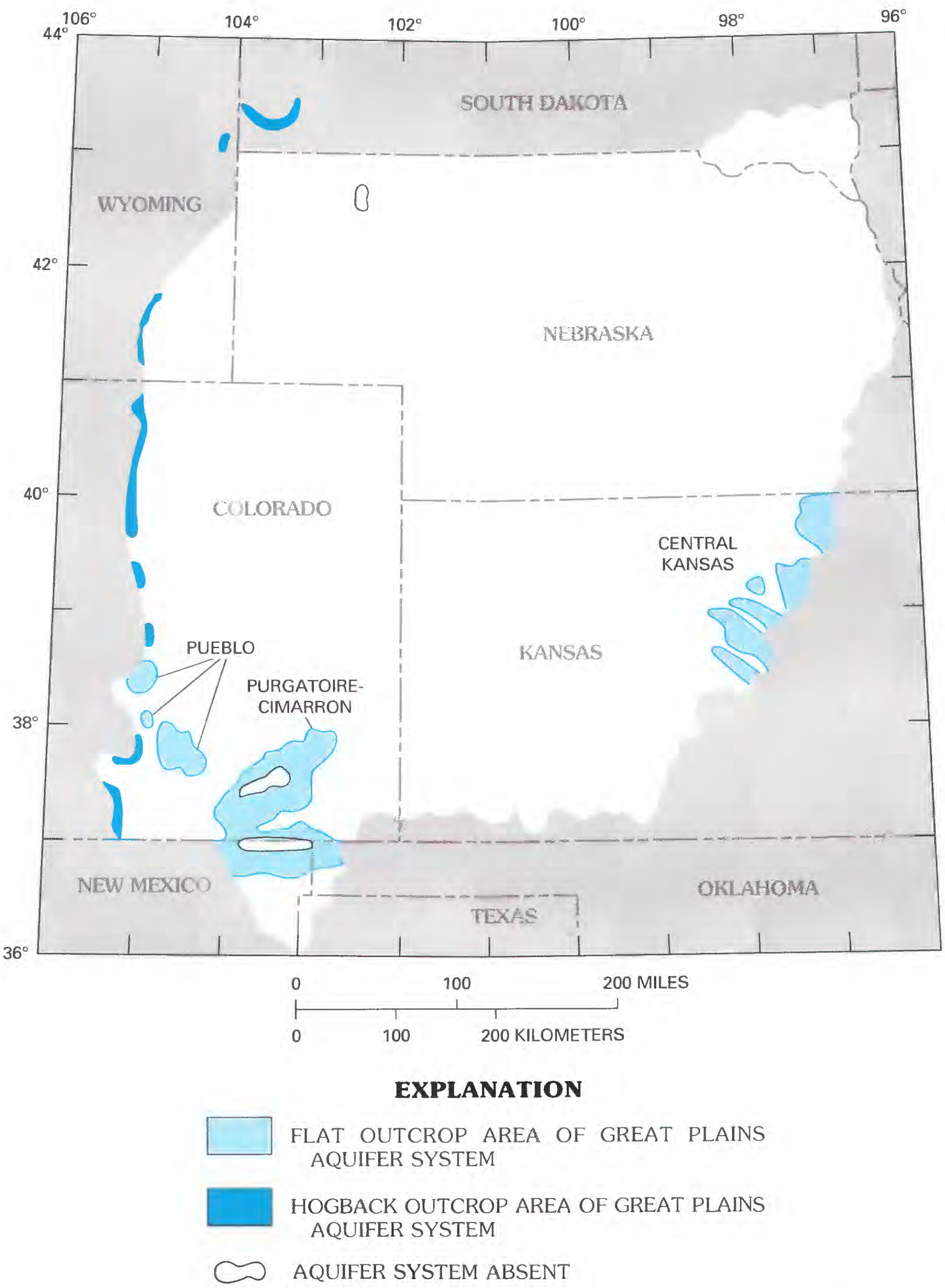


FIGURE 30.—Areas of recharge by direct infiltration to Great Plains aquifer system.

accept recharge directly to the aquifer system. The recharge rate to the regional system, estimated as previously described, is also about 10 ft^3/s in the Purgatoire-Cimarron outcrop area.

The Pueblo outcrop area includes an assemblage of outcrops in and near Pueblo County, Colorado. These areas collectively accept recharge, estimated as previously described, at a rate of about 5 ft^3/s. Flow-net analyses near individual outcrop areas (E.R. Banta, U.S. Geological Survey, written commun., 1983; Banta, 1985) give comparable results.

The quality of water in the aquifer system near the large areas of flat outcrop reflects recharge conditions. Water in these areas of the aquifer system contains small concentrations of dissolved solids and chloride (pls. 6, 8) and is commonly a calcium carbonate type (pl. 7). The calcium and bicarbonate ions probably are derived chiefly by dissolution of ubiquitous calcium carbonate in the outcrop areas by carbon-dioxide-charged meteoric water that constitutes the recharge.

Outcrop areas in the form of hogbacks (fig. 30) occur where strata have been eroded along the western edge of the study area in association with uplift of the Rocky Mountain system. Along the foothills of the Rocky Mountains in Colorado and Wyoming, the hogbacks consist of strata dipping steeply into the Denver and Raton basins. Along parts of the foothills, faulting has severed the aquifer system (Hoeger, 1968; E.R. Banta, U.S. Geological Survey, written commun., 1983; Banta, 1985; Huntoon, 1985; Robson and Banta, 1987). Truncation or offsetting of the aquifer system by the faults (fig. 31) effectively cuts off recharge to the aquifer system. Along segments of the western margins of the basins where no surface evidence of faulting exists, aquifer continuity is assumed, although faulting at depth may restrict flow.

Even without any disruption by faulting, rates of recharge to the aquifer system through hogback areas are small because of the very small hydraulic conductivity in this part of the study area and the small areal extent of the outcrop. A relatively abrupt transition from fresh, calcium bicarbonate water near the hogback outcrops (generally not depicted at the scale of plates 6 and 7) to saline, sodium bicarbonate or sodium chloride water in the Denver basin attests to the effectiveness of structural or stratigraphic barriers to easterly flow. Combined recharge to the regional aquifer system from all of the Colorado and Wyoming hogback areas is only about 4 ft^3/s as estimated from Darcy's law with available hydraulic-conductivity and hydraulic-gradient data. Southeasterly flow into the study area from recharge at the southern edge of the Black Hills uplift in southwestern South Dakota, calculated in the same way, is about 5 ft^3/s. These outcrops are north of the study area but affect the regional aquifer system. Relatively fresh water in the aquifer system in northwestern Nebraska is a result of this recharge (pl. 6). A comparable rate of recharge has been determined farther north along part of the east flank of the Black Hills (Miller and Rahn, 1974), although that water flows eastward and does not enter the study area.

In sum, the total direct recharge to the aquifer system in outcrop areas is estimated to be about 35 ft^3/s.

Leakage From Overlying Rock Units

Recharge by downward leakage to the aquifer system through the overlying strata occurs over most of

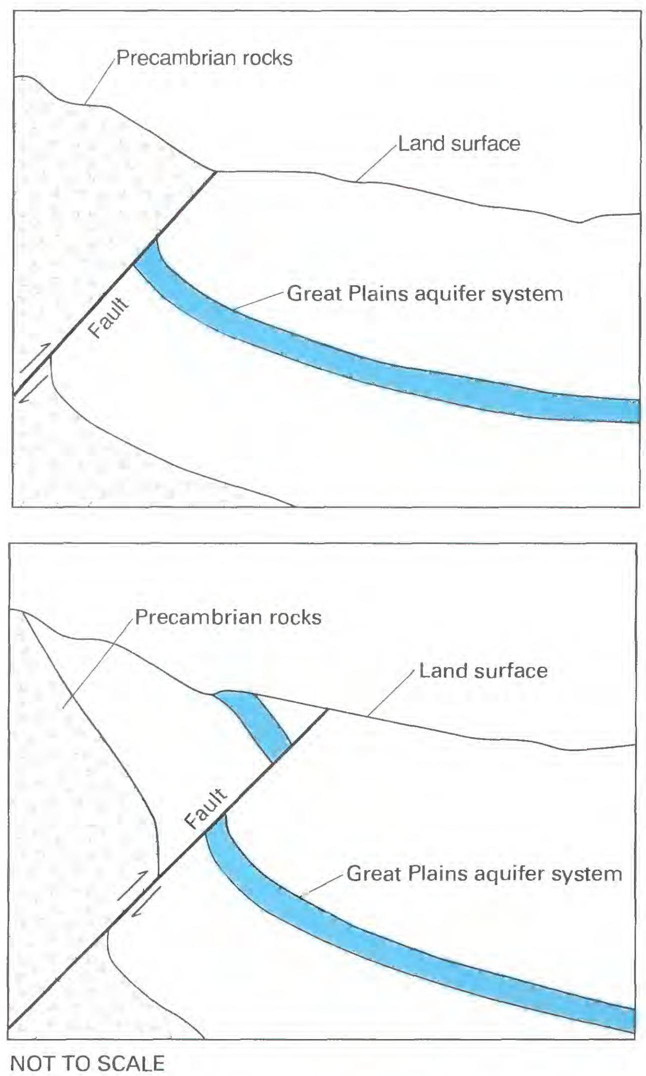


Figure 31.—Severing of aquifer system by faulting along west margin of study area due to truncation (top) or offsetting (bottom) of aquifer-system strata (modified from Robson and Banta, 1987).

the study area. Rates and distribution of this leakage are functions of hydraulic heads in the two adjacent rock units and vertical hydraulic conductivity of the overlying materials.

Head differences between the regional water table and the potentiometric surface of the Great Plains aquifer system (fig. 26) indicate a downward hydraulic gradient (and thus a downward potential for flow) almost everywhere except near the eastern and southern edges of the study area. Head differences are greatest in the Denver basin (as much as 3,000 ft) and Raton basin (as much as 2,000 ft) and gradually decrease eastward. Assuming a plausible value (for example, 0.0001 ft/d) for vertical hydraulic conductivity of shale (the principal rock type of the Great Plains confining system), calculations using Darcy's equation indicate that the downward leakage rate per unit area to the aquifer system is very small, perhaps about 0.01 ft^3/s per square mile. The leakage rate per unit area would be smallest where vertical hydraulic conductivity is smallest, in the western basins where the thickness of the confining system (depth of burial) is greatest. Where the aquifer system is overlain by the Great Plains confining system, dissolved-solids concentrations normally exceed 2,000 mg/L, and water is dominantly a sodium bicarbonate or chloride type. Although leakage rates per unit area are very small, a common increase of dissolved-solids concentration with depth within the aquifer system is evidence that ground water near the top of the aquifer system has mixed with water, having smaller dissolved-solids concentrations, that has leaked through overlying rock units.

Near the southern and eastern edges of the study area, the aquifer system is shallower, and regional flow becomes supplanted by local flow with more intricate recharge and discharge patterns. In several places in the southern and eastern parts of the study area, the Great Plains confining system is absent, and the Great Plains aquifer system is overlain directly by the High Plains aquifer (fig. 18). The effective hydraulic connection between these two aquifers results in relatively small natural vertical-head differences. However, their permeable character lends potential for large leakage rates, even with small vertical gradients. Dissolved-solids concentrations less than 1,000 mg/L in these areas of the Great Plains aquifer system substantiate its hydraulic connection with the High Plains aquifer. It is possible that leakage between these units could exceed the total leakage through the Great Plains confining system across the remainder of the study area; however, the data are inadequate to quantify leakage between the two aquifers.

Leakage From Underlying Rock Units

Hydrologic relations between the aquifer system and underlying rock units are obscure. Hydraulic-head data are meager, and numerous rock units subcrop beneath the aquifer system. Definitive data describing hydraulic-head variations with depth are needed to better understand vertical-flow relations.

Most underlying strata (fig. 17) are of very slight permeability and tend to restrict vertical flow regionally, particularly where extensive evaporite deposits occur within a few hundred feet below the aquifer system. Upward flow to the aquifer system from underlying rock units is likely along the Missouri River, which is an area of regional ground-water discharge. Subcrops of the Cedar Hills Sandstone in central Kansas and the Entrada Sandstone and Dockum Group in southeastern Colorado and adjacent states provide areas of relatively effective hydraulic connection with the aquifer system (fig. 17). These sandstone units occur stratigraphically above most of the evaporite deposits and could permit significant rates of vertical flow. Upward flow from the Cedar Hills Sandstone, known to contain brine, is apparent from hydrochemical information. Sodium chloride type water containing more than 20,000 mg/L dissolved solids and more than 10,000 mg/L chloride (pls. 6, 8, and 10) characterizes the aquifer system in that area. A similar condition in a smaller area near Lincoln, Nebraska (Engberg, 1984), also probably represents upwelling of saline water from underlying rock of Paleozoic age.

Russell (1961) suggested that water containing more than 100,000 mg/L dissolved solids on the east flank of the Denver basin might be ascribed to upwelling of saline water from underlying salt-bearing strata of Permian age along faults or fractures. This area, in the Nebraska panhandle (pl. 6), is characterized by a steep concentration gradient of dissolved solids on the west (upgradient) side and an inferred attenuated gradient to the east, suggesting a localized source consistent with Russell's (1961) interpretation.

Calcium sulfate water dominates an area in northeastern Nebraska (pl. 7); it normally contains less than 2,000 mg/L of dissolved solids, of which about 500 to 1,000 mg/L is sulfate. Swenson (1968) and Dyer and Goehring (1965) suggested that the calcium sulfate water in eastern South Dakota migrated upward from underlying anhydrite- and gypsum-bearing rocks. Because sulfate-bearing minerals are uncommon in rocks of the Great Plains aquifer system and more common in underlying and overlying strata, the presence of extensive sulfate waters in the Great Plains aquifer system probably reflects upward leakage if hydraulic-head relations in that area are also considered. Minor quantities of sulfate also may be produced by oxidation of sulfides associated with organic matter.

Boundary Recharge

Lateral flow within the aquifer system across the study-area boundaries is termed "boundary flow." The aquifer system extends beyond the study area along several segments of the study boundary, the longest being along the Nebraska-South Dakota State line. The potentiometric surface shows that most of this boundary is approximately parallel to the direction of regional lateral flow (pl. 5). Deviations from this condition probably allow small amounts of boundary flow (estimated to be a few cubic feet per second), which is consistent with Downey's (1986) description of conditions along the same boundary. Elsewhere, boundary flow is assumed to be negligible. The study boundary in northeastern New Mexico also approximately parallels the direction of ground-water flow. The northeastern study boundary coincides with the Big Sioux River and part of the Missouri River, which appear to act as discharge areas for the aquifer system.

Seepage Through Streambeds

Recharge by stream leakage directly into the aquifer system (in outcrop areas) probably occurs locally and discontinuously. Perennial streams on the outcrop areas generally do not recharge the aquifer system except perhaps during short periods of high flow. Because seepage from streams is short-term and localized, it probably is an insignificant part of the total recharge of the regional system.

DISCHARGE

Water is discharged from the aquifer system by upward leakage to overlying rock units, by downward leakage to underlying rock units, by lateral flow through boundaries out of the study area, and by discharge in outcrop areas as base flow to streams, evapotranspiration, or springflow.

Leakage To Overlying Rock Units

Hydraulic-head differences between the water table (in overlying rock units) and the potentiometric surface for the Great Plains aquifer system indicate potential for upward discharge along the Missouri River valley (southeastern South Dakota and northeastern Nebraska), along parts of the eastern and southern edges of the system, and along part of the Arkansas River valley in Colorado (fig. 32). Concentrations of dissolved solids and chloride in water from the aquifer system in these areas are commonly larger than in water from surficial alluvial sediments. Upward flow from the aquifer system along the Missouri River and other parts of eastern South Dakota has long been recognized (Darton, 1909). Where the aquifer system is directly overlain by the High Plains aquifer along the eastern and southern edges of the area, discharge rates may be substantial. As discussed previously, data are inadequate to accurately define local flow patterns.

Leakage To Underlying Rock Units

As previously noted, data are insufficient to map vertical interchange across the base of the aquifer system. The greatest potential for downward discharge exists where the aquifer system directly overlies the Entrada Sandstone and Dockum Group or the Cedar Hills Sandstone (fig. 17). Some downward leakage also may be possible where the evaporite-rich strata are absent in eastern Nebraska, southern Colorado, and northeastern New Mexico.

Boundary Discharge

Lateral discharge through boundaries is considered to be negligible except, possibly, across the northern boundary as discussed previously.

Discharge In Outcrop Areas

Discharge from the aquifer system is significant in the Purgatoire-Cimarron and central Kansas outcrop areas (fig. 30). Other outcrop areas in the western part of the study area serve as discharge points only for local flow systems, where small streams traverse the areas. Other outcrop areas on the eastern and southern edges of the study area are of small extent and of little regional significance.

Discharge in the outcrop areas is in the form of base flow to streams, evapotranspiration, and springflow. Base flow is estimated from streamflow data collected at appropriate gaging stations that approximately bracket the outcrop area. Flow-duration information compiled by Hedman and Engel (1989) provides a basis for estimating base flow, which is commonly assumed to be the flow rate that is exceeded 70 percent of the time. Evapotranspiration directly from the aquifer system occurs in vegetated areas of shallow water table along streams. Such areas were approximately delineated from topographic maps and related information. Rates of evapotranspiration then were estimated from potential evapotranspiration data (Dugan and Peckenpaugh, 1985), allowing for that part of the potential evapotranspiration rate that would be satisfied by precipitation. Springflow is unmeasured but is assumed to be negligible in relation to the regional system.

Thus, base flow plus evapotranspiration is assumed to approximate the long-term discharge rates

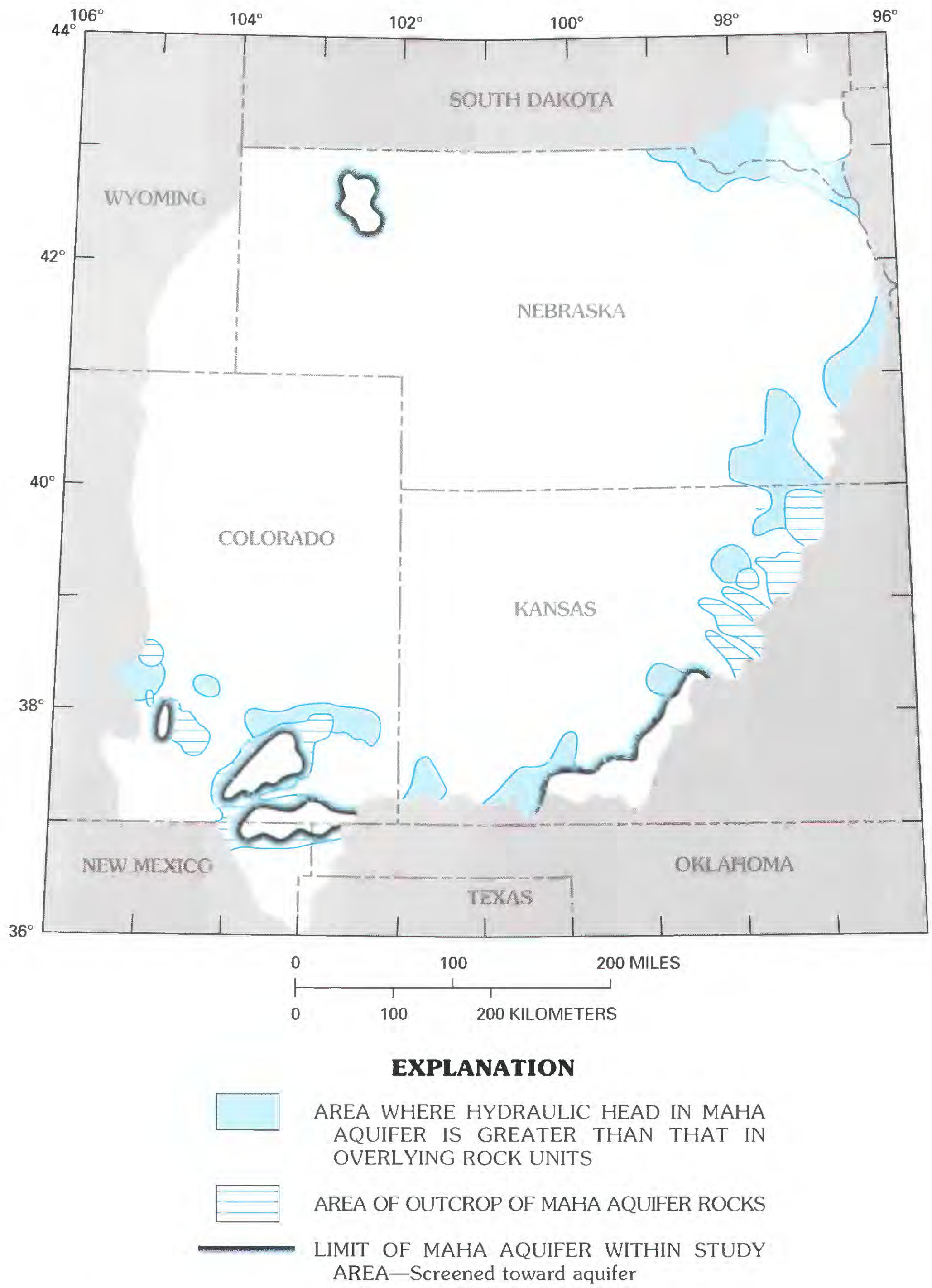


FIGURE 32.—Areas of potential upward discharge from Maha aquifer to overlying units.

in the outcrop areas. The estimated discharge for the Purgatoire-Cimarron area is about 20 ft^3/s, virtually all of which is evapotranspiration along the Purgatoire and Cimarron Rivers. The estimated discharge for the central Kansas area is about 60 ft^3/s; this total consists of base flow and evapotranspiration discharges along the Republican, Solomon, Saline, and Smoky Hill Rivers, which trend southeasterly across the outcrop area. These estimates are considered to be upper limits because most of the base flow and evapotranspiration actually is discharged from alluvial deposits covering the rocks of the Great Plains aquifer system along the streams; some unknown part of that rate is supplied by water that flows into the alluvium from the aquifer system.

REGIONAL FLOW

The main features of the regional flow system are reflected in the predevelopment potentiometric surface (pl. 5). The surface portrays a general easterly component of lateral flow through the aquifer system. The character of the potentiometric surface provides another insight for the conceptual model of flow.

Large hydraulic-head values in southeastern Colorado and southeastern New Mexico (pl. 5) suggest a major recharge area for the regional aquifer system. Most flow from this area is in a northeasterly or easterly direction. Some of the ground water moves upward to be discharged in the Arkansas River valley, but the river probably does not fully intercept the regional northeasterly flow. The predominance of the sodium cation in water in most of southeastern Colorado (pls. 7, 10) probably has resulted from ion exchange of sodium in shale for calcium in recharge water during downward leakage through the Great Plains confining system. Water containing less than 200 mg/L of chloride occurs on the southeast flank of the Denver basin (pl. 8) to depths exceeding 4,000 feet. Patterns of the water types, ion ratios, dissolved solids, and chloride concentrations (pls. 6–9) are consistent with recharge of meteoric water and lateral flow to the northeast.

A small potentiometric high is present in Sheridan County, Nebraska (pl. 5), on the Chadron arch, where the (partially eroded) aquifer system is more than 1,000 feet below land surface. Within this small area, the upper part of the aquifer system is unsaturated, an unusual condition for such a great depth of occurrence that was recognized first by DeGraw (1969). Apparently, the potentiometric high is maintained as a result of the structural high at this location; however, leakage from overlying rock units is insufficient to maintain full saturation in the aquifer system.

A broad westward curvature of potentiometric contours (pl. 5) in the west-central part of the study area (Denver basin) reflects the underpressured condition discussed previously. A similar condition appears to exist in the Raton basin, although this observation is based on very few data.

Steep hydraulic gradients on the west sides of the Denver and Raton basins (pl. 5) probably reflect hydraulic discontinuities caused by faulting as well as small aquifer transmissivity (Hoeger, 1968; Robson and Banta, 1987). Faulting not associated with the basins, in Pueblo County, Colorado, has a restrictive effect on ground-water flow within the aquifer system (Banta, 1985; Robson and Banta, 1987). These restrictions cause only local effects, not apparent on plate 5, within the regional flow pattern.

Flat hydraulic gradients in central Nebraska (pl. 5) and surrounding areas reflect large transmissivity, which is largely a result of 400 feet or more of thickness (fig. 16). In north-central Kansas, larger hydraulic gradients have developed in a shale-rich part of the aquifer system (fig. 15) having small transmissivity. Irregularities in the potentiometric surface tend to increase toward the eastern outcrop areas, where stream incision has caused local flow patterns to become dominant.

Ground water moves very slowly through the Great Plains aquifer system in most areas. Calculations of average lateral velocity based on hydraulic conductivity, hydraulic gradient, and porosity indicate velocities generally in the range of 0.01 to 10 ft/yr. Velocities are least in the deep structural basins. Heat-flow modeling of western Nebraska by Gosnold (1984) reproduced observed temperature and heat-flow data using flow velocities of about 1 to 3 ft/yr.

Vertical leakage in the flow system is probably greatest where the High Plains aquifer directly overlies the Great Plains aquifer system (parts of the southern and eastern edge of the area). In most parts of the study area, small permeability of vertically adjacent rock units restricts interchange of water between rock units. Because of the large area of contact, however, cumulative leakage is an important element of the regional aquifer system. Darton (1905) described recharge at western outcrop areas and transmittal of water laterally to eastern outcrop areas, but he also noted a "certain but unknown amount of general leakage through the so-called impermeable strata***." Recognition of the vertical-flow component has been important to improved understanding of water-quality distribution, hydraulic-head distribution, and overall water budget (Russell, 1961; Dyer and Goehring, 1965; Swenson, 1968; Schoon, 1971; Miller and Rahn, 1974; Milly, 1978; Bredehoeft and others, 1983; Neuzil and others, 1984).

The slow velocities that prevail in the aquifer system indicate that ground water would require a few million years to move across the study area. Therefore, much of the regional flow system is virtually stagnant except in terms of geologic time. The presence of saline water, oil, and gas in much of the study area indicates incomplete flushing of connate water from the aquifer system. Even the present distributions of dissolved solids and chloride appear to be related largely to environment of deposition, with limited modification by postdepositional flow patterns. Except in relatively small areas, concentrations of these constituents are less than in modern seawater, a condition consistent with a freshwater to brackish-water depositional environment.

Although deposition of Lower Cretaceous sediments occurred more than 90 million years ago, incomplete flushing of formation fluids seems probable under conditions imposed by the depositional and postdepositional history. The nearshore depositional environment probably included original formation water of fresh to moderately saline composition. The fluctuating continental-to-marine conditions would have permitted some introduction of fresh meteoric water into the sediments during and soon after their deposition. Lateral northwesterly flow of freshwater, seaward from the coastline, has been hypothesized (D.B. Tait, geologic consultant, Lakewood, Colo., written commun., 1986), which may have caused dilution of some of the original formation water.

Widespread marine deposition over these sediments prevailed through the remainder of Cretaceous time. The small-permeability clays that predominate within the Upper Cretaceous strata have effectively prevented flushing of the aquifer system by infiltration of precipitation into the underlying Lower Cretaceous sediments. Subsurface flow that developed as a result of subsidence and compaction was probably outward from the developing basin (Ottman, 1984), thus tending to oppose the flow direction of any lateral recharge into the aquifer system.

Following deformation into a deep basinal configuration, truncation of aquifer-system strata by erosion of the steep west flank may have allowed some west-to-east recharge of meteoric water (Ottman, 1984). Such a process may have been short-lived because of fault development that has since impeded significant recharge to the basin along its west flank. The aquifer system retained continuity in other directions, but hydraulic conductivity is small, and the overall structural attitude of the region may not have deviated significantly from horizontal through much of Tertiary time. Until late Tertiary uplift of the Denver basin (Ottman, 1984) led to the development of the modern west-to-east hydraulic gradient (pl. 5), there was little impetus for flushing of formation fluids by recharge water from any source. The modern hydraulic gradient was superimposed on a relict system, within which hydrochemical conditions in most of the central part of the area reflect the original environment of deposition. Water-quality conditions portrayed on plate 10 reflect a diverse hydrochemistry resulting from greater hydraulic continuity and greater influence of relatively recent flow patterns than in the main areas of incomplete flushing of the connate water to the north.

Interpretations of potentiometric conditions in the Denver basin have indicated a general northeasterly gradient (Hoeger, 1968), or a general northeasterly trending potentiometric trough with closed low areas (Gibbons and Self, 1978; Ottman, 1984). Ottman (1984) attributed an apparent inward flow in the basin to unloading (erosion of overlying sediments) and cooling that began during Tertiary time. The effect of that phenomenon may be complicated by pressure changes associated with oil and gas withdrawal. The area of particularly small and areally variable hydraulic heads is centered within the main development area of oil and gas, suggesting that oil and gas withdrawal is a factor contributing to the complex head distribution. The trend of regional underpressuring (fig. 25) is best explained by restriction of recharge in the west and the increase in transmissivity to the east (Hoeger, 1968; Belitz, 1985; Robson and Banta, 1987). This condition allows water to move laterally eastward at a more rapid rate than the aquifer system is recharged.

Thus, flow in the Great Plains aquifer system varies widely. In the deepest part of the Denver basin, connate fluids are essentially "trapped" by strata of very slight permeability. The variable water chemistry in the basin is consistent with this interpretation. Larger transmissivities and more effective lateral recharge occur north and south of the Denver basin. These conditions allow northeasterly flow from outcrop areas in southern Colorado and northeastern New Mexico, and southeasterly flow from outcrop areas bordering the Black Hills in western South Dakota. According to geophysical-log analysis, large areas of the aquifer system in southern Nebraska and northern Kansas contain water with dissolved-solids concentrations exceeding 10,000 mg/L (pl. 6). Analyses of water samples from these areas are unavailable; however, water containing more than 5,000 mg/L dissolved solids in adjoining areas is of the sodium chloride type, probably representing residual estuarine water or seawater, as well as vertical migration of saline water from adjacent salt-bearing strata. Water in this part of the aquifer system may be a mixture of inflow having small dissolved-solids concentrations with original formation water having large dissolved-solids concentrations, and this mixture flows slowly to the east.

As discussed previously, one plume of highly mineralized water originates in the Nebraska panhandle and extends eastward (pl. 6). The western boundary of this plume occurs within the petroleum-production area. However, considering the elongated west-east pattern and extremely slow rates of flow, recent withdrawals of formation fluids are not likely to have caused this plume. Rather, these conditions support the concept of downgradient lateral migration of brine, which leaked upward from underlying strata in response to the natural underpressuring in the Great Plains aquifer system.

Ground-water flow may be as rapid as 10 to 100 ft/yr locally along eastern and southern outcrops. Direct recharge of meteoric water to the system in these areas has formed a wide band of relatively fresh, dominantly calcium bicarbonate water (pls. 6, 7), yet with variable dissolved-solids concentrations and water type, along the eastern study margin. The persistence of these conditions in eastern Nebraska, where regional flow is directly toward the edge of the aquifer, suggests that water moving toward the eastern edge is diluted substantially by meteoric-water recharge in exposed or thinly covered parts of the aquifer system.

COMPUTER MODEL

A computer model was used to help develop an improved understanding of the aquifer system, estimate flow rates, and evaluate responses to stress.

The model (McDonald and Harbaugh, 1983) simulates ground-water flow in three dimensions using finite-difference methods. Flow through porous media can be expressed as

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \quad (7)$$

where x, y, and z are Cartesian coordinates aligned along the major axes of hydraulic-conductivity tensors K_{xx}, K_{yy}, K_{zz} $[l]$,

K is hydraulic conductivity $[lt^{-1}]$,

h is the potentiometric head $[l]$,

W is a volumetric flow per unit volume and represents sources or sinks of water $[t^{-1}]$,

S_s is the specific storage of the porous material $[l^{-1}]$, and

t is time $[t]$.

This relation allows for spatial variations of aquifer properties, hydraulic heads, and flow rates, and temporal variations of hydraulic heads and flow rates. The model subdivides the aquifer system three-dimensionally into blocks, or cells, within which any property, hydraulic head, or flow rate associated with that cell is applied uniformly over the extent of the cell. The model requires values for hydraulic properties, boundary conditions, sources and sinks, and initial hydraulic-head distributions. Primary results from the model consist of head distributions and a volumetric water budget. The model uses a modular programming structure comprising a main program and various subroutines to simulate aspects of the aquifer system.

Certain limitations of and modifications to the model used in this study need to be discussed. The steep dip of the aquifer system into the Denver and Raton basins along their western flanks violates an assumption of layer horizontality in the model (McDonald and Harbaugh, 1983), introducing error to hydraulic-head calculations. The steepness also makes it impossible to properly represent rapidly changing features of the aquifer system (such as altitude of the top or hydraulic head) without more detailed data and finer discretization. Consequently, model results are very inaccurate along the western margin.

Density of fluid in the aquifer system varies spatially due to effects of salinity, temperature, and pressure. This violates an assumption of constant fluid density implicit to flow calculations made in the model (McDonald and Harbaugh, 1983). However, differences in hydraulic head due to nonuniform density are small (generally much less than 100 feet) compared to regional head differences. Therefore, this density variation probably will not induce much error in use of the model on a regional scale, if all hydraulic heads are converted into equivalent freshwater heads on the basis of density.

Nonuniform density and viscosity also affect hydraulic conductivity used in the model. Hydraulic conductivity is adjusted and was discussed under "Hydraulics" in the section entitled "Geohydrology."

Some model modifications, not affecting the basic program function, were made. Changes include tracking of recharge, discharge, or boundary flows on a layer-by-layer basis. Auxiliary programs were developed to prepare the data and to process model results to aid in evaluation. Initial processing included generation of arrays of transmissivity and vertical conductance (leakance). Processing of model results included calculation of layer-by-layer water budgets, compilation of flow rates for selected inflow and outflow areas, plots of hydraulic-head distributions, and statistics describing degree of agreement between simulated and field estimated heads.

MODEL FORMULATION

A grid (fig. 33) was superimposed on a map of the aquifer system to facilitate discretization of data and enable finite-difference computations. The x-axis of the grid is aligned N. 35° W., and the y-axis is aligned N. 55° E. The axes approximately parallel major bedrock joint patterns in the midcontinent region, and the orientation coincides with that of the grid system used for the regional CMRASA model (D.C. Signor, U.S. Geological Survey, written commun., 1987), which covers the entire CMRASA study area. Thus, the axes of the model grid are generally parallel to principal regional directions of hydraulic conductivity.

DISCRETIZATION

Horizontally, the uniform grid system consists of 46 rows and 35 columns (fig. 33). Each cell represents an area 14 miles square. The modeled aquifer system is divided vertically into four layers. Layer 1, the top layer, represents the Great Plains confining system (where it is present) and part of the High Plains aquifer and undifferentiated Quaternary deposits (in places where they directly overlie the Great Plains aquifer system). In most of the study area, where the High Plains aquifer is underlain by the Great Plains confining system, the High Plains aquifer is not simulated and is not included in layer 1. This omission of the High Plains aquifer in the simulation creates no significant hydrologic errors because the Great Plains confining system generally is about 2 to 10 times as thick as the High Plains aquifer. Therefore, the vertical leakage into the Great Plains aquifer system, where both the High Plains aquifer and Great Plains confining system are present, is dominantly affected by the hydraulic characteristics of the Great Plains confining system, not the High Plains aquifer.

Layers 2 and 3 represent the Maha and Apishapa aquifers, respectively. (The Apishapa confining unit, which separates the two aquifers, is not simulated as a model layer, but its vertical restrictive effect between the two aquifers is simulated by the model.) Layer 4 represents 150 feet of strata (arbitrarily) below the base of the Great Plains aquifer system, which is equivalent to the top part of the Western Interior Plains confining system in most of the area. In the northeastern part of the study area, the Western Interior Plains confining system is absent, and layer 4 represents the Western Interior Plains aquifer system. Farther northeast, the basement confining unit forms the lower boundary to the Great Plains aquifer system.

Layers 2 and 3, representing the aquifers of interest, are of primary concern. Layers 1 and 4 are overlying and underlying "boundary" layers to account for hydraulic interchange between the aquifer system and vertically adjacent rock units. Simulated flow within each layer is strictly horizontal and is perpendicular to grid-cell faces. Simulated flow between layers is strictly vertical between vertically adjacent cells.

The distribution of active cells within each layer (figs. 34–37) is defined by the extent of the geohydrologic unit(s) within the model area. The limits of the modeled area are related to the extent of the Great Plains aquifer system. The limits coincide with truncated edges where appropriate (such as the western and eastern margins) and extend a few cells beyond the study area where the aquifer system continues farther (such as the northern and southwestern boundaries). Layer 1 (fig. 34), therefore, is active everywhere except where the aquifer system is exposed. Layer 4 (fig. 37) is active everywhere except where the basement confining unit or the evaporite-rich strata, considered impermeable, directly underlie the aquifer system.

Internal limits for layers 2 and 3 (figs. 35, 36) are established in small areas where the Maha or Apishapa aquifers are absent, such as on the Sierra Grande and Apishapa uplifts in the southwestern part of the area and on a small part of the Chadron arch in northwestern Nebraska. Other internal limits for layer 2 (fig. 35) are imposed where the Maha aquifer does not extend as far as the Apishapa aquifer because of erosion; this condition is found mainly in the Purgatoire-Cimarron outcrop area and along the outer edge of the study area in south-central Kansas. In central Kansas, the eastward limit of layer 3 (fig. 36) corresponds to a pinchout of the Apishapa aquifer beneath the Apishapa confining unit, which extends farther east. In northern Kansas and across Nebraska, the limit of layer 3 is placed arbitrarily about two cells east of the eastward margin of the Apishapa confining unit. This placement serves to simulate a zone in which the two aquifers merge; east of this zone, the modeled aquifer system consists only of layer 2.

HYDRAULIC-PROPERTY SPECIFICATION

The model requires values of transmissivity and vertical conductance. These properties are spatially distributed, one value per cell in each model layer. For transient simulations, in which conditions are time-dependent, changes in ground-water storage can occur, and the model also requires storage-coefficient data.

Transmissivity distribution depends on thickness and hydraulic conductivity. Model-cell values for these parameters were derived from contour maps or other information explained in the following paragraphs. Thickness maps were used for each layer except layer 4, for which a uniform 150 feet was assigned. Thickness values for layer 1 correspond to the thickness of the Great Plains confining system or thickness of the High Plains aquifer or undifferentiated Quaternary deposits, which are directly overlying the aquifer system, for the given grid cell.

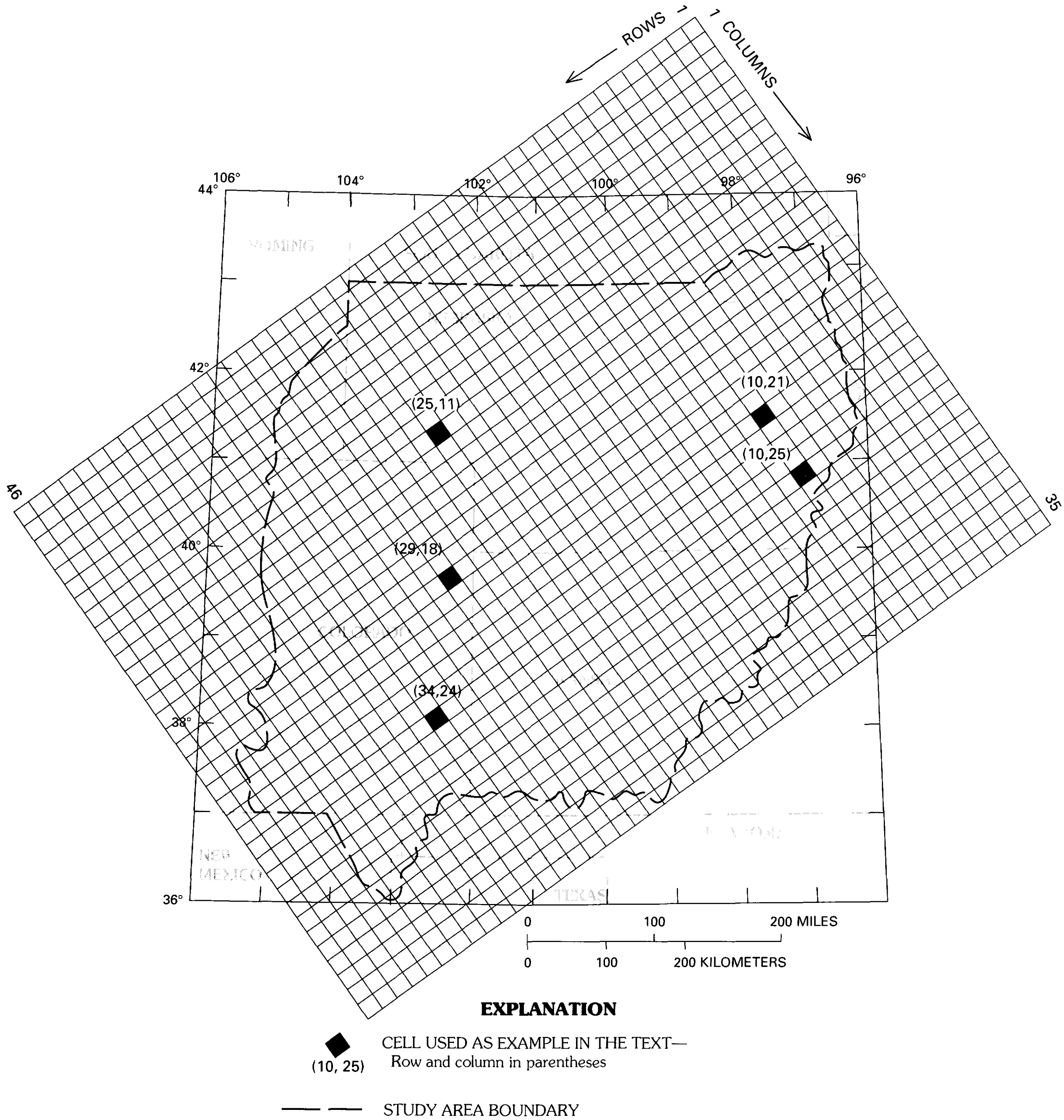


FIGURE 33.—Horizontal finite-difference grid for ground-water flow model.

Hydraulic conductivity for the aquifer system (fig. 22) was assumed to apply identically to layers 2 and 3 at any given cell location. However, the areal distribution of hydraulic conductivity is variable because depth of burial is the dominant control on regional variations in hydraulic conductivity. Variations in salinity and temperature have been incorporated in calculating hydraulic conductivity as a function of intrinsic permeability, fluid specific weight, and viscosity.

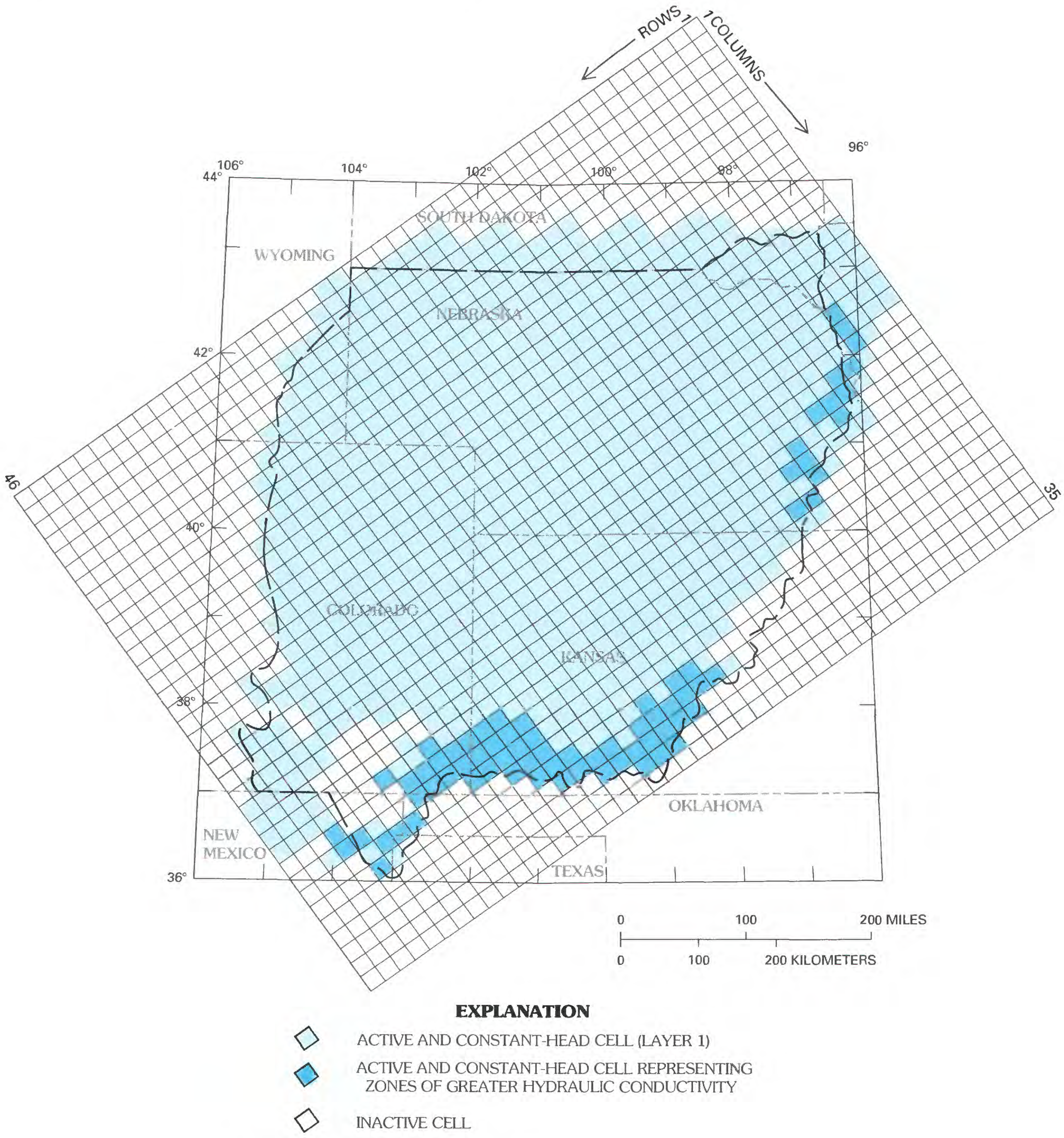


FIGURE 34.—Extent of model layer 1 (rock units directly overlying Great Plains aquifer system) and properties of model cells.

Lateral hydraulic-conductivity values for layers 1 and 4 are not used in the model because only vertical flow in these two layers is considered to be significant. However, lateral values are assigned for the purpose of estimating vertical hydraulic conductivity, which will be discussed later. The lateral hydraulic-

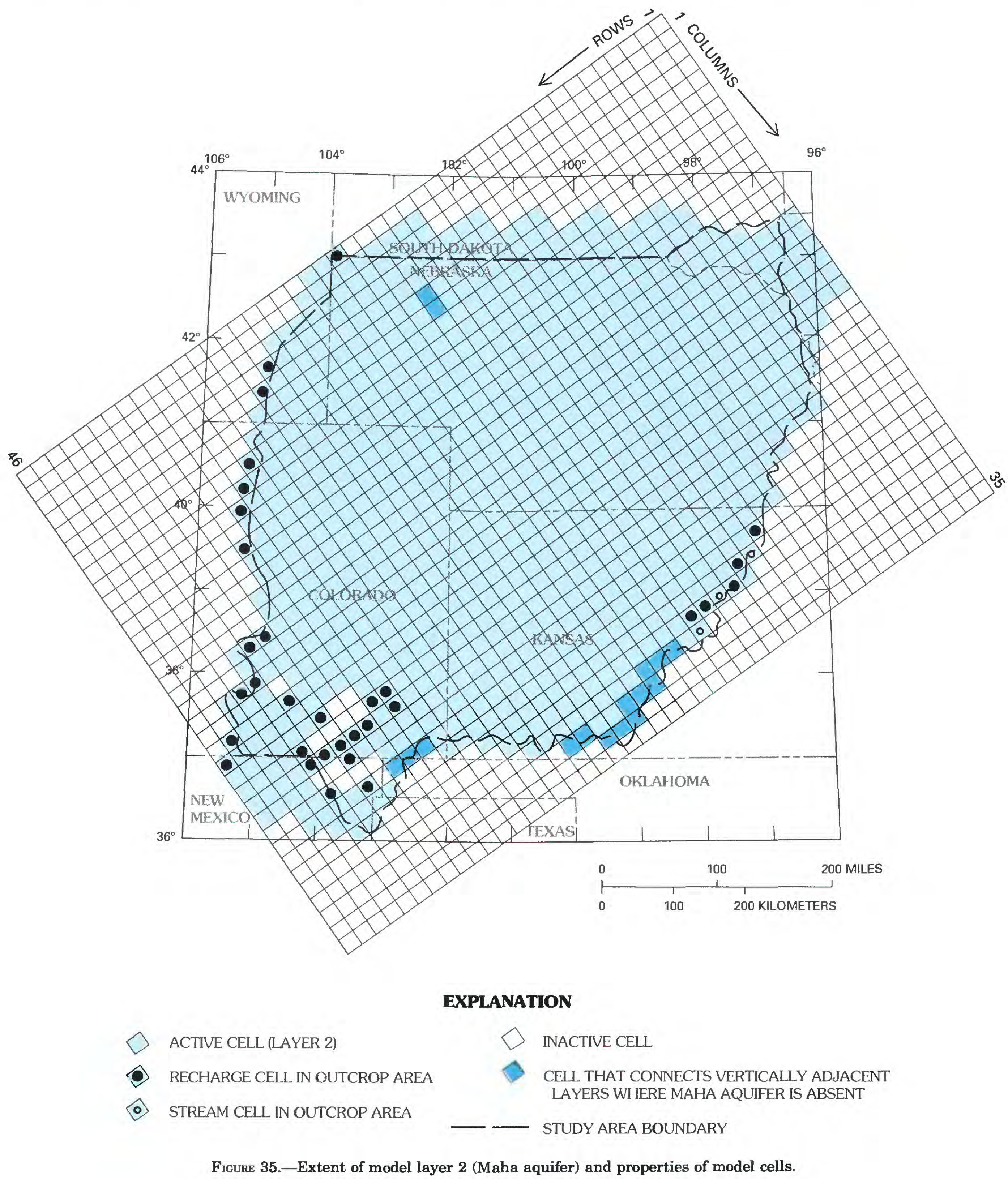


FIGURE 35.—Extent of model layer 2 (Maha aquifer) and properties of model cells.

conductivity values for layers 1 and 4 were assigned as certain fractions of the values for layers 2 and 3. These fractions were applied uniformly within each layer, thereby imparting a dependence on depth of burial which parallels the relations defined for the aquifer system. The fractions used were between 0.00001 and 0.001 because hydraulic conductivity of shale, the major component of both the overlying and

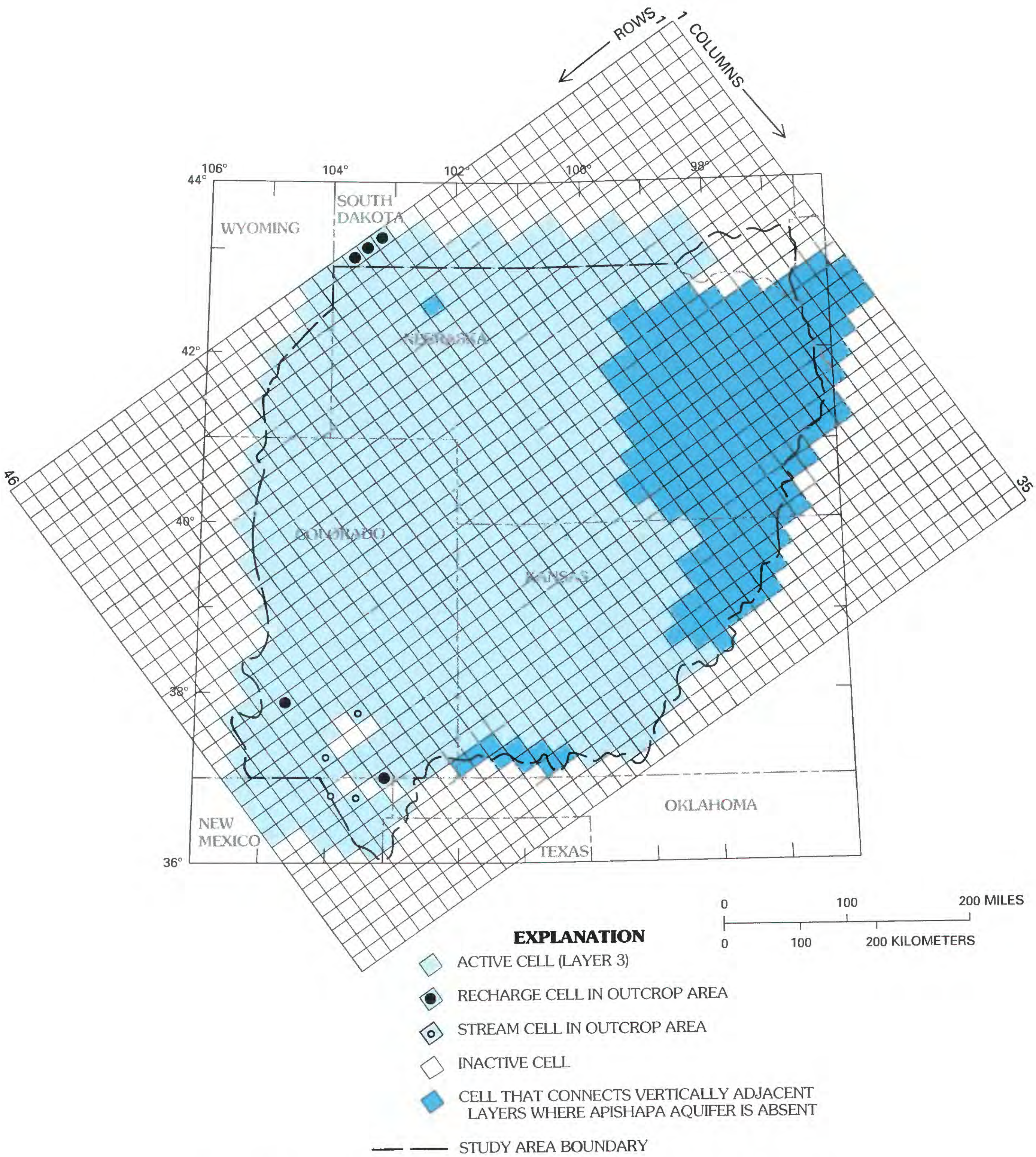


FIGURE 36.—Extent of model layer 3 (Apishapa aquifer) and properties of model cells.

underlying rock units, is typically several orders of magnitude less than that of sandstone, which is the principal rock type of the aquifer system.

Departures from this procedure are invoked for areas of overlying and underlying rock units that do not consist of shale, that is, areas of effective vertical

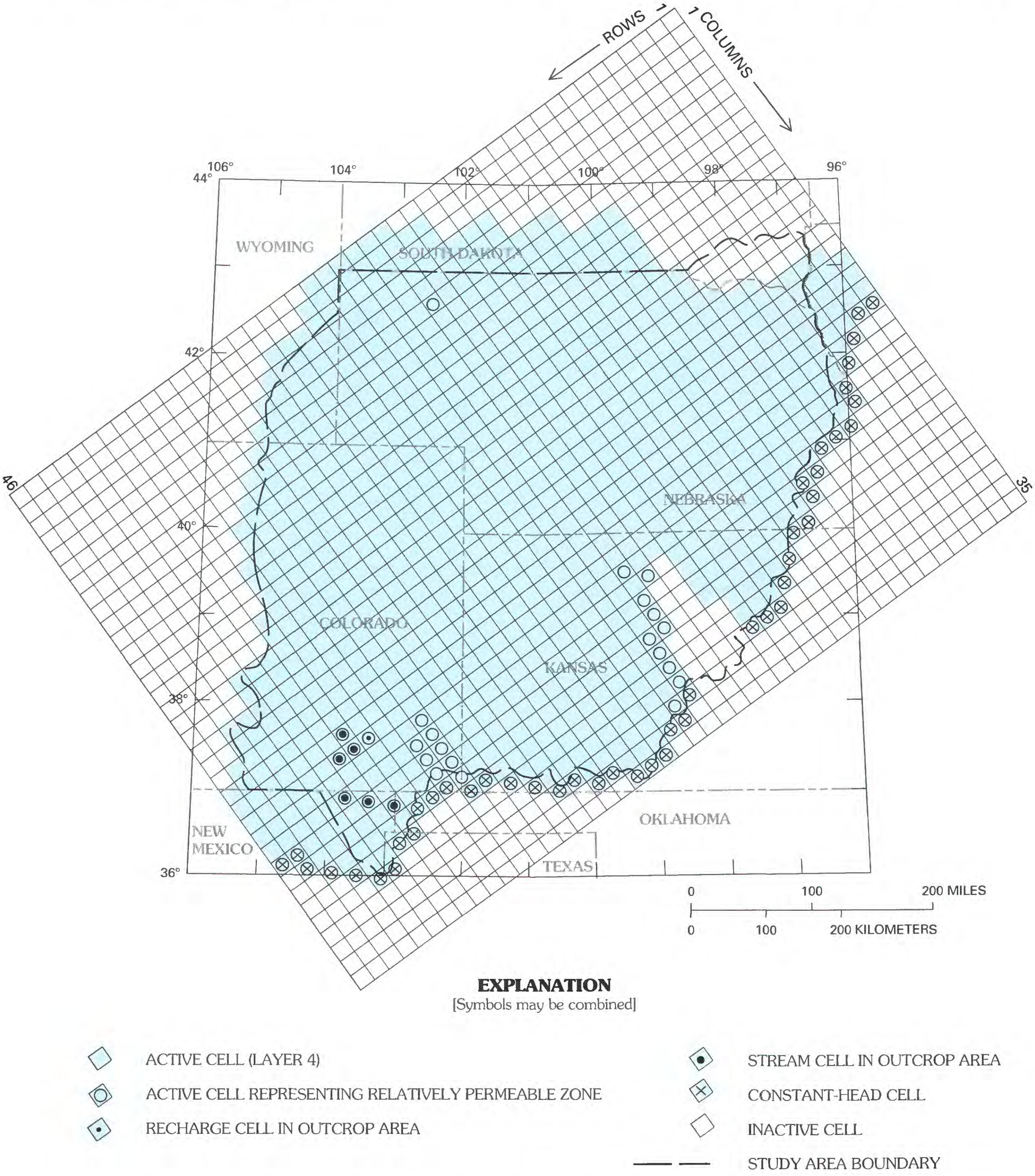


FIGURE 37.—Extent of model layer 4 (rock units directly underlying Great Plains aquifer system) and properties of model cells.

hydraulic connection with the aquifer system. Where the High Plains aquifer or Missouri River alluvium directly overlies the aquifer system, a lateral hydraulic-conductivity value of 40 ft/d was assigned to the appropriate cells in layer 1 (fig. 34). Where the Cedar Hills Sandstone or Entrada Sandstone and Dockum Group directly underlie the aquifer system, a lateral hydraulic-conductivity value of 5 ft/d was assigned within layer 4 (fig. 37). All such conditions occur at relatively shallow depths, allowing omission of the depth-of-burial consideration. The lateral hydraulic-conductivity value of 5 ft/d was also assigned to layer 4 (fig. 37) in exposed areas on the Sierra Grande uplift, at the crest of the Chadron arch, and just beyond the eastern and southern boundaries of the study area.

Vertical conductance (leakance), *VC*, is a property that controls the rate of vertical flow between layers. It is calculated by one of two methods. The first is based on the relation

$$VC=K'/b \quad [t^{-1}] \tag{8}$$

where K' is vertical hydraulic conductivity of the confining unit $[lt^{-1}]$ and b is confining-unit thickness $[l]$. This relation defines vertical flow through a well-defined confining unit. It was applied to control flow (1) between layer 1 and the layer directly beneath it, where layer 1 represents the Great Plains confining system, and (2) between layers 2 and 3, where the aquifers they represent are separated by the Apishapa confining unit.

The second method is based on the relation

$$VC=2(K'_u)(K'_l)/[(K'_u)(b_l)+(K'_l)(b_u)] \quad [t^{-1}] \tag{9}$$

where the subscript u refers to an upper geohydrologic unit and the subscript l refers to a lower geohydrologic unit. This relation controls vertical flow between two adjacent geohydrologic units where an intervening confining unit does not exist.

Vertical hydraulic-conductivity values for each layer were assumed to be a certain fraction of that layer's lateral hydraulic conductivity. Ratios of vertical to lateral hydraulic conductivity were assumed to be about 0.01 for units consisting mostly of shale (such as layer 1 where it represents the Great Plains confining system) and about 0.1 for aquifers (layers 2 and 3).

Storage coefficient, used in transient simulations, was based on estimates previously discussed under "Hydraulics" in the section entitled "Geohydrology." Where confined conditions prevail, storage coefficient was set equal to the estimated specific storage (9.5×10^{-7} per foot) times thickness. To represent unconfined conditions, storage coefficient was set equal to 0.15 (specific yield).

Boundary Conditions

The character of regional flow is dependent on boundary conditions as well as hydraulic properties of the aquifer system. Several types of boundary conditions are important in the Great Plains aquifer system. To represent these conditions, model cells were designated as (1) constant-head cells, where hydraulic head in the cell does not change; (2) no-flow cells, where the cell is inactive; (3) recharge cells, where a specified rate of recharge is input; or (4) stream cells, where discharge or recharge through a streambed is simulated.

Constant heads were assigned to every cell in layer 1 (fig. 34), each value being set equal to the altitude of the near-surface water table (in most of the study area, they are the water levels in the High Plains aquifer) representative of that area. Thus, these cells act as sources or sinks with respect to the underlying layer, depending on vertical hydraulic-head gradients. The rate of simulated interlayer flow is controlled by the vertical conductance.

The assumption of a constant-head water table for simulation purposes can be justified by a calculation of the amount of water-table change represented by the downward-leakage rate. A downward-leakage rate of 0.01 ft^3/s per square mile, as estimated previously, would represent a water-table decline of about 0.1 in./yr, less than the usual ground-water recharge rate (from precipitation) over most of the region.

Constant heads also were assigned to a line of cells in layer 4 just beyond the eastern and southern limit of the study area (fig. 37). This permits simulation of discharge (or recharge, depending on hydraulic-head gradients) through the layer underlying the aquifer system. A break in this line of constant-head cells coincides with the area of nearly impermeable evaporite rocks subcropping directly beneath the aquifer system in central Kansas.

No-flow boundaries (inactive cells, figs. 34–37) were assigned around the entire perimeter of the model, except along the eastern and southern edges of layer 4 as previously discussed. These no-flow boundaries correspond mostly to truncated edges, except along the northern and southwestern edges where the no-flow boundaries approximately parallel the regional flow directions. No-flow boundaries also were assigned to interior surficial areas where units have been eroded. However, where a geohydrologic unit is absent in the subsurface (between two other geohydrologic units), the no-flow property in the model layer representing that missing unit applies only to the lateral direction; transmissivity was set equal to zero in these cells, but vertical connection was kept in order to maintain the model continuity (figs. 35, 36). The bottom no-flow boundary of the model is at the base of layer 4, except in areas where layer 4 is composed of the basement confining unit (extreme northeastern part of the area) or the evaporite-rich section (central Kansas). In those areas, the bottom no-flow boundary is at the base of layer 3.

Cells representing outcrop areas of the aquifer system (or underlying rock unit) within the modeled area were designated as either recharge cells or stream cells (figs. 35–37). Recharge cells represent all hogback outcrop areas and parts of the flat outcrop areas between streams (fig. 30). Simulated recharge rates correspond to the estimations described earlier in the section entitled "Concept of Predevelopment Flow."

Stream cells were assigned where major streams traverse either of the two largest flat outcrop areas (Purgatoire-Cimarron or central Kansas) (fig. 30). Other streams, such as the Arkansas, Platte, and Missouri Rivers, are not simulated because interaction between the streams and the Great Plains aquifer system is restricted by intervening geohydrologic units, mainly the Great Plains confining system. Designation of a stream cell requires values for stream head (river-stage altitude), altitude of the bottom of the streambed, and conductance of the streambed. The conductance term incorporates area of the stream within the cell, hydraulic conductivity of the streambed, and thickness of the streambed. Hydraulic conductivity and thickness of streambed, which are not mapped and are undoubtedly quite variable, are combined into a single term, streambed leakance (hydraulic conductivity divided by thickness), which is assumed to be about 0.1 d^{-1}.

Simulated interchange of water between streams and the aquifer system can be in either direction depending on relative hydraulic-head values of the stream and aquifer. If the head in the aquifer is below the bottom of the streambed, leakage from the stream remains at a constant maximum value. Evapotranspiration along streams is not directly simulated by the model but is considered to form part of the simulated discharge to streams.

MODEL CALIBRATION

Reasonable magnitudes and distributions of hydraulic head and flow rates were simulated using properties and boundary conditions presented earlier. Calibration of the model was done using both steady-state and transient simulations, discussed in the following sections.

Predevelopment Conditions

The model was calibrated primarily by simulating flow in the aquifer system under natural, predevelopment conditions. However, data are not adequate to accurately define predevelopment conditions. Therefore, predevelopment conditions were surmised from climatic and hydrologic data, most of which was obtained during 1950–80. Climatic conditions that prevailed during that period are assumed to be typical of long-term, natural, steady-state conditions. The hydraulic head and flow rates described previously are the field or estimated conditions against which the model results are compared.

Steady-state simulation results were evaluated by the following calibration methods:

1. Simulated head distribution was compared with field or estimated hydraulic-head distribution, visually and statistically.
2. Individual simulated hydraulic-head values (layer 2) were compared with estimated heads, at cells receiving direct recharge.
3. Simulated rates of discharge to streams were compared with estimated rates for the Purgatoire-Cimarron and central Kansas outcrop areas.

The statistical evaluation of differences between simulated and field or estimated hydraulic heads is based on the following equations (Spiegel, 1961):

$$\Sigma X_n = X_1 + X_2 + X_3 + \ldots + X_n + \ldots + X_N, \tag{10}$$

where ΣX_n is the sum of absolute deviations [l]; X_n is the absolute deviation [l] at grid cell n; and N is the number of cells;

$$\bar{X} = X_n/(N-1), \tag{11}$$

where $\bar{X}$ is mean deviation [l]; and

$$SD = \sqrt{\sum (X_n - \bar{X})^2 / (N-1)} \tag{12}$$

where SD is standard deviation [l]. Minimization of these statistical parameters was one aim of the calibration procedure.

Simulated hydraulic-head values for layers 2 and 3 were very close throughout the model analysis. Therefore, hydraulic-head values for layer 2 (Maha aquifer), being representative of both layers 2 and 3, are used for purposes of evaluating model results.

Application of all calibration methods, along with rational variations of some parameters to be discussed below, resulted in a steady-state solution selected as the most satisfactory simulation of the regional flow system. Rates of simulated direct recharge to the regional aquifer system in outcrop areas were not changed from original estimates. For flat outcrop areas, these rates were based on estimates of Dugan and Peckenpaugh (1985), derived from climatic and soils data. For hogback outcrop areas, the rates were based on Darcy's equation calculations of flow, as previously discussed.

Original assigned values of lateral hydraulic conductivity for layers 2 and 3 (representing the aquifers) were multiplied by 1.2 during calibration. This change retains the relative areal distribution of transmissivity, but minimizes the statistical differences between simulated and field or estimated hydraulic heads.

Lateral hydraulic conductivity for layers 1 and 4 is not used in the model; however, it is used for estimating the vertical hydraulic conductivity. Lateral hydraulic conductivities for cells in layer 1, excluding cells representing the High Plains aquifer or Missouri River alluvium, were assigned values equal to 0.0001 times the corresponding grid values assigned for layer 2 or 3. Cells in layer 4, excluding cells representing the Cedar Hills Sandstone or Entrada Sandstone and Dockum Group, were assigned lateral hydraulic conductivities equal to 0.00006 times those assigned for layer 2 or 3. These factors, obtained by trial and error, produced the best simulated hydraulic-head distribution when all other input data were set at their respective calibration values.

Ratios of vertical to lateral hydraulic conductivity were assigned values of 0.1 for cells representing the High Plains aquifer and undifferentiated Quaternary deposits, 0.05 for cells representing the Maha and Apishapa aquifers, and 0.01 for cells representing rock units dominated by shale, which is the principal rock type of the confining units.

Streambed leakance was specified as 0.2 d^{-1} at cells representing streams in the central Kansas outcrop area, and 0.5 d^{-1} for cells representing the Purgatoire and Cimarron Rivers.

The largest differences between simulated and field or estimated hydraulic heads (fig. 38) occur along the western margin of the study area, where the model cannot reproduce the geohydrologic complexities of the steep, faulted, west flanks of the basins (fig. 39). An area of large differences (up to 640 feet) also appears in eastern Colorado, where the effect of a water-table high, modeled as constant head in layer 1, is transmitted to the simulated hydraulic head in layer 2.

Simulated hydraulic-head values at recharge cells in outcrop areas are in suitable agreement with corresponding field or estimated values. All agree within 100 feet in flat outcrop areas and within 500 feet in hogback outcrop areas.

Simulated discharge rates to streams in outcrop areas were less than the upper limits estimated from field information. Simulated discharge was 4 ft^3/s in the Purgatoire-Cimarron area, where the upper limit was estimated to be 20 ft^3/s. Simulated discharge was 46 ft^3/s in the central Kansas area, where the upper limit was estimated to be 60 ft^3/s. Due to the very large model-grid size compared to stream areas and the inaccuracies associated with modeling stream-aquifer relations, it is difficult to evaluate the differences between simulated and field or estimated discharge rates.

The predevelopment, steady-state budget (inflow equals outflow) of the aquifer system was simulated as 342 ft^3/s (table 3), most of which is interchange vertically with adjacent rock units rather than lateral flow from or to outcrop areas. The distribution of vertical interchange rates per grid cell with the overlying layer, layer 1 (fig. 40), shows a decrease of several orders of magnitude westward into the Denver basin. Rates of simulated downward or upward volumetric flow at some individual grid cells exceed 10 ft^3/s (0.05 ft^3/s per square mile) where direct connection with the High Plains aquifer or Missouri River alluvium exists. Simulated volumetric rates in the deepest part of the Denver basin are less than 0.001 ft^3/s per grid cell (5×10^{-6} ft^3/s per square mile). The direction of this simulated flow is everywhere downward into the aquifer system except along much of the eastern and southern edge. Vertical interchange where the Great Plains aquifer system directly underlies the High Plains aquifer or Missouri River alluvium constitutes about 60 percent of the simulated water budget. If recharge or discharge at outcrop areas is considered also, the proportion increases to more than 70 percent.

Simulated vertical volumetric interchange with underlying units (fig. 41) is very small over most of the area, exceeding 0.1 ft^3/s per grid cell (5×10^{-4} ft^3/s per square mile) only along the eastern and southern edge of the study area. The volumetric flow rate per cell generally decreases to the west. The directions of simulated vertical flow appear hydrologically realistic; the simulated upward flow along the Missouri River valley is reasonable. Upward leakage from underlying strata was proposed by Schoon (1971) to explain calcium sulfate water from underlying strata in the aquifer system in southeastern South Dakota. Upward flow from underlying strata to the aquifer system also was simulated in central Kansas just west of the evaporite subcrop area. In this area, flow may be restricted by these nearly impermeable rocks, then diverted upward.

Transient Conditions During 1940–79

A simulation of transient conditions in the Great Plains aquifer system was made for 1940–79 by adding fluid withdrawals to the predevelopment conditions defined by the model. Simulated withdrawal rates, by decade, are in accordance with estimates described above in the section entitled "Present Development." County totals were used or subdivided as appropriate to assign rates of withdrawal to cells corresponding with areas of development. All pumpage of oil, gas, and saline water was assigned to layer 2; freshwater pumpage was assigned to layer 2 or 3 as appropriate. The

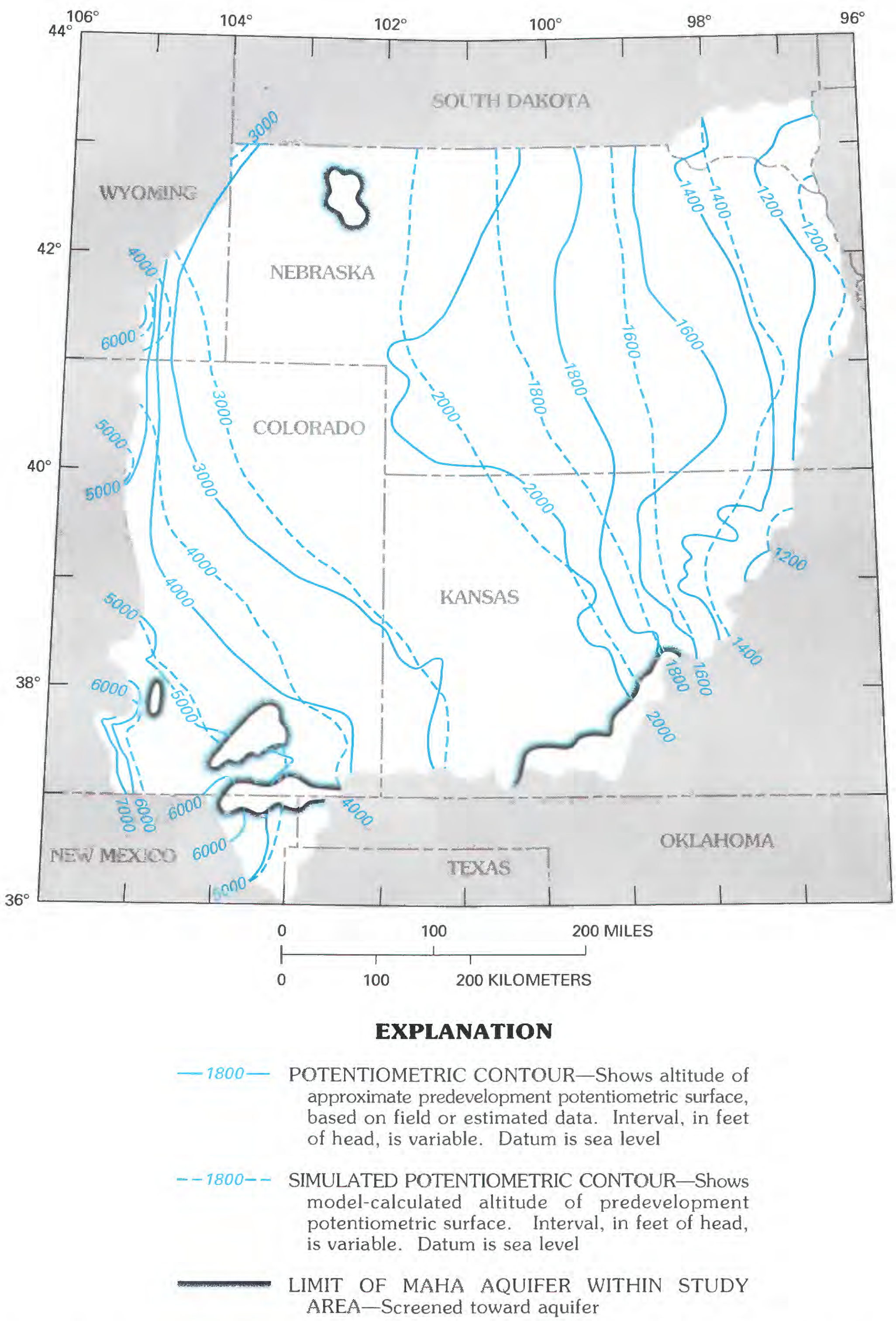
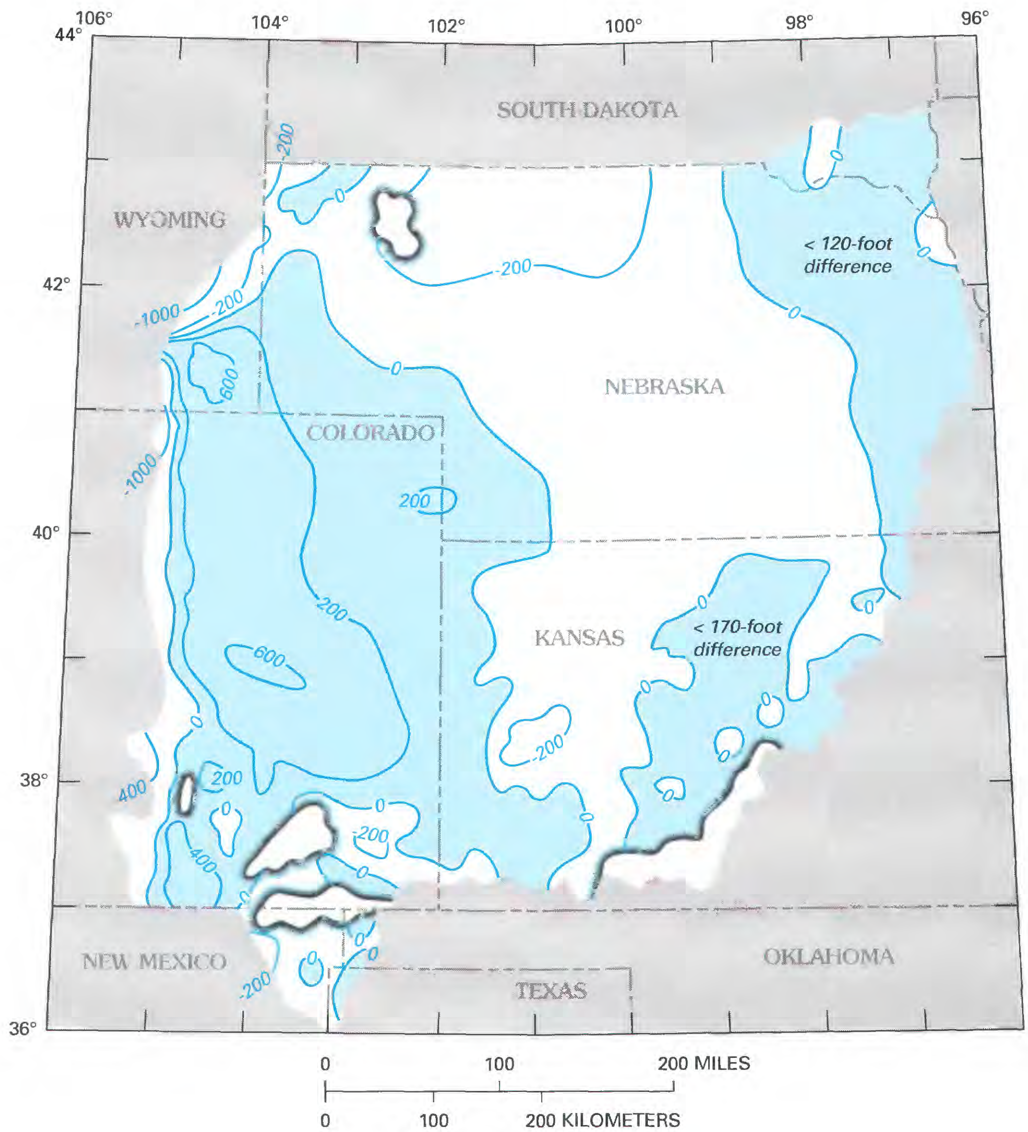


FIGURE 38.—Comparison of field or estimated and simulated predevelopment hydraulic-head distributions for Maha aquifer.

simulation consisted of four 10-year periods, and pertinent model results were recorded at the end of each period.

Development before 1940 was minimal in comparison to later decades and was not simulated. Also, the effects of climatic variations on recharge and water levels were assumed to be negligible during the 40-year simulation period.

The effect of development of the overlying High Plains aquifer was included in the transient simulation. Water-table declines in the High Plains aquifer have been substantial in two areas where the potential



EXPLANATION

-200 LINE OF EQUAL DIFFERENCE BETWEEN SIMULATED AND ESTIMATED PREDEVELOPMENT HEAD—Interval, in feet of head, is variable

AREA WHERE SIMULATED HEAD EXCEEDS FIELD OR ESTIMATED HEAD

LIMIT OF MAHA AQUIFER WITHIN STUDY AREA—Screened toward aquifer

FIGURE 39.—Difference between simulated and field or estimated predevelopment hydraulic head in Maha aquifer.

TABLE 3.—*Simulated predevelopment steady-state water budget of the Great Plains aquifer system in the study area*

[Values in cubic feet per second]

	Volumetric rate
Recharge	
Direct infiltration in outcrop areas	38
Leakage from overlying units	296
Leakage from underlying units	8
Total	342
Discharge	
Discharge in outcrop areas (streams)	50
Leakage to overlying units	238
Leakage to underlying units	54
Total	342

effect on the Great Plains aquifer system is significant because of direct hydraulic connection. These declines (from predevelopment conditions to 1980) in the High Plains aquifer are as large as 100 feet in southwestern Kansas and as large as 20 feet in southeastern Nebraska (Gutentag and others, 1984). Thus, layer 1 hydraulic-head values, which are held constant in the model during any given period within a simulation, were appropriately decreased in these two areas for the fourth period (1970–79) of the transient simulation.

Other parameters assigned to the model are identical to those used for calibration of predevelopment conditions, except for the addition of pumpage and the specification of storage coefficient. At the beginning of the simulation, the storage coefficient was assigned a value of 0.15 at cells in layers 2, 3, and 4 representing areas of unconfined conditions, mostly at or near outcrop areas (fig. 42). At the end of each 10-year period, the storage coefficient also was changed to 0.15 at other grid cells where simulated conditions had changed from confined to unconfined during that period. This change occurred in layer 2 during the second period (1950–59) at nine cells representing part of east-central Colorado, and during the third period (1960–69) at one cell representing an area in southeastern Nebraska (fig. 42).

Simulated withdrawals of oil, gas, and saline water (Denver basin) resulted in simulated hydraulic-head declines of 500 feet or more in the area of most intense development by the end of the 40-year period (fig. 43). The magnitude and extent of the simulated hydraulic-head declines generally resemble the differences between inferred predevelopment head and current head (all are equivalent freshwater heads). The large hydraulic-head declines due to fluid withdrawals in the Denver basin reflect the small transmissivity of the aquifer system in the basin.

Simulated 1940–79 hydraulic-head declines in response to freshwater pumpage are tens of feet in parts of southern Colorado, southwestern Kansas, eastern and northeastern Nebraska, and southeastern South Dakota (fig. 43). The simulated hydraulic-head declines exceed 100 feet locally. Declines are tempered where the overlying High Plains aquifer can provide a direct source of induced recharge. Although agreement between simulated and measured hydraulic-head declines is variable (fig. 44), available historical water-level records do provide some evidence of long-term decline in the areas of development. The simulated hydraulic-head declines in southwestern Kansas (as large as 100 feet) (fig. 43) are mainly a result of the lower water-table (constant) heads specified for layer 1 for the fourth period (1970–79), which were included to account for the effects of pumpage from the High Plains aquifer.

SENSITIVITY ANALYSES

Sensitivity to several parameters were tested as part of the model analysis. Effects of an increase and decrease in a specific parameter value of as much as 100 percent were determined, during which all other parameters were retained at their original (calibration) values. The effects of these changes on simulated hydraulic head and simulated discharge to streams (as compared to field or estimated head and discharges) were of principal interest, as these were the main bases for calibration.

Hydraulic-head differences are most sensitive to lateral hydraulic conductivity (fig. 45) and direct recharge at outcrops (fig. 46). That is, the difference between simulated and estimated hydraulic head increases significantly if hydraulic conductivity or outcrop recharge are changed from calibration values. Sensitivity of hydraulic-head differences to vertical hydraulic conductivity of the overlying rock unit is somewhat less, and sensitivity to vertical hydraulic conductivity of the underlying rock unit is notably less. Sensitivity to streambed leakance, which affects discharge to streams in outcrop areas, is extremely small.

Simulated discharge to streams is most sensitive to lateral hydraulic conductivity (fig. 47) and much less sensitive to other parameters. Comparison of simulated discharge to streams with upper-limit estimated values shows that the upper limit is exceeded if hydraulic-conductivity values are increased by about 70 percent above the calibration values.

The distribution of simulated hydraulic-head changes associated with a change in value of a parameter also is significant. Head-change distributions resulting from a 100-percent increase in lateral hydraulic conductivity and outcrop recharge (fig. 48) are similar but opposite in sign. Magnitudes of hydraulic-head change increase to the west, to about 1,000 feet along the extreme western margin. This distribution reflects a sensitive balance between the very

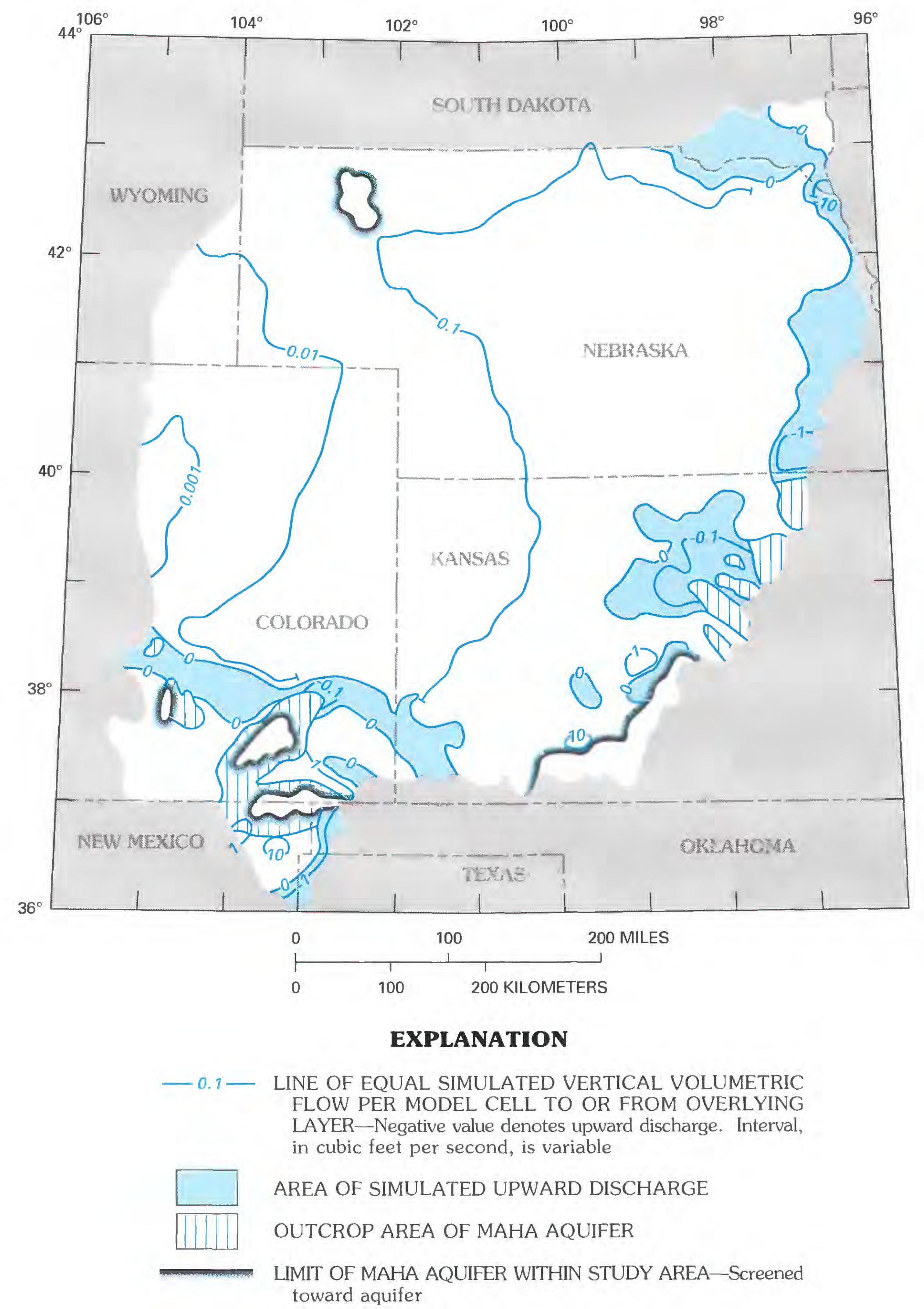


FIGURE 40.—Simulated vertical volumetric flow between Maha aquifer and overlying units.

small hydraulic conductivity along the western margin and recharge rates at hogback outcrop areas.

Sensitivity to change in storage coefficient was tested by repeating the transient simulation of 1940–79

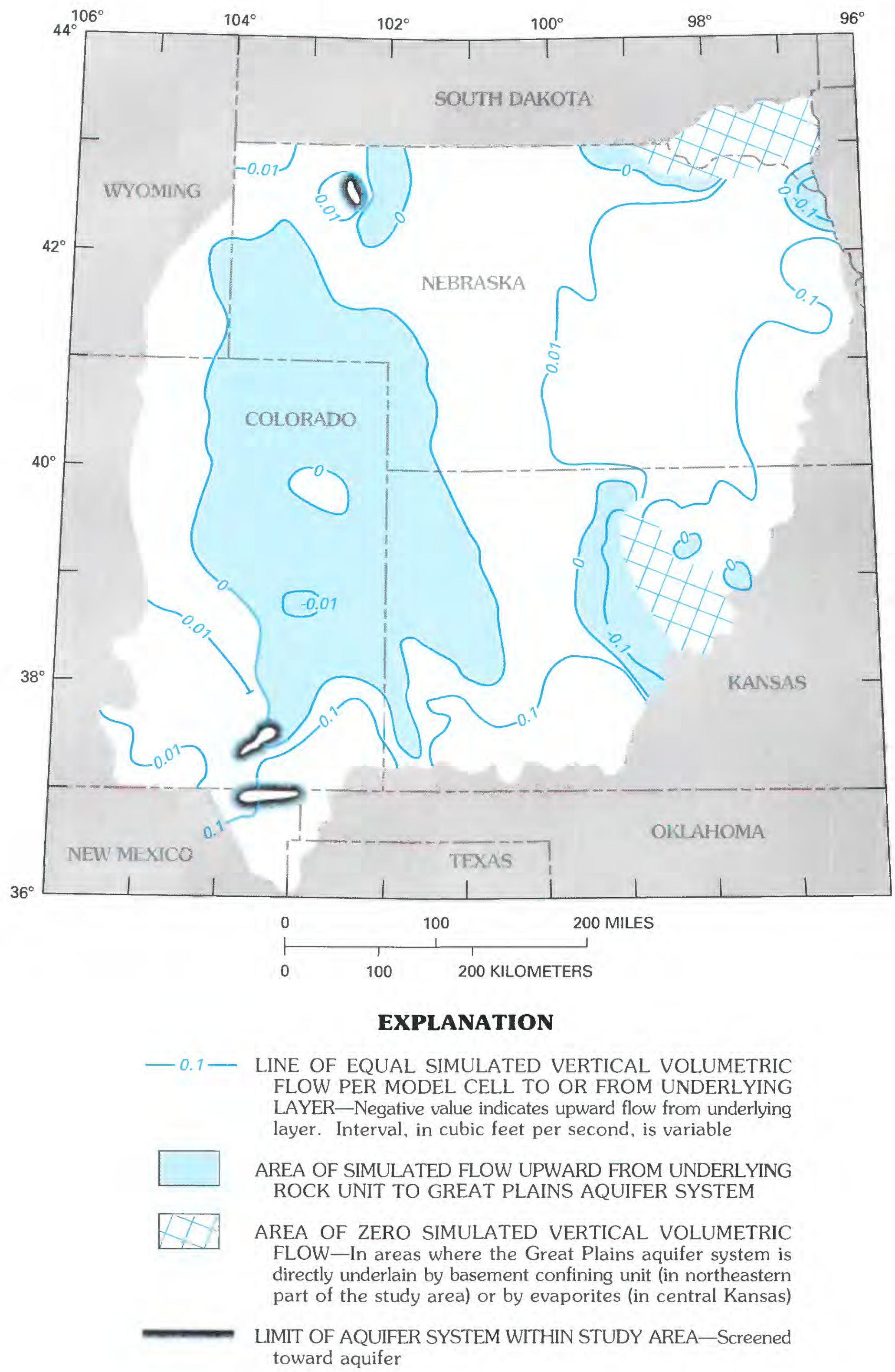


FIGURE 41.—Simulated vertical flow between Great Plains aquifer system and underlying units.

development conditions with a 100-percent increase in specific storage. Resulting differences in simulated hydraulic-head declines were not especially significant except in parts of the Denver basin, where declines

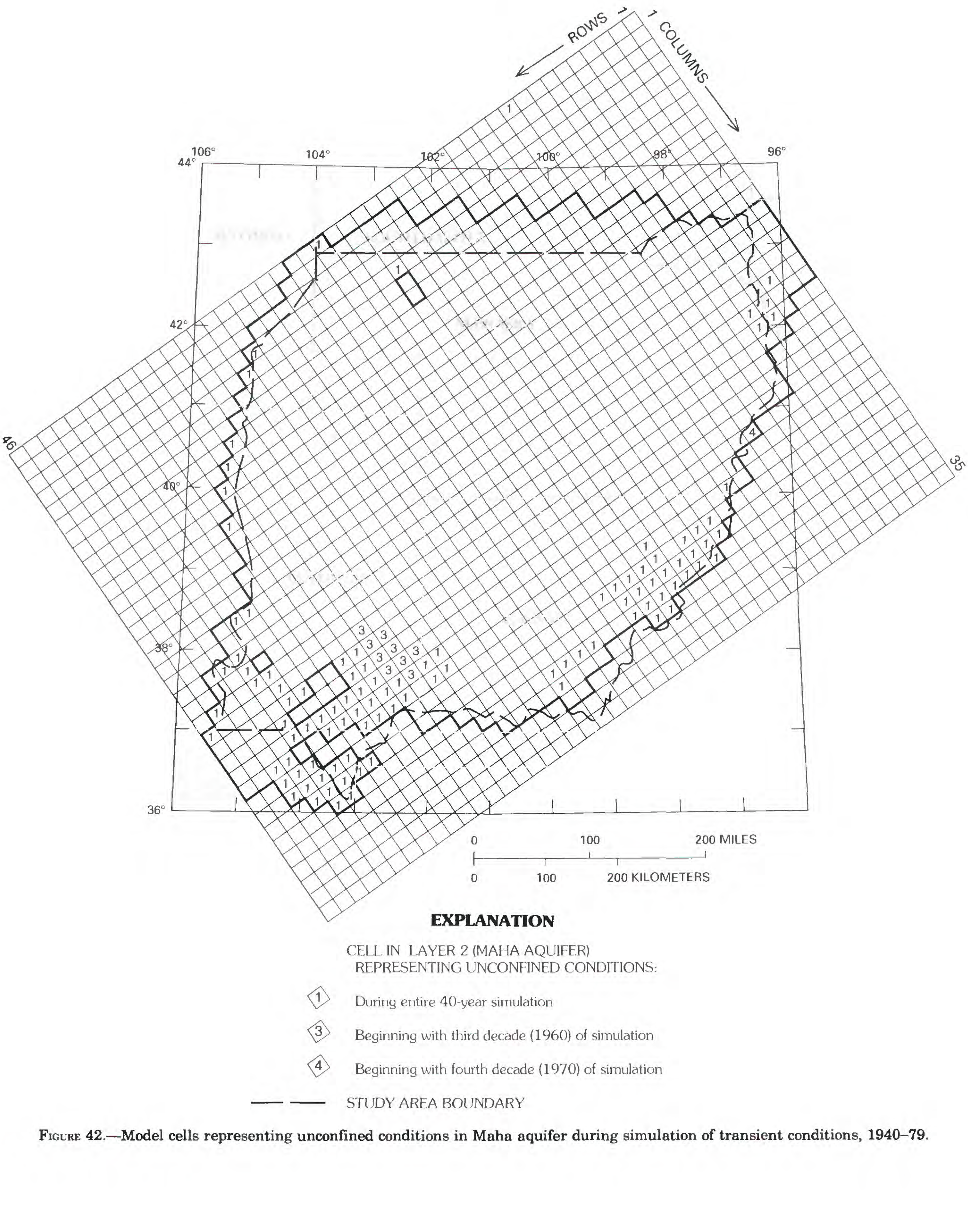


FIGURE 42.—Model cells representing unconfined conditions in Maha aquifer during simulation of transient conditions, 1940–79.

were several hundred feet less. Use of either the modified or original (calibration) value of specific storage results in simulated hydraulic-head declines that are comparable to inferred regional declines. The calibration value, however, results in slightly better agreement in overall head-decline distribution.

DEVELOPMENT POTENTIAL

An understanding of the geohydrology of the Great Plains aquifer system provides the basis for assessing the potential for development of the system. The diverse character of this system makes it suitable for a

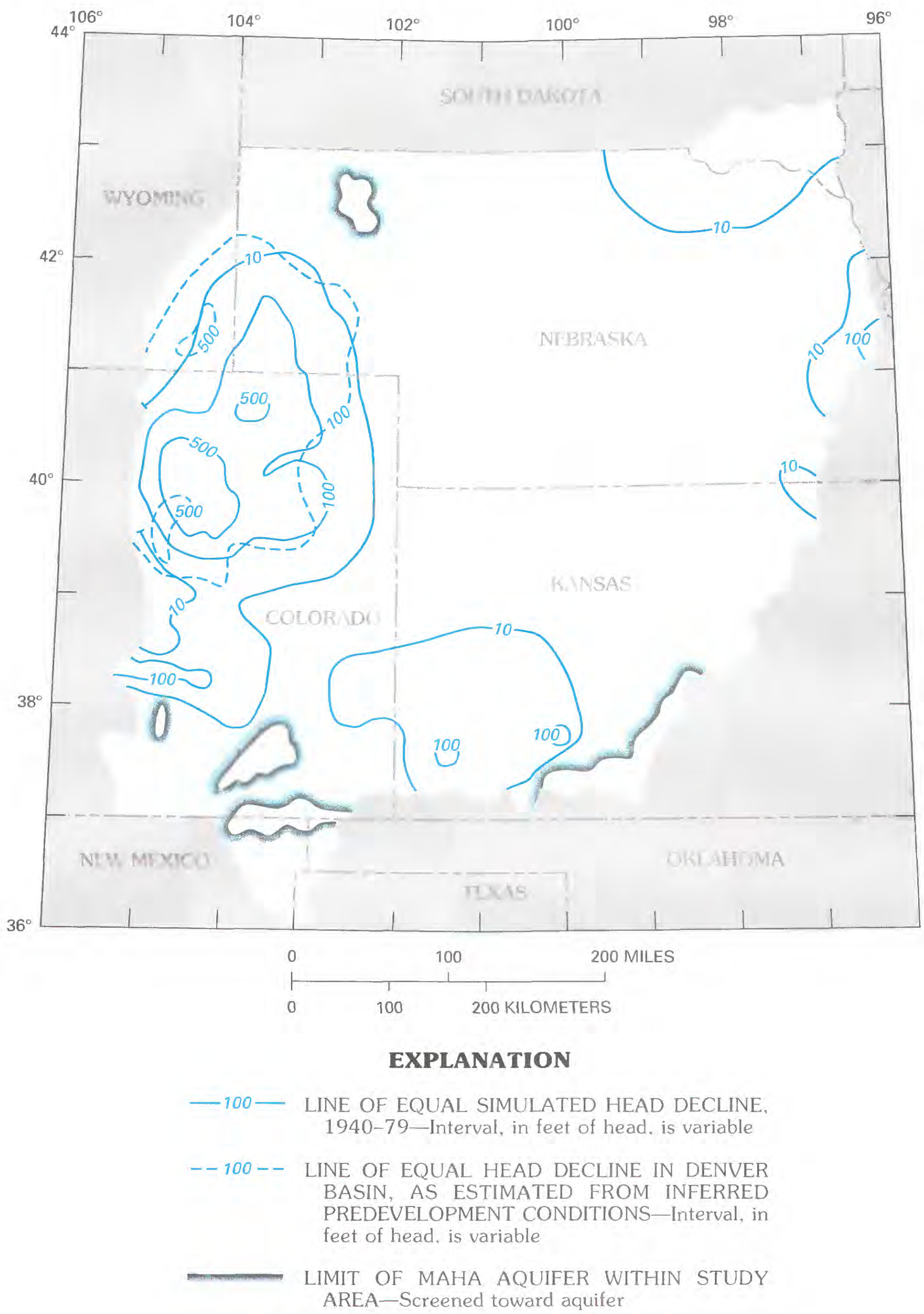


FIGURE 43.—Inferred hydraulic-head declines in Denver basin and simulated hydraulic-head declines in response to development of Great Plains aquifer system.

wide range of uses. Resources of the system that have already been developed are (1) oil and gas supply; (2) freshwater supply for irrigation, municipal, industrial, domestic, stock, or other purposes; and (3) saline water, produced mainly in association with oil, and much of which is reinjected to maintain reservoir pressure (secondary-recovery procedures). Potential uses of the system, in addition to the existing uses, include (1) other saline-water withdrawals for uses that may require desalinization or other treatment, and (2) geothermal-resource development for heat energy.

Assessment of the oil and gas resources is not within the scope of this study. Other uses are addressed herein based on the current understanding of the regional hydrology. This assessment cannot incorporate the local variations in geohydrologic conditions that need to be considered.

WATER-SUPPLY POTENTIAL

The significance of the aquifer system as a source of water has been demonstrated in relatively shallow

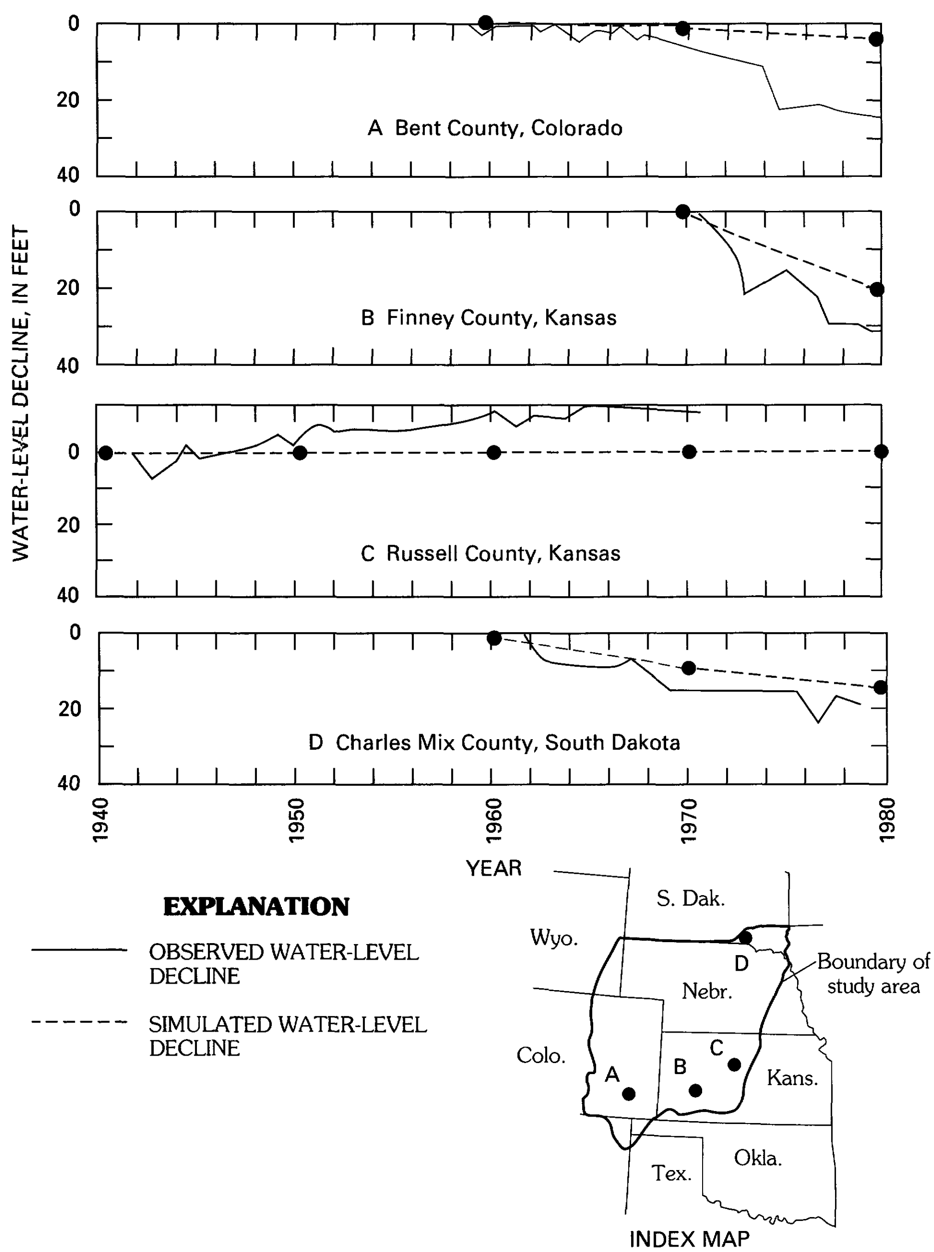


FIGURE 44.—Comparison of observed and simulated water-level changes at selected locations in Great Plains aquifer system.

areas. However, deeper parts of the system are unexplored for water, and effects of sustained development have not been evaluated. This discussion is based solely on ground-water hydraulics and does not consider other important but variable factors, such as water-quality suitability, economics, or operational feasibility of the development project.

AQUIFER SYSTEM RESPONSE TO DEVELOPMENT

Long-term water-yielding capability depends on the capacity of the hydrologic system to adjust in order to sustain the rates of withdrawal. Withdrawals imposed upon the system affect the system's storage, recharge, and discharge, or some combination of these, depending upon rates and location of the withdrawals.

Considering only the Great Plains aquifer system itself, withdrawals may do one or more of the following:

1. Intercept water that would have discharged upward to overlying units.
2. Intercept water that would have discharged downward to underlying units.
3. Intercept water that would have discharged to streams or evapotranspiration in aquifer-system outcrop areas.
4. Remove water from aquifer-system storage.

Development also may induce flow from sources of water in hydraulic connection with the aquifer system. These sources are (1) the High Plains aquifer, (2) other adjacent geohydrologic units, and (3) streams in outcrop areas of the aquifer system.

The computer model of the flow system makes possible an accounting of simulated changes in recharge, discharge, and storage resulting from simulated withdrawals. Certain limitations of the model must be recognized, particularly in relation to simulation of induced flow from sources other than the Great Plains aquifer system. The specification of constant heads in layer 1 assumes no change of storage (decline of water table) in units represented by layer 1. Potential error from this assumption is greatest where layer 1 represents the High Plains aquifer,

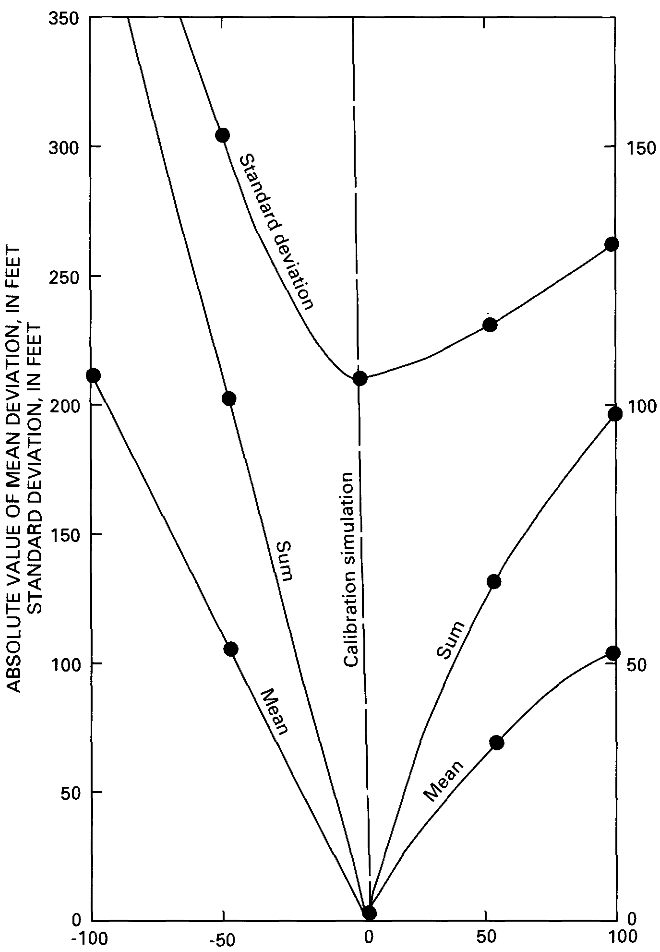


FIGURE 45.—Effect of variations in lateral hydraulic conductivity on simulated hydraulic head for Great Plains aquifer system.

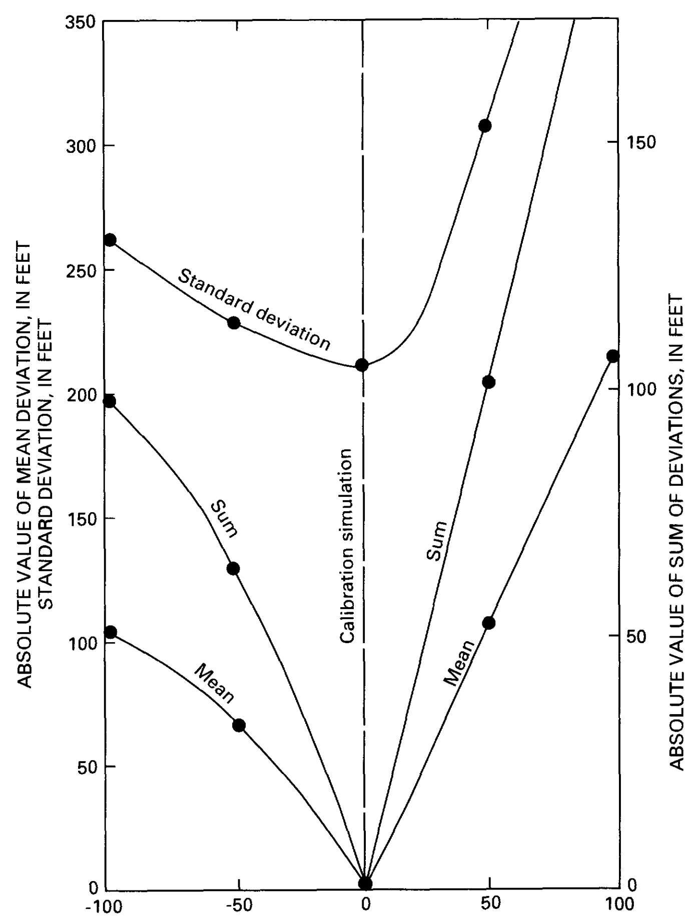


FIGURE 46.—Effect of variations in outcrop recharge on simulated hydraulic head for Great Plains aquifer system.

which has had significant water-table declines already and will undergo as-yet-unknown changes in the future. Although water-table altitudes in two areas of the High Plains aquifer were lowered during simulation of 1940–79 conditions, no further changes are introduced in simulating future response of the system. Simulation of induced flow from above is restricted by appropriate vertical-conductance properties but is modeled as an infinite source. Therefore, interpretation of model results must be modified if depletion of the High Plains aquifer significantly reduces its role as a source of induced flow to the Great Plains aquifer system.

Similarly, the constant-head cells in layer 4 just beyond the eastern and southern edge of the aquifer system form a potential, though less direct, source of induced flow. Induced flow from streams in outcrop areas, although the rates are affected by streambed leakance, is also unlimited as modeled. Therefore, if simulated hydraulic heads decline below streambed altitudes representing the Purgatoire River, Cimarron River, or the central Kansas streams, interpretation of model results should include comparisons of simulated induced flow from streams with actual streamflow available.

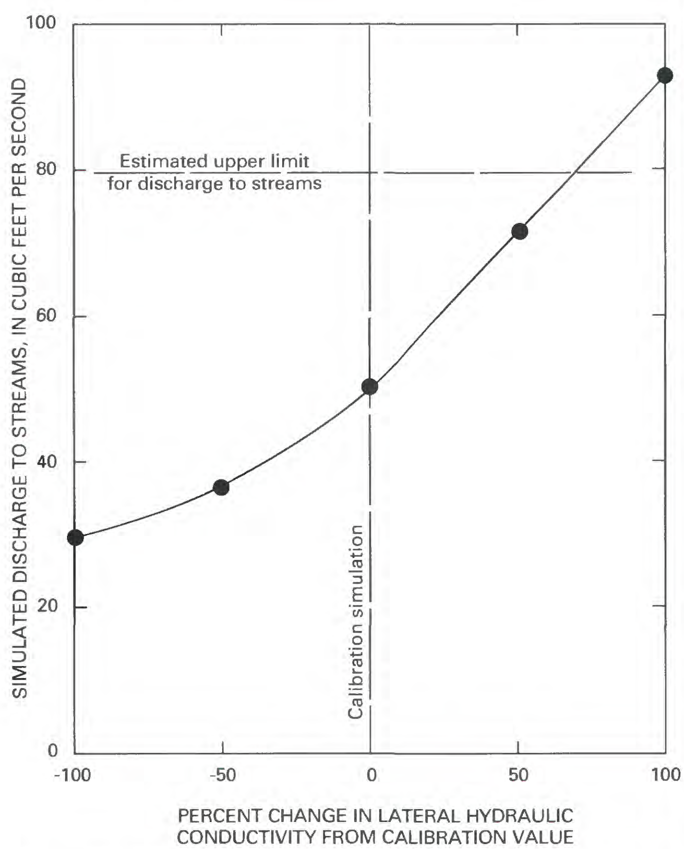


FIGURE 47.—Effect of variations in lateral hydraulic conductivity on simulated discharge to streams from Great Plains aquifer system.

Evaluation of the water budget and its changes through the simulation of 1940–79 conditions allowed estimates of effects on recharge, discharge, and storage (fig. 49). Pumpage during the first period of the simulation (representing 1940–49) was derived largely by inducing recharge from, or intercepting discharge to, overlying units. A small part represents intercepted discharge to streams or evapotranspiration. Only a very small part of withdrawal (not visible in figure 49) was obtained from storage, indicating that the aquifer system had reached a quasi-equilibrium state. During later periods, significant storage depletion occurred in response to much larger simulated withdrawal rates. During all periods, most of the simulated pumpage was derived from induced recharge from, or intercepted discharge to, overlying units. For 1970–79, about 70 percent of simulated pumpage was derived from induced recharge from, or intercepted discharge to, overlying units, and about 29 percent was derived from storage.

The response of the Great Plains aquifer system to withdrawals is areally variable. Where the aquifer system is in direct contact with the High Plains aquifer, leakage from above is easily induced, and storage depletion is minimal if leakage is maintained. Where adequate leakage is not available, storage is depleted. The response of the system, therefore, depends partly on the location of withdrawals. The 1970–79 estimated rate of withdrawal was about 850 ft^3/s, which greatly exceeded the predevelopment recharge rate (about 340 ft^3/s). Distribution and rates of withdrawal are such that nearly one-third of water withdrawn is derived from storage depletion.

A steady-state simulation that included fluid withdrawal from the aquifer system was made to evaluate the ultimate response of the system to development. Assigned starting conditions for the simulation were identical to the ending conditions for the 1940–79 transient simulation. The condition of fluid withdrawal was assumed to be the same as that simulated during the 1970–79 period, as well as the assumption of a constant water table.

Simulated new-equilibrium hydraulic-head declines, along with the 1940–79 declines, for selected model cells are shown in figure 50. In an area where the High Plains aquifer or Missouri River alluvium directly overlies the Great Plains aquifer system (cell 10,25 in figure 33), hydraulic head in the aquifer system will be maintained as long as adequate flow can be induced from above. Where such conditions prevail, equilibrium is reached within about 1 year.

Where the aquifer system is overlain by the Great Plains confining system (cells 34,24 or 25,11 in figure 33), induced flow from above is much more restricted.

In these areas, 1980 hydraulic-head values are far from equilibrium (fig. 50). Visual extrapolations of head-decline trend suggest that hundreds or thousands of years may be required for a new equilibrium to be reached in these parts of the system. The very slow rate of adjustment to withdrawals in the Denver basin (cell 25,11) is consistent with the concepts of extremely small hydraulic conductivity, poor hydrau-

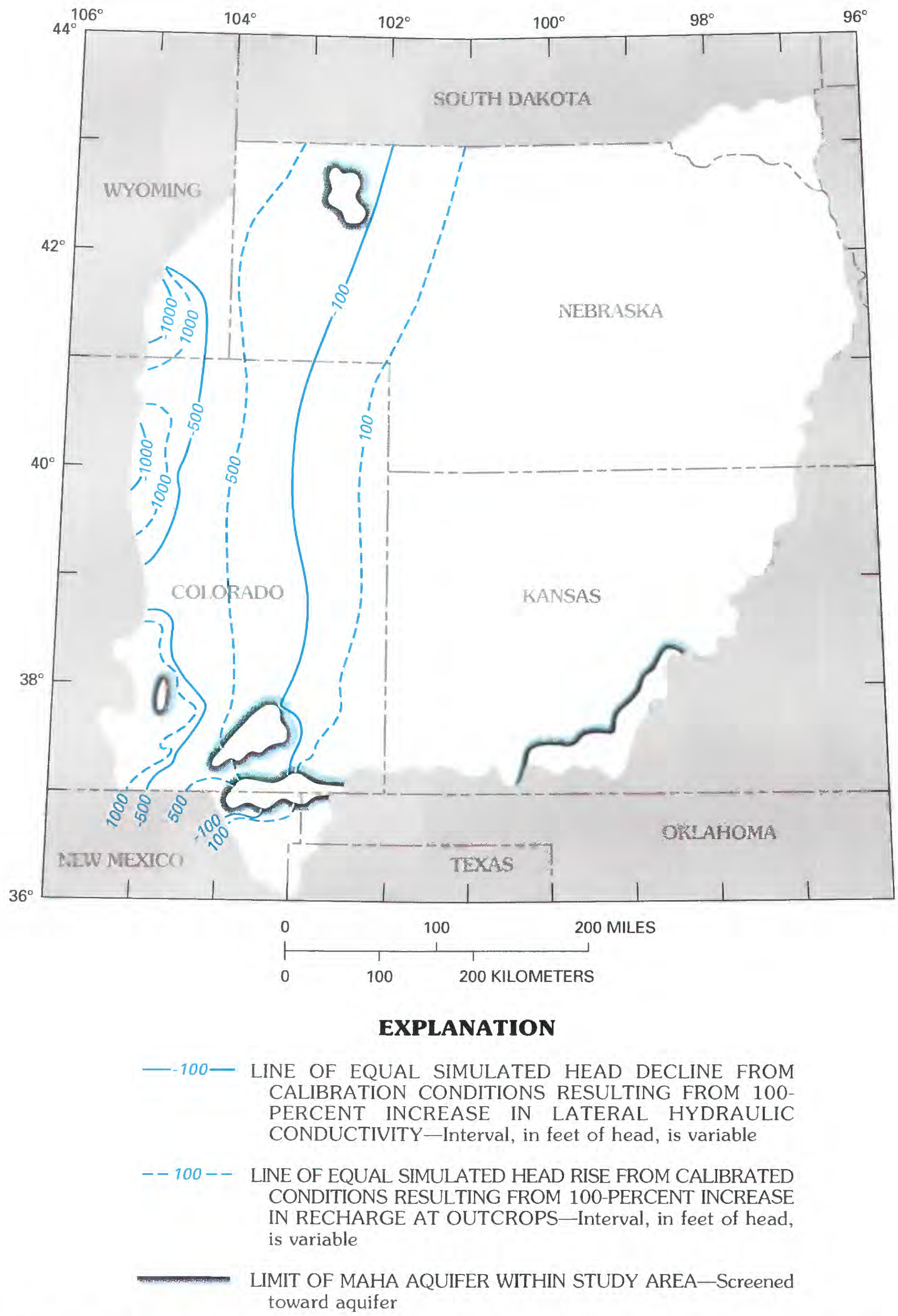


FIGURE 48.—Change in simulated hydraulic head resulting from increase in assigned lateral hydraulic conductivity or recharge at outcrops.

lic continuity, and a virtually stagnant system in that area.

A 10-year transient simulation was made to evaluate the aquifer system in response to a hypothetical continuous withdrawal of 10,000 gal/min (22.28 ft^3/s) at cell 10,21. No other stresses were imposed on the system, and initial conditions were set to the steady-state calibration conditions. The resulting simulated declines in hydraulic head affect much of the northeast half of the study area (fig. 51). The asymmetric configuration of the hydraulic-head declines is a result of the High Plains aquifer or Missouri River alluvium directly overlying the aquifer system east of the pumping center. At the end of the 10-year simulation, 39 percent of the simulated withdrawal was derived from storage, 36 percent was induced leakage from overlying rock units, and 18 percent was intercepted upward leakage. After 10 years of pumping, the system would be far from equilibrium.

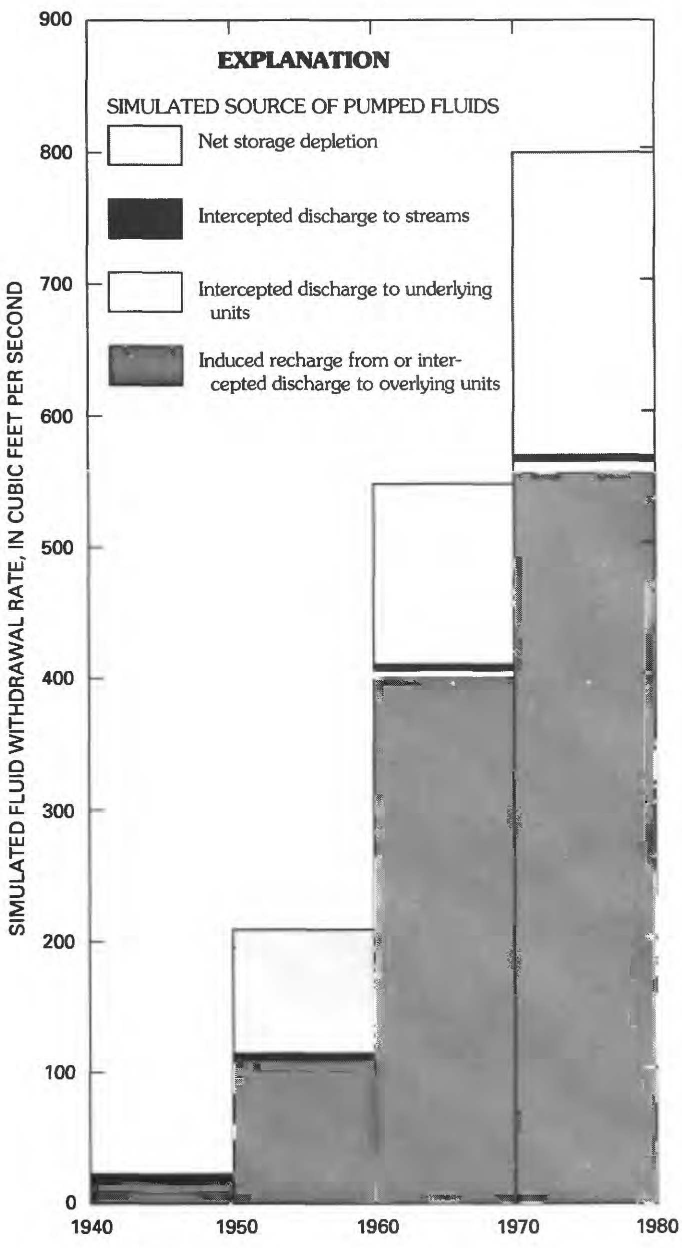


FIGURE 49.—Simulated changes in recharge, discharge, and storage in response to 1940–79 pumpage from Great Plains aquifer system.

The simulation was repeated assuming a withdrawal rate of 50,000 gal/min (111.40 ft^3/s) at the same cell. This much greater stress produced larger and more extensive simulated hydraulic-head declines (fig. 52). The simulated hydraulic-head decline at the cell was about 360 feet after 10 years of withdrawal; at the end of the simulation, 52 percent of the simulated withdrawal was derived from storage, 34 percent was induced leakage from overlying rock units, and 12 percent was intercepted upward leakage. The assumption of constant heads in the High Plains aquifer and Missouri River alluvium where they directly overlie the aquifer system may cause simulation errors (that is, undersimulated hydraulic-head decline in the area east of the pumping center).

IMPLICATIONS FOR SUSTAINED DEVELOPMENT

Large-scale withdrawals from the Great Plains aquifer system would be accompanied by severe depletion of storage because of limited natural recharge of the aquifer system. The storage depletion would be accompanied by declining water levels, which could increase pumping costs, decrease well yields, and ultimately lead to dewatering of the system if development is sufficiently intense.

The simulations described above provide some guidelines for the response that might be expected under various levels of development. Significant declines in hydraulic head may develop over a period of years, decades, or longer. Therefore, sustained water-supply potential must be defined in terms of the degree of storage depletion or other effect that cannot be tolerated.

The hydraulic connection between parts of the Great Plains aquifer system and High Plains aquifer holds important implications for both. Results of a previous model study in southwestern Kansas (Watts, 1989) suggest that hydraulic-head changes in the High Plains aquifer in response to pumpage from the Great Plains aquifer system are small compared to changes caused by pumpage from the High Plains aquifer. As development continues, definition of the interrelations between the two aquifers will be important for appropriate planning and management.

Although the analyses presented herein contribute to a preliminary evaluation of regional water-supply potential of the Great Plains aquifer system, some limitations must be recognized. The eastern and southern parts of the aquifer system are most likely to undergo development because the system is most accessible there and generally contains water of better quality. The large grid size and generalized properties and boundary conditions used for the model analyses described herein should not be applied directly to specific small areas.

WASTE-DISPOSAL POTENTIAL

Some parts of the Great Plains aquifer system possess hydrologic characteristics potentially favorable for accepting liquid wastes. Successful and safe subsurface disposal of liquid wastes requires an aquifer with porosity and hydraulic conductivity sufficient to accept the wastes, and hydrogeologic conditions that would prevent movement of the wastes into areas where water quality is suitable for development.

Capability for accepting wastes as affected by hydraulic properties generally decreases with increases in depth of burial. As shown by extensive injection of oilfield brine, the strata are commonly capable of accepting waste, despite relatively large depths of burial. Garbarini and Veal (1968) identified the southern flank of the Denver basin as potentially suitable for waste disposal at depths exceeding 1,000 feet. As discussed earlier, flow approaches stagnation in most of the Denver basin, a favorable characteristic for waste disposal. Presuming that flow of solutes would be principally advective (that is, with the flow of water), flow velocities of the waste would be equally slow. The overlying confining system would restrict flow upward from the aquifer system, although its integri-

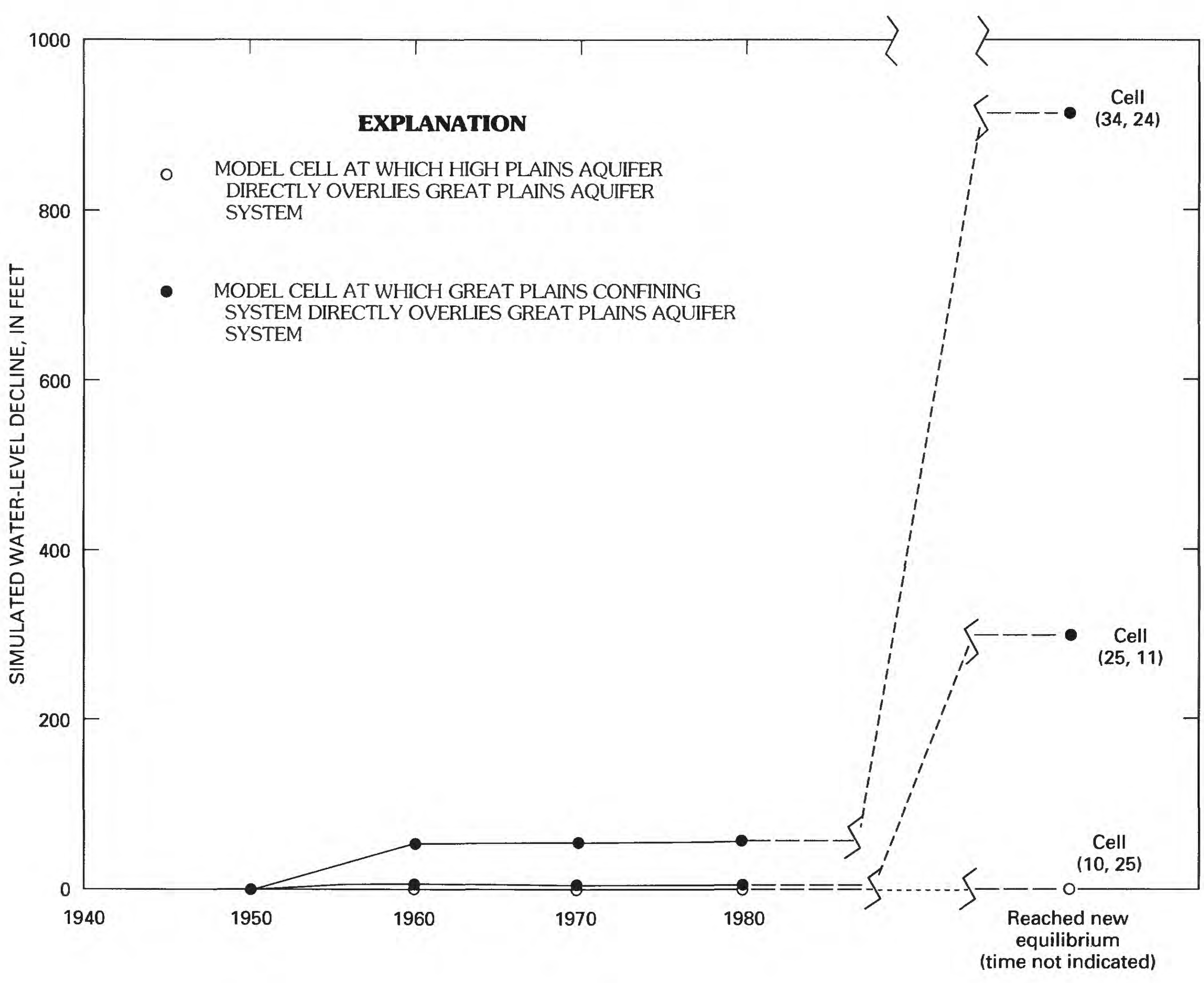


FIGURE 50.—Simulated hydraulic-head declines at selected model cells representing Great Plains aquifer system.

ty may be reduced by improperly abandoned wells. A large downward hydraulic-head gradient prevails in most of the area, which creates favorable potential to keep the injected wastes in the aquifer system in the Denver basin.

The computer model was used to simulate regional hydraulic-head changes in response to a hypothetical injection of nontoxic liquid into the aquifer system at a depth of about 3,000 feet on the eastern flank of the Denver basin. A 10,000 gal/min (11.14 ft^3/s) injection

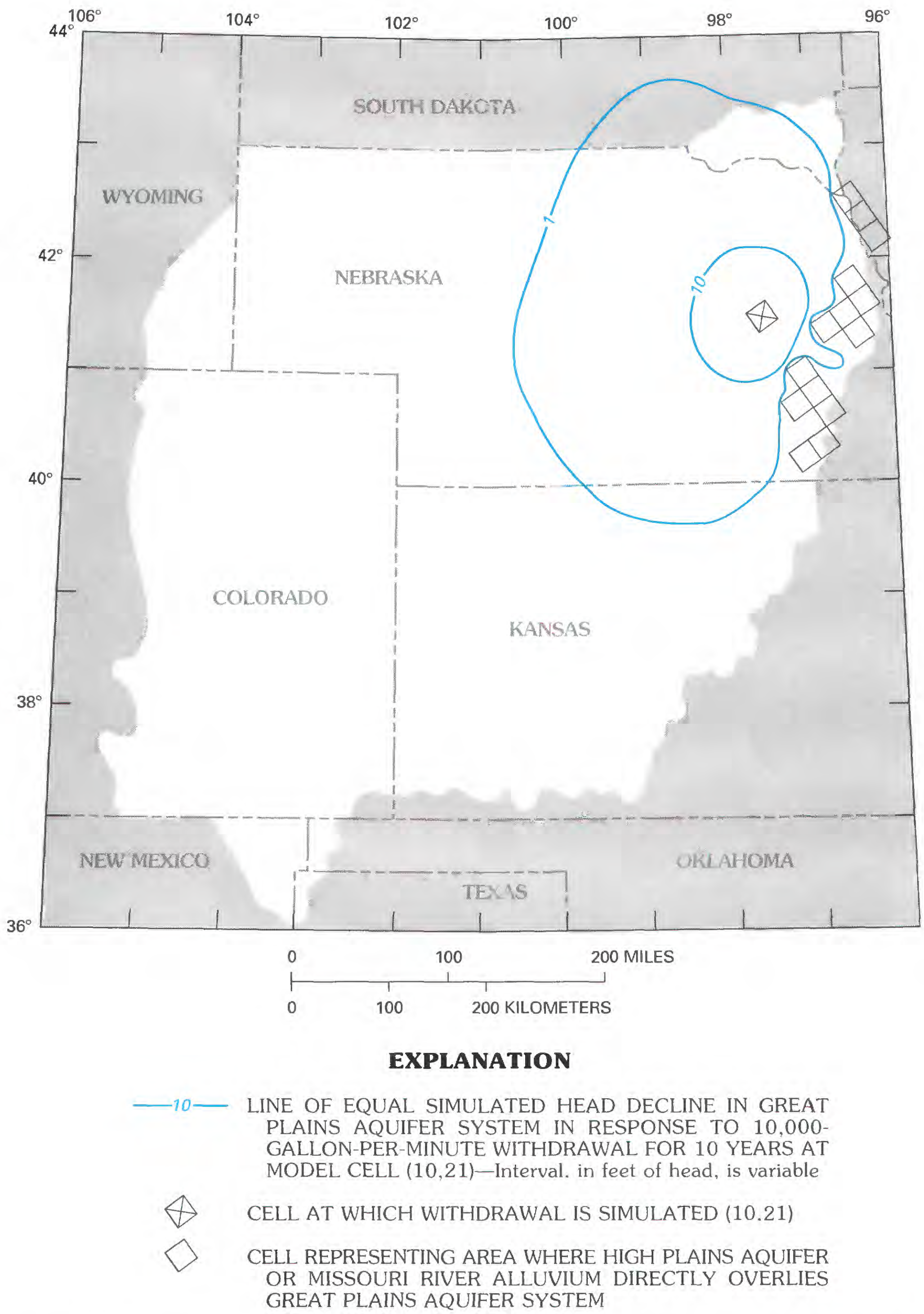


FIGURE 51.—Simulated regional hydraulic-head decline in Great Plains aquifer system in response to 10-year continuous withdrawal of 10,000 gallons per minute in eastern Nebraska.

was simulated at cell 29,18 (location shown in figure 33). Because transmissivity values for the Maha and Apishapa aquifers are about equal in this area, one-half of the total injection rate was applied to model layer 2, and one-half was applied to model layer 3. Simulated regional hydraulic-head rises in the aquifer system after 10 years of injection are shown in figure 53. The simulated hydraulic-head rise at the injection cell was 438 feet. A cone of impression, such as shown in figure 53, would increase the regional

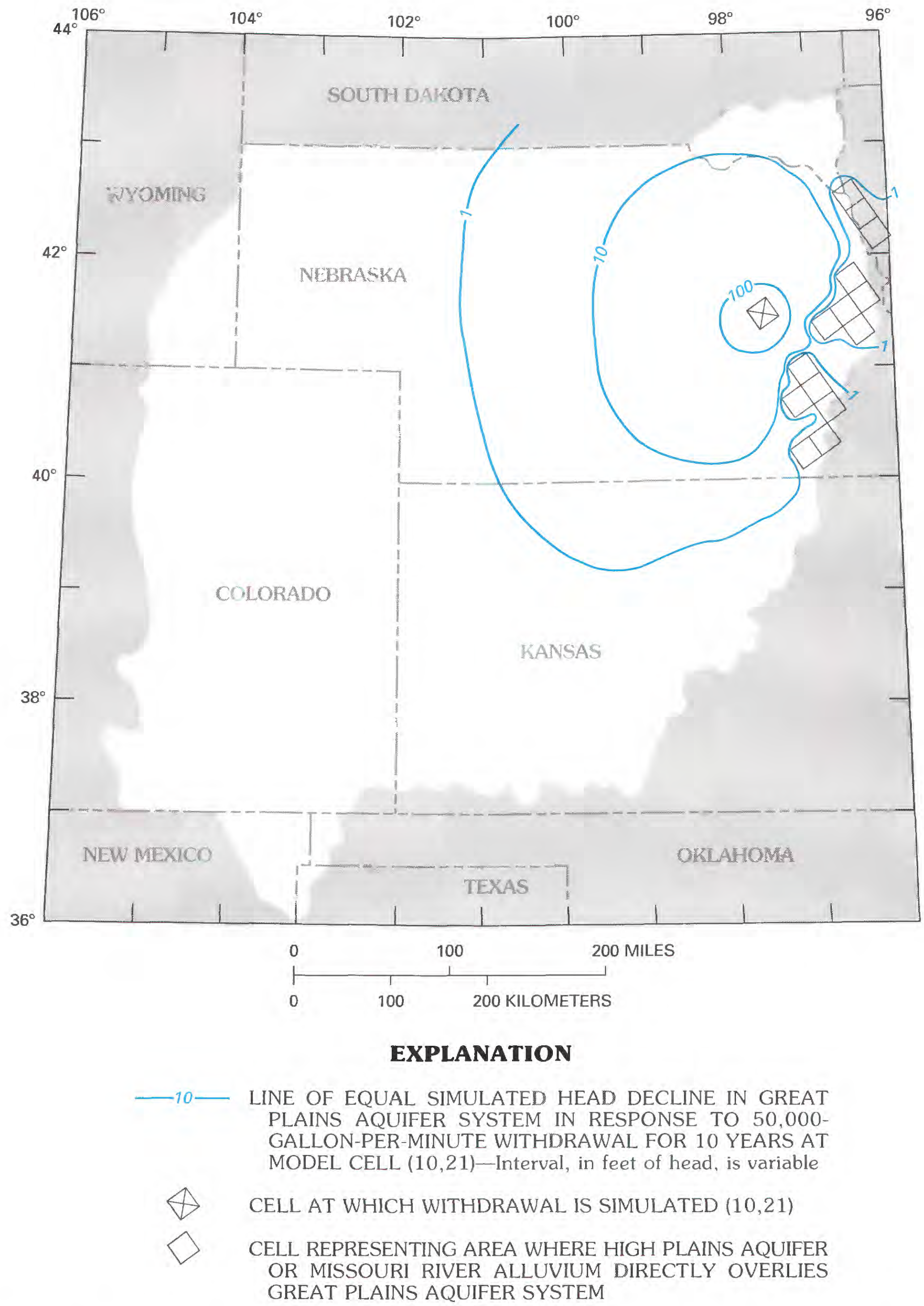


FIGURE 52.—Simulated regional hydraulic-head decline in Great Plains aquifer system in response to 10-year continuous withdrawal of 50,000 gallons per minute in eastern Nebraska.

hydraulic gradient to the northeast (refer to plate 5) by about 20 percent. This would increase regional flow velocities by about 20 percent, which would still be essentially a stagnant condition.

The model results describe hydraulic-head changes, not actual movement of fluid. Assuming that flow would be basically a volume-displacement process, the injected fluid would theoretically displace water in the aquifer system over an area of a few square miles around the injection area, at the specified injection rate and simulated time period. However, accurate definition of the effects of injection also depends on density, viscosity, and chemical composition of the fluid. The model used herein assumes the fluid is equivalent to fresh water at 60 °F. This exercise is for broad evaluation only; for evaluation of a particular

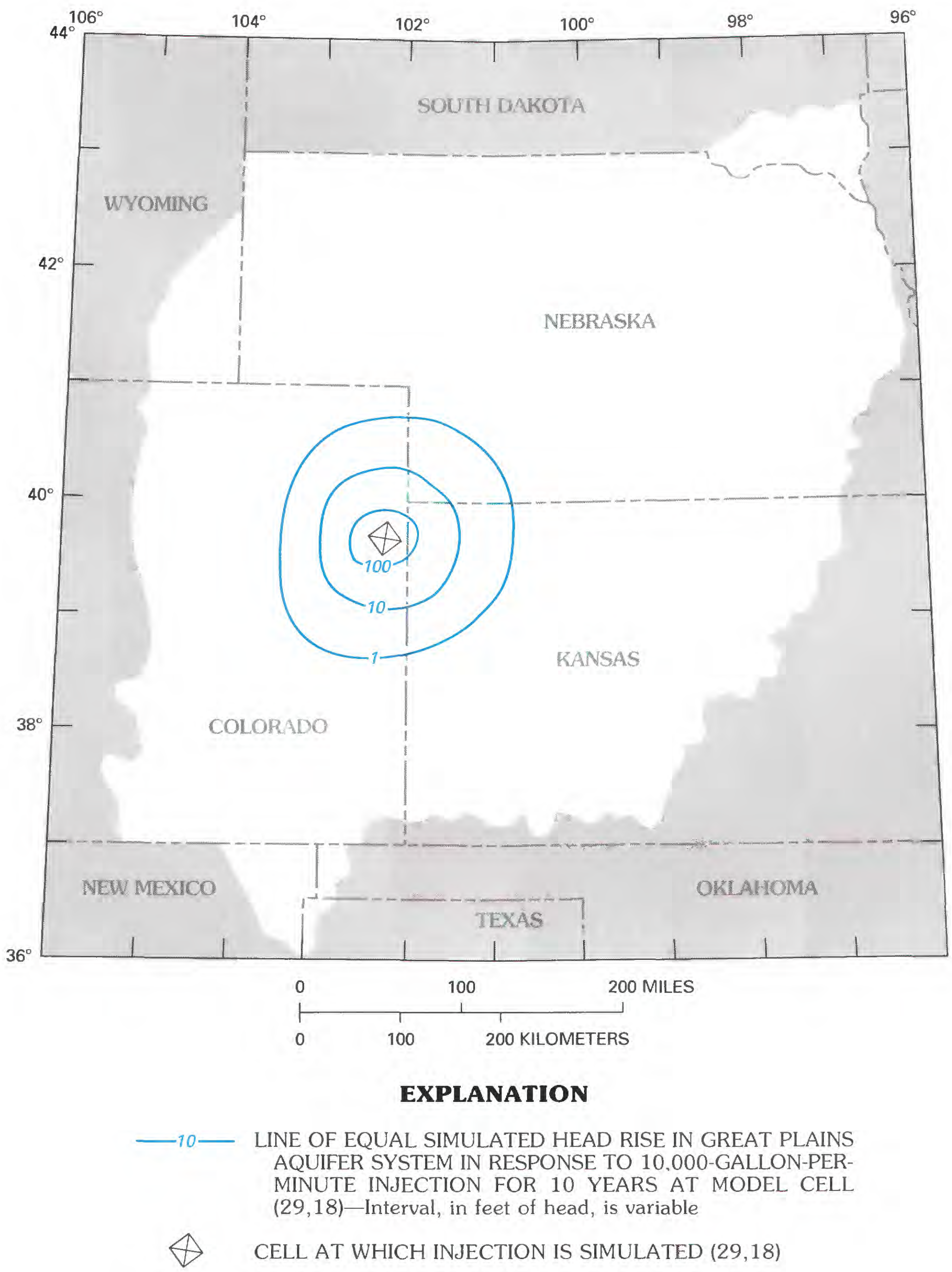


FIGURE 53.—Simulated regional hydraulic-head rise in Great Plains aquifer system in response to 10-year continuous injection of 10,000 gallons per minute in eastern Colorado.

waste disposal, solute-transport and chemical-reaction models should be used and the impact of waste toxicity on the aquifer system should be considered.

WATER-QUALITY CONSIDERATIONS

Water quality is a major factor influencing current or projected development. The chemical quality of water in the Great Plains aquifer system and the standards pertinent to the many water uses are diverse. Because of this diversity, and the very limited availability of data describing the regional distribution of major and minor constituents, water quality is discussed herein only in general terms.

CHEMICAL SUITABILITY FOR USE

The suitability of water for most uses decreases as the concentration of dissolved solids increases. The recommended maximum level of dissolved solids for drinking water is 500 mg/L (U.S. Environmental Protection Agency, 1986); domestic and irrigation water from the Great Plains aquifer system commonly exceed that level. Water containing more than 2,000 to 3,000 mg/L generally is too mineralized to drink and is unsuitable for irrigation. Most water containing less than 3,000 mg/L dissolved solids was obtained from domestic or irrigation wells near the eastern and southern boundaries of the study area or in a narrow band along the mountain front. Analyses of water samples and estimates from geophysical logs from deeper wells indicate that the dissolved-solids concentration generally exceeds 3,000 mg/L and commonly exceeds 10,000 mg/L in the central and western part of the area. Water containing more than 10,000 mg/L is unsuitable for most uses.

The concentrations of ionic constituents further limit the suitability of water for use. For example, the recommended maximum concentration for both chloride and sulfate in drinking water is 250 mg/L. Excessive chloride concentrations may impart a salty taste to drinking water, and excessive sulfate concentrations may have a cathartic effect. If the dissolved solids consisted principally of sodium and chloride or sulfate, water containing less than 1,000 mg/L dissolved solids might be unsuitable for domestic use or irrigation. Conversely, if the dissolved solids consisted principally of calcium and bicarbonate, water containing more than 1,000 mg/L dissolved solids might be suitable for both uses. Therefore, the water type (pl. 7) should be considered in conjunction with the dissolved-solids concentration (pl. 6) in assessing the suitability of water for specific uses.

Irrigation waters normally are classified in terms of the total concentration of soluble salts (salinity hazard), the relative proportion of sodium to other cations (sodium or alkali hazard), and the concentration of boron or other elements that may be toxic to crops. The salinity hazard is a measure of interference by dissolved solids with the processes by which plants extract water from the soil. The sodium hazard is a measure of the amount of sodium that may accumulate in the soil, largely as a result of ion exchange, which adversely affects plant growth as well as soil permeability and tilth.

To illustrate the wide variability of water in the Great Plains aquifer system, analyses of samples from wells near or along section *D–D′* (pl. 10) are plotted on a diagram developed by the U.S. Salinity Laboratory Staff (1954) for the classification of water (fig. 54) for irrigation. In the diagram, the salinity hazard is classified in terms of specific conductance, a measure of the ability of water to conduct electricity. Specific conductance is a readily determined index of the chemical quality of water. Its magnitude depends on the concentration and activity of the individual ionic constituents, but it is roughly proportional to the concentration of dissolved solids.

The linear regression equation relating dissolved solids *DS* to specific conductance *SC* for 181 water-sample analyses near and along the line of section (*D–D′*) is

$$DS = 0.585\,SC + 77.22 \tag{13}$$

where *DS* is measured in milligrams per liter, and *SC* is measured in microsiemens per centimeter (μS/cm) at 25 °C. The correlation coefficient is 0.96.

The sodium (alkali) hazard is reported in terms of the sodium adsorption ratio (SAR), defined by the U.S. Salinity Laboratory Staff (1954) as

$$\mathrm{SAR} = \frac{\mathrm{Na}+}{\sqrt{\dfrac{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}{2}}} \tag{14}$$

where Na^{+}, Ca^{2+}, and Mg^{2+} are the concentrations of dissolved sodium, calcium, and magnesium, respectively, in milliequivalents per liter. The water classified as high to very high sodium hazard (fig. 54) contains more than 660 mg/L dissolved solids (specific conductance greater than about 1,000 μS/cm), with sodium as the principal cation. The water with a low sodium hazard, but a high salinity hazard, commonly is of the calcium sulfate type.

Large SAR values indicate that soil structure may be damaged by sodium replacing calcium and magnesium adsorbed on clay particles. Large SAR values also may characterize water containing sodium displaced from marine clay by natural infiltration or application of calcium- or magnesium-rich water. Although the sodium sulfate type water in shallow wells along the Arkansas River (and in the river itself) may have been derived by leaching from the overlying shale, it is possible that its composition partly represents irrigation return flow.

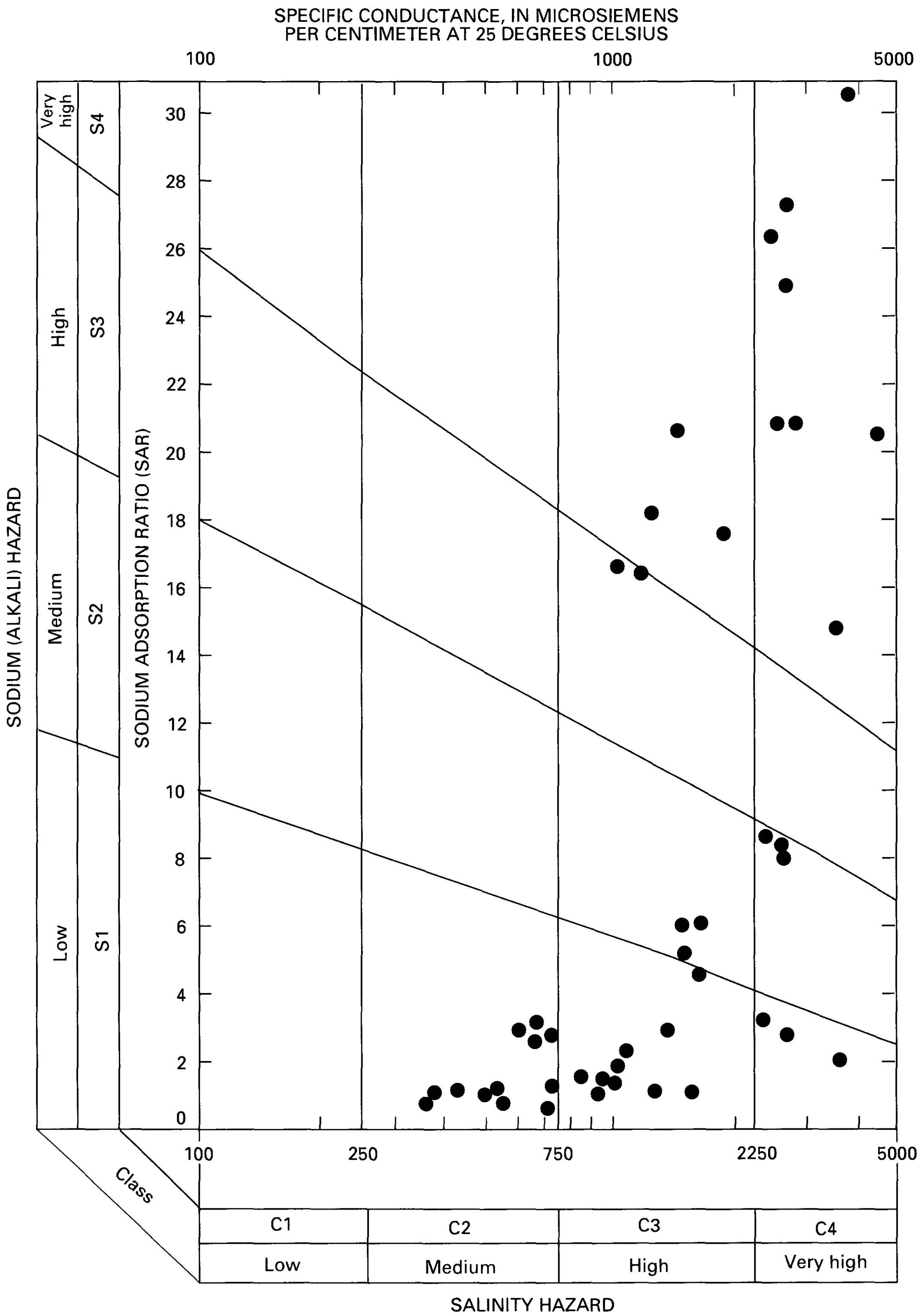


FIGURE 54.—Classification of salinity and sodium hazards for water from Great Plains aquifer system along section *D–D′* (shown on plate 10).

As shown on plates 6–10, sodium is the principal cation in most water containing more than 3,000 mg/L dissolved solids; analyses of samples of that water would plot outside of the boundaries of the classification diagram (fig. 54). If that relation persists, most of the water in the aquifer system in the undeveloped central part of the area is neither potable nor suitable for irrigation. However, it is important to recognize that the concentrations shown on plates 6–10 are based on median values that commonly mask stratification, including known occurrences of fresher water in the top part of the aquifer system.

GEOTHERMAL POTENTIAL

Potential for development of low-temperature (40 to 90 °C) geothermal energy is favorable in most of the northwestern half of the study area (Reed, 1983). This large area of warmer water (fig. 55) is a result of steep geothermal gradients, the insulating effect of overlying shale, and convective heat transfer by ground-water flow. On the eastern flank of the Denver basin, observed heat-flow conditions are consistent with ground-water flow updip out of the basin (Reed, 1983; Gosnold, 1984). In north-central Nebraska, upward flow of warmer water from below is probably an important heat-transfer mechanism (Schoon and McGregor, 1974; Gosnold and Eversoll, 1981). The aquifer system also contains warm water in south-central Colorado in the Canon City embayment and Raton basin (Zacharakis and Pearl, 1982; Robson and Banta, 1987).

The area of warmer water shown in figure 55 was included in a nationwide assessment of low-temperature geothermal resources (Reed, 1983; Sorey and Reed, 1984). Quantitative estimates of both in-storage and recoverable heat energy indicate a significant long-term thermal resource that is virtually untapped. Some use of warm water from the aquifer system in north-central Nebraska for stock watering, irrigation, and farm-building heating was reported by Gosnold and Eversoll (1982). A preliminary evaluation of the use of water for a large-scale heating project was described by Shroder and Becker (1984).

SUMMARY AND CONCLUSIONS

The Great Plains aquifer system is a major geohydrologic unit that extends throughout much of the midcontinent region. Study of the aquifer system's regional hydrology for a 170,000-square-mile area was a part of the Central Midwest Regional Aquifer-System Analysis (CMRASA). The study area is limited on the east and south by the natural extent of the aquifer system; the other study boundaries coincide with CMRASA project boundaries.

The Great Plains aquifer system consists of, in ascending order, the Apishapa aquifer (Cheyenne Sandstone and equivalents), Apishapa confining unit (Kiowa Shale and equivalents), and Maha aquifer (Dakota Sandstone and equivalents). The aquifer system has been developed for both water and petroleum resources; findings of this study are based on data collected in association with water and petroleum exploration and development. Data are sparse in a large part of the study area; however, abundant data in some areas necessitated selecting a few of the representative data in order to serve the regional scope of the study.

Strata of the aquifer system were deposited mostly during Early Cretaceous time. The major rock units reflect a general marine transgression-regression-transgression sequence; however, local complex stratigraphy resulted from a fluctuating marine-shoreline-nonmarine depositional environment. The Laramide orogeny of Late Cretaceous and early Tertiary time caused structural downwarping of the western part of the study area to form the Denver and Raton basins and Canon City embayment. Deep burial (by several thousand feet of younger sediments) and faulting along the western margin of the Denver and Raton basins have effectively isolated much of the aquifer system hydraulically from surface and shallow-subsurface water. Erosion has exposed the rocks of the aquifer system along the eastern and southern parts of the study area.

The aquifer system consists mainly of sandstone, siltstone, and shale but includes lesser amounts of other sedimentary rocks. Strata of the aquifer system exhibit wide variations in texture, degree of cementation, degree of fracturing, and thickness. Regional trends in sandstone percentage, particularly within the Maha aquifer, reflect increasing prevalence of marine shale to the northwest. Total thickness of the aquifer system ranges generally from 200 to 800 feet, being greatest in north-central Nebraska. The Apishapa confining unit generally thins eastward and is absent in the eastern half of Nebraska and adjacent areas. Where the confining unit pinches out, the two aquifer units merge into a single hydrologic unit considered as the Maha aquifer.

Strata are generally flat-lying except in the basins. The top of the aquifer system is regionally smooth except near the truncated eastern and southern edges and in faulted areas. Faults with large vertical offsets form an abrupt western boundary of the study area. Faulting in southwestern Kansas is a result of dissolution of underlying evaporite rocks. Faults within the study area probably have had no significant effect on regional hydrology.

Rock units overlying and underlying the aquifer system are confining systems in most areas. The major exceptions are areas where the High Plains aquifer and Missouri River alluvium directly overlie the Great Plains aquifer system along parts of the southern and eastern edges of the study area. Effective hydraulic connection with the underlying rock units occurs at subcrops of the Cedar Hills Sandstone in Kansas and the Entrada Sandstone and Dockum Group in the Colorado-Kansas-Oklahoma tri-state area. The lower boundary of the Great Plains aquifer system is nearly impermeable where basement rocks subcrop in the extreme northeastern part of the study area and where evaporite rocks subcrop in central Kansas.

Regionalized sandstone porosity is correlated inversely with depth of burial of the aquifer system. Porosity ranges from about 10 to 30 percent, generally

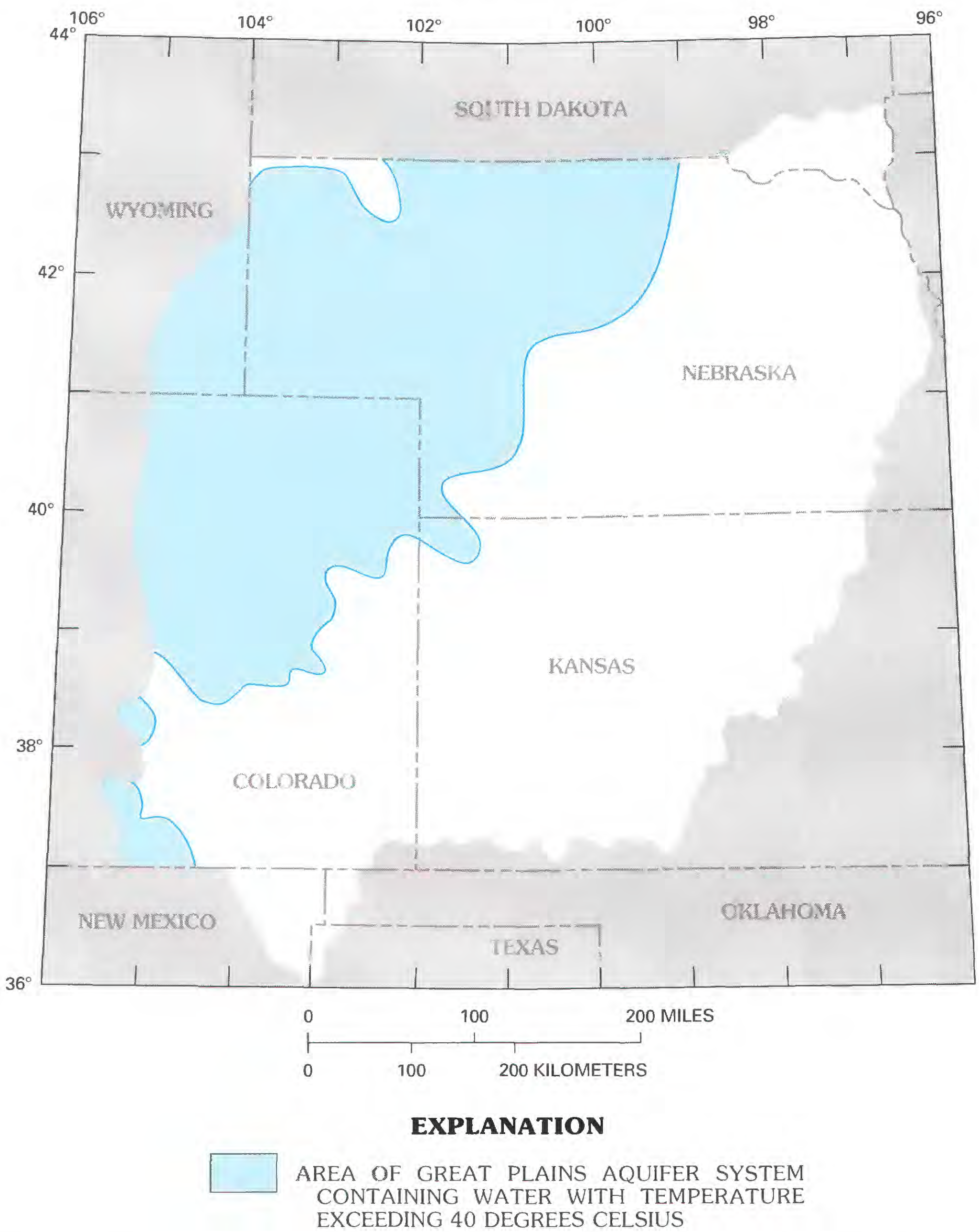


FIGURE 55.—Areas of low-temperature geothermal potential in Great Plains aquifer system (modified from Gosnold and Eversoll, 1982; Stavnes and Steeples, 1982; Sorey and Reed, 1984; and Robson and Banta, 1987).

being smallest in the deep basins. In outcrop areas of the system, where unconfined conditions are present, the storage coefficient (specific yield) averages about 0.15. Where the aquifer system is confined (most of the study area), specific storage is estimated to be 9.5×10^{-7} per foot. The volume of drainable water within the aquifer system is estimated to be about 3 billion acre-ft.

Representative values of intrinsic permeability and hydraulic conductivity of sandstone decrease by several orders of magnitude with depth of burial. The hydraulic conductivity of sandstone ranges from about 0.1 to 50 ft/d. The hydraulic conductivity for shale is assumed to be four orders of magnitude smaller at any given location. Regionalized aquifer properties for the Maha and Apishapa aquifers are assumed to be identical. Water density and viscosity variations have relatively insignificant effects on hydraulic conductivity in comparison to the effect of depth of burial. Regional transmissivity distributions approximately parallel the hydraulic-conductivity distributions.

The distribution of equivalent freshwater heads indicates that regional lateral flow is generally west to east. Confined conditions prevail throughout most of the aquifer system, but the aquifer system is generally underpressured (small confined heads), due to progressive increase in transmissivity toward discharge areas in the east. Some of the greatest underpressuring coincides with the area of oil and gas development in the Denver basin. Inferred predevelopment heads in the Denver basin are as much as several hundred feet higher than present heads. The average withdrawal rate of oil and gas (in equivalent freshwater volume) and associated saline water during the 1970's is estimated to be about 15 ft^3/s. The freshwater withdrawal rate is estimated to be about 850 ft^3/s for the 1970's.

The water in much of the aquifer system is brackish (1,000 to 10,000 mg/L dissolved solids). Major ions characterizing the water vary considerably, but extensive areas of sodium chloride, sodium bicarbonate, calcium sulfate, and calcium bicarbonate water are apparent.

The Great Plains aquifer system transmits water very slowly. The deeply buried part of the system is virtually stagnant. Present hydrochemical conditions appear to be related largely to environment of deposition, with limited modification by later introduction of meteoric water. Basin development, associated faulting, and subsequent structural attitude of the region probably restricted recharge and prevented complete flushing of original formation water from much of the aquifer system.

A computer flow model was used to help in understanding the hydrodynamics of the aquifer system for both predevelopment and development conditions. The model simulates flow in three dimensions using finite-difference methods. The aquifer system is discretized horizontally by a 46×35 uniform grid (each cell is 14 miles square) and vertically by four layers. Layer 2 represents the Maha aquifer, layer 3 represents the Apishapa aquifer, and layers 1 and 4 represent the appropriate overlying and underlying rock units. Lateral hydraulic-conductivity values for all layers reflect a regional relation to depth of burial. Larger values of hydraulic conductivity were assigned to model cells representing the High Plains aquifer, Missouri River alluvium, Cedar Hills Sandstone, or Entrada Sandstone and Dockum Group where these rock units are in direct contact with the aquifer system.

Vertical conductance, which affects vertical rates of flow between layers, is dependent on vertical hydraulic conductivity and unit thickness. The ratio of vertical-to-lateral hydraulic conductivity was assumed to be 0.01 for confining units and 0.05 to 0.1 for aquifer units.

Constant heads corresponding to the near-surface water table were assigned to every cell in layer 1. Constant heads also were assigned to layer 4 along the eastern and southern boundaries. All other outer-boundary cells were specified as no-flow cells. Cells representing outcrop areas of the aquifer system were designated as recharge cells (with assigned recharge rates) or stream cells (allowing stream-aquifer interchange).

The model was calibrated mainly against field or estimated steady-state predevelopment heads, discharge to streams, and hydraulic-head declines in response to oil, gas, and water withdrawals. Steady-state calibration was based on the statistical evaluation of the difference between simulated and field or estimated hydraulic heads. These differences were generally less than 500 feet in the western part of the study area and less than 200 feet elsewhere. Simulated discharge to streams was comparable to measured flows. Hydraulic-head declines resulting from transient simulations of pumpage were plausible.

Simulated hydraulic head was most sensitive to values of lateral hydraulic conductivity and recharge in the outcrop areas. This sensitivity is greatest in the areas of small hydraulic conductivity (the western basins). Simulated discharge to streams was most sensitive to lateral hydraulic conductivity. Hydraulic-head declines resulting from transient simulations of pumpage were not especially sensitive to storage coefficient, except in the Denver basin.

Model calibration essentially supported and helped refine the conceptual model. The predevelopment steady-state water budget for the Great Plains aquifer system was simulated as about 340 ft^3/s. About 87 percent of simulated recharge was leakage from overlying units, 11 percent was direct infiltration in outcrop areas, and 2 percent was leakage from underlying rock units. About 70 percent of simulated discharge was leakage to overlying units, 15 percent was leakage to underlying units, and 15 percent was discharge to streams in outcrop areas. About 60 percent of the total water budget was interchange with the High Plains aquifer where it directly overlies the Great Plains aquifer system. The greatest flux within the modeled aquifer system was in local flow zones along the eastern and southern edges of the area. Flow also occurs northeasterly from outcrop areas in the southwestern part of the study area and southeasterly from outcrops bordering the Black Hills. In the deepest part of the Denver basin, virtually stagnant conditions prevail. Very irregular hydraulic-head and water-quality conditions typify the basin. In most of the basin and in much of southern Nebraska and northern Kansas, very small hydraulic conductivity prevents complete flushing of original fluids from the aquifer system.

Oil and gas development is inferred to have caused several hundred feet of hydraulic-head decline in parts of the Denver basin. Freshwater withdrawals have resulted in hydraulic-head declines of several tens of feet in parts of southern Colorado, Kansas, eastern Nebraska, and southeastern South Dakota. In southwestern Kansas and eastern Nebraska, much of the head decline is in response to pumpage from the overlying High Plains aquifer. Recent (1970–79) rates of withdrawal from the Great Plains aquifer system (about 850 ft^3/s) are more than twice its natural recharge rate (about 340 ft^3/s). Although a significant part of pumpage is derived from intercepted or induced vertical leakage, the rate of adjustment to pumping is extremely slow in most areas, and storage depletion (reflected in hydraulic-head declines) may be substantial. At the end of a 1940–79 transient simulation, about 70 percent of pumpage was being derived from intercepted or induced vertical leakage, and the remainder was being derived from storage. Continued or increased development will result in continued storage depletion except where direct connection with the overlying High Plains aquifer permits sufficient rates of induced recharge to balance pumpage.

Deeper parts of the Great Plains aquifer system appear favorable for disposal of nontoxic liquid waste. Simulations indicate that hydraulic-head adjustments from liquid injections would not significantly change regional flow rates or patterns.

The chemical suitability of the water for use varies greatly within the aquifer system. In the central and western parts of the study area, the suitability of the water for consumption or irrigation is limited by the predominance of sodium chloride type water with dissolved-solids concentrations exceeding 3,000 mg/L.

The great depth of occurrence of the aquifer system affords potential for development of low-temperature geothermal energy. Water temperatures in the aquifer system exceed 40 °C in most of the northwestern half of the study area, as a result of steep geothermal gradients and the insulating effects of the overlying Great Plains confining system.

REFERENCES CITED

Anna, L.O., 1986, Geologic framework of the ground-water system in Jurassic and Cretaceous rocks in the Northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402–B, 36 p.

Athy, L.F., 1930, Density, porosity, and compaction of sedimentary rocks: American Association of Petroleum Geologists Bulletin, v. 14, p. 1–24.

Back, William, 1960, Origin of hydrochemical facies of groundwater in the Atlantic Coastal Plain: International Geological Congress, 21st Session, Copenhagen, part I, p. 87–95.

Baker, C.H., Jr., and Kenny, J.F., 1990, Kansas water supply and use, *in* U.S. Geological Survey, National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, p. 259–266.

Baldwin, Brewster, and Butler, C.O., 1985, Compaction curves: American Association of Petroleum Geologists Bulletin, v. 69, no. 4, p. 622–626.

Banta, E.R., 1985, The Dakota aquifer near Pueblo, Colorado—Faults and flow patterns: U.S. Geological Survey Water-Resources Investigations Report 85–4186, 23 p.

Bass, N.W., 1958, Subsurface geology of the Dakota Sandstone in the oilfields area of the Denver basin, Colorado and Nebraska: U.S. Geological Survey Open-File Report 58–10, 23 p.

Belitz, Kenneth, 1985, Hydrodynamics of the Denver basin—An explanation of subnormal fluid pressures: Stanford, California, Stanford University, Ph.D. thesis, 194 p.

Bredehoeft, J.D., Neuzil, C.E., and Milly, P.C.D., 1983, Regional flow in the Dakota aquifer—A study of the role of confining layers: U.S. Geological Survey Water-Supply Paper 2237, 45 p.

Brenner, R.L., Bretz, R.F., Bunker, B.J., Iles, D.L., Ludvigson, G.A., McKay, R.M., Whitley, D.L., and Witzke, B.J., 1981, Cretaceous stratigraphy and sedimentation in northwest Iowa, northeast Nebraska, and southeast South Dakota: Iowa Geological Survey Guidebook Series No. 4, 172 p.

Case, H.L., III, 1984, Hydrology of Inyan Kara and Dakota-Newcastle aquifer system, South Dakota, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology: Worthington, Ohio, National Water Well Association, p. 147–165.

Clark, B.A., 1978, Stratigraphy of the Lower Cretaceous J Sandstone, Boulder County, Colorado—A deltaic method, *in* Pruit, J.D., and Coffin, P.E., eds., Symposium on Energy Resources of the Denver Basin: Denver, Rocky Mountain Association of Geologists, p. 237–244.

Clayton, J.L., and Swetland, P.J., 1980, Petroleum generation and migration in Denver basin: American Association of Petroleum Geologists Bulletin, v. 64, no. 10, p. 1613–1633.

Condra, G.E., and Reed, E.C., 1959, The geologic section of Nebraska (with revisions by E.C. Reed): Nebraska Geological Survey Bulletin 14A, 52 p.

Dahlberg, E.C., 1982, Applied hydrodynamics in petroleum exploration: New York, Springer-Verlag, 161 p.

Darton, N.H., 1896, Preliminary report on artesian waters of a portion of the Dakotas: U.S. Geological Survey 17th Annual Report, part 2, chapter G, p. 603–694.

———1905, Geology and underground water resources of the central Great Plains: U.S. Geological Survey Professional Paper 32, 433 p.

———1909, Geology and underground waters of South Dakota: U.S. Geological Survey Water-Supply Paper 227, 156 p.

———1918, Artesian waters in the vicinity of the Black Hills, South Dakota: U.S. Geological Survey Water-Supply Paper 428, 64 p.

Dealy, M.T., Kume, Jack, and Jenkins, E.D., 1984, Geohydrology and development of the Dakota aquifer in southwest Kansas, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology: Worthington, Ohio, National Water Well Association, p. 209–220.

DeGraw, H.M., 1969, Subsurface relations of the Cretaceous and Tertiary in Western Nebraska: Nebraska Geological Survey Open-File Report, 137 p.

Downey, J.S., 1986, Geohydrology of bedrock aquifers in the northern Great Plains in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402–E, 87 p.

Dugan, J.T., and Peckenpaugh, J.M., 1985, Effects of climate, vegetation, and soils on consumptive water use and ground-water recharge to the Central Midwest regional aquifer system, mid-continent United States: U.S. Geological Survey Water-Resources Investigations Report 85–4236, 78 p.

Dyer, C.F., and Goehring, A.J., 1965, Artesian-water supply of the Dakota formation, southeastern South Dakota: U.S. Geological Survey Open-File Report 65–51, 49 p.

Eicher, D.L., 1960, Stratigraphy and micropaleontology of the Thermopolis Shale: Peabody Museum Natural History, Yale University Bulletin 15, 126 p.

Ellis, M.J., 1984, Overview of Dakota aquifer system in Nebraska, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology: Worthington, Ohio, National Water Well Association, p. 48–55.

Engberg, R.A., 1984, Appraisal of data for ground-water quality in Nebraska: U.S. Geological Survey Water-Supply Paper 2245, 54 p.

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

Finch, W.C., Cullen, A.W., Sandberg, G.W., Harris, J.D., and McMahon, B.E., 1955, The oil and gas fields of Nebraska, a symposium: Denver, Rocky Mountain Association of Geologists, 264 p.

Franks, P.C., 1975, The transgressive-regressive sequence of the Cretaceous Cheyenne, Kiowa, and Dakota formations, of Kansas, *in* Caldwell, W.G.E., ed., The Cretaceous System of the western interior of North America: Geological Association of Canada Special Paper 13, p. 469–521.

Garbarini, G.S., and Veal, H.K., 1968, Potential of Denver basin for disposal of liquid wastes, *in* Galley, J.E., ed., Subsurface disposal in geologic basins—A study of reservoir strata: American Association of Petroleum Geologists Memoir 10, p. 165–185.

Geldon, A.L., 1989, Ground-water hydrology of the central Raton Basin, Colorado and New Mexico: U.S. Geological Survey Water-Supply Paper 2288, 81 p.

Geyer, A.P., and Pritchett, R.W., 1978, The Davis-Joyce Field—Western Nebraska, *in* Pruit, J.D., and Coffin, P.E., eds., Symposium on Energy Resources of the Denver Basin: Denver, Rocky Mountain Association of Geologists, p. 63–74.

Gibbons, R.D., and Self, G.W., 1978, J sandstone potentiometric surface, *in* Pruit, J.D., and Coffin, P.E., eds., Symposium on Energy Sources of the Denver Basin: Denver, Rocky Mountain Association of Geologists, plate 3.

Gosnold, W.D., 1984, Heat flow and groundwater movement in the central Great Plains, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology: Worthington, Ohio, National Water Well Association, p. 176–181.

Gosnold, W.D., Jr., and Eversoll, D.A., 1981, Usefulness of heat flow data in regional assessment of low-temperature geothermal resources with special reference to Nebraska: Geothermal Resources Council Transactions, v. 5, p. 79–82.

———1982, Geothermal resources of Nebraska: National Geophysical and Solar-Terrestrial Data Center, National Oceanic and Atmospheric Administration, scale 1:500,000, 1 sheet.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984, Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–B, 63 p.

Gutentag, E.D., Lobmeyer, D.H., and Slagle, S.E., 1981, Geohydrology of southwestern Kansas: Kansas Geological Survey Irrigation Series 7, 73 p.

Haun, J.D., and Kent, H.D., 1965, Geologic history of Rocky Mountain Region: American Association of Petroleum Geologists Bulletin, v. 49, no. 11, p. 1781–1800.

Hedman, E.R., and Engel, G.B., 1989, Flow characteristics for selected streams in the Great Plains subregion of the Central Midwest regional aquifer system and selected adjacent areas—Kansas and Nebraska, and parts of Colorado, Iowa, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigation Atlas HA–708, scale 1:1,000,000, 3 sheets.

Helgesen, J.O., Jorgensen, D.G., Leonard, R.B., and Signor, D.C., 1982, Regional study of the Dakota aquifer (Darton's Dakota revisited): Ground Water, v. 20, no. 4, p. 410–414.

Higley, D.K., and Gautier, D.L., 1986, Median-permeability contour maps of the J Sandstone, Dakota Group, in the Denver basin, Colorado, Nebraska, and Wyoming: U.S. Geological Survey Miscellaneous Field Studies Map MF–1837, scale 1:500,000, 1 sheet.

Hoeger, R.L., 1968, Hydrodynamic study of the western Denver basin, Colorado, *in* Geophysical and geological studies of the relationships between the Denver earthquake and the Rocky Mountain Arsenal Well: Colorado School of Mines Quarterly, v. 63, no. 1, p. 245–251.

Hubbert, M.K., 1940, Theory of ground-water motion: Journal of Geology, v. 48, no. 8, part 1, p. 785–944.

———1953, Entrapment of petroleum under hydrodynamic conditions: American Association of Petroleum Geologists Bulletin, v. 37, no. 8, p. 1954–2026.

Huntoon, P.W., 1985, Fault-severed aquifers along the perimeters of Wyoming artesian basins: Ground Water, v. 23, no. 2, p. 176–181.

International Oil Scouts Association, 1977, International oil and gas development: Austin, Texas, International Oil Scouts Association, v. 46, part 2 (production).

Jorgensen, D.G., 1989, Using geophysical logs to estimate porosity, water resistivity, and intrinsic permeability: U.S. Geological Survey Water-Supply Paper 2321, 24 p.

Jorgensen, D.G., Gogel, Tony, and Signor, D.C., 1982, Determination of flow in aquifers containing variable density water: Ground Water Monitoring Review, v. 2, no. 2, p. 40–45.

Jorgensen, D.G., Helgesen, J.O., and Imes, J.L., 1993, Aquifer systems underlying Kansas, Nebraska, and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming—Geohydrologic framework: U.S. Geological Survey Professional Paper 1414–B, 72 p.

Jorgensen, D.G., and Signor, D.C., 1981, Plan of study for the Central Midwest regional aquifer system analysis in parts of Arkansas, Colorado, Kansas, Missouri, Nebraska, New Mexico, Oklahoma, South Dakota, and Texas: U.S. Geological Survey Water-Resources Investigations, Open-File Report 81–206, 28 p.

Karl, H.A., 1976, Depositional history of Dakota Formation (Cretaceous) sandstones, southeastern Nebraska: Journal of Sedimentary Petrology, v. 46, no. 2, p. 124–131.

Keene, K.M., and Bayne, C.K., 1977, Ground water from lower Cretaceous rocks in Kansas: Kansas Geological Survey Chemical Quality Series 5, 18 p.

Kolm, K.E., and Peter, K.D., 1984, A possible relation between lineaments and leakances through confining layers in South Dakota, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology: Worthington, Ohio, National Water Well Association, p. 121–134.

Latta, B.F., 1948, Geology and ground-water resources of Kiowa County, Kansas: Kansas Geological Survey Bulletin 65, 144 p.

Lawton, D.R., Goodenkauf, Owen, Hanson, B.V., and Smith, F.A., 1984, Dakota aquifers in eastern Nebraska, aspects of water quality and use, *in* Jorgensen, D.G., and Signor, D.C. eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology: Worthington, Ohio, National Water Well Association, p. 221–228.

Leonard, R.B., 1964, A method for evaluating oil-field-brine pollution of the Walnut River in Kansas: U.S. Geological Survey Professional Paper 501–B, p. B173–B176.

Leonard, R.B., Signor, D.C., Jorgensen, D.G., and Helgesen, J.O., 1983, Geohydrology and hydrochemistry of the Dakota aquifer, central United States: Water Resources Bulletin, v. 19, no. 6, p. 903–911.

Lobmeyer, D.H., and Weakly, E.C., 1979, Water in the Dakota Formation, Hodgeman and northern Ford counties, southwestern Kansas: Kansas Geological Survey Irrigation Series 5, 41 p.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

McDonald, M.G., and Harbaugh, A.W., 1983, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 83–875, 528 p.

McGovern, H.E., 1984, Overview of Dakota aquifer in Kansas, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology: Worthington, Ohio, National Water Well Association, p. 58–61.

Meinzer, O.E., 1923, The occurrence of ground water in the United States: U.S. Geological Survey Water-Supply Paper 489, 321 p.

———1928, Compressibility and elasticity of artesian aquifers: Economic Geology, v. 23, p. 263–291.

Meinzer, O.E., and Hard, H.A., 1925, The artesian water supply of the Dakota Sandstone in North Dakota, with special reference to the Edgeley quadrangle: U.S. Geological Survey Water-Supply Paper 520–E, p. 73–95.

Merriam, D.F., 1963, The goologic history of Kansas: Kansas Geological Survey Bulletin 162, 317 p.

Miller, R.H., and Rahn, P.H., 1974, Recharge to the Dakota sandstone from outcrops in the Black Hills, South Dakota: Bulletin of the Association of Engineering Geologists, v. 11, p. 211–214.

Milly, C.D., 1978, Mathematical models of groundwater flow and sulfate transport in the major aquifers of South Dakota: Princeton, New Jersey, Princeton University, B.S. thesis, 46 p.

Munter, J.A., Ludvigson, G.A., and Bunker, B.J., 1983, Hydrogeology and stratigraphy of the Dakota formation in northwest Iowa: Iowa Geological Survey Water Supply Bulletin 13, 55 p.

Neuzil, C.E., 1980, Fracture leakage in the Cretaceous Pierre shale and its significance for underground waste disposal: Baltimore, Johns Hopkins University, Ph.D. thesis, 150 p.

Neuzil, C.E., Bredehoeft, J.D., and Wolff, R.G., 1984, Leakage and fracture permeability in the Cretaceous shales confining the Dakota aquifer in South Dakota, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology: Worthington, Ohio, National Water Well Association, p. 113–120.

Ottman, J.D., 1984, Evolution of formation fluids in "J" sandstone, Denver basin, Colorado, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology: Worthington, Ohio, National Water Well Association, p. 77–87.

Parker, J.M., 1962, Colorado-Nebraska oil and gas field volume, 1961: Denver, Rocky Mountain Association of Geologists, 390 p.

Pearl, R.H., 1984, Dakota aquifer system in the state of Colorado, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology: Worthington, Ohio, National Water Well Association, p. 41–47.

Reed, M.J., ed., 1983, Assessment of low-temperature geothermal resources of the United States—1982: U.S. Geological Survey Circular 892, 73 p.

Robson, S.G., and Banta, E.R., 1987, Geology and hydrology of deep bedrock aquifers in eastern Colorado: U.S. Geological Survey Water-Resources Investigations Report 85–4240, 6 sheets.

Russell, W.L., 1928, The origin of artesian pressure: Economic Geology, v. 23, no. 1, p. 132–157.

———1961, Reservoir water resistivities and possible hydrodynamic flow in Denver basin: American Association of Petroleum Geologists Bulletin, v. 45, no. 12, p. 1925–1940.

Schmoker, J.W., and Halley, R.B., 1982, Carbonate porosity versus depth—A predictable relation for south Florida: American Association of Petroleum Geologists Bulletin, v. 66, no. 12, p. 2561–2570.

Schoon, R.A., 1971, Geology and hydrology of the Dakota Formation in South Dakota: South Dakota Geological Survey Report of Investigations, 104, 55 p.

Schoon, R.A., and McGregor, D.J., 1974, Geothermal potentials in South Dakota: South Dakota Geological Survey Report of Investigations 110, 76 p.

Shroder, J.F., Jr., and Becker, D.J., 1984, Geology of Dakota aquifer and geothermal evaluation at Scottsbluff, Nebraska, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology: Worthington, Ohio, National Water Well Association, p. 182–187.

Sorey, M.L., and Reed, M.J., 1984, Low-temperature geothermal resources in the Dakota aquifer, *in* Jorgonsen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology: Worthington, Ohio, National Water Well Association, p. 169–175.

Spiegel, M.R., 1961, Theory and problems of statistics: New York, Schaum Publishing Company, 359 p.

Spinazola, J.M., and Dealy, M.T., 1983, Hydrology of the Ogallala aquifer in Ford County, southwestern Kansas: U.S. Geological Survey Water-Resources Investigations Report 83–4226, 58 p.

Stavnes, S.A., and Steeples, D.W., 1982, Geothermal resources of Kansas: National Geophysical Data Center, National Oceanic and Atmospheric Administration, scale 1:500,000, 1 sheet.

Stone, W.J., 1984, Dakota aquifer in New Mexico, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology: Worthington, Ohio, National Water Well Association, p. 62–68.

Swenson, F.A., 1968, New theory of recharge to the artesian basin of the Dakotas: Geological Society of America Bulletin, v. 79, p. 163–182.

Tóth, József, 1980, Cross-formational gravity-flow of ground water—A mechanism of the transport and accumulation of petroleum (the generalized hydraulic theory of petroleum migration), *in* Roberts, W.H., III, and Cordell, R.J., eds., Problems of petroleum migration: American Association of Petroleum Geologists Studies in Geology No. 10, p. 121–167.

U.S. Environmental Protection Agency, 1986, Secondary maximum contaminant levels (section 143.3 of part 143, national secondary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised as of July 1, 1986, p. 587–590.

U.S. Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Department of Agriculture Handbook 60, 160 p.

Watts, K.R., 1989, Potential hydrologic effects of ground-water withdrawals from the Dakota aquifer, southwestern Kansas: U.S. Geological Survey Water-Supply Paper 2304, 47 p.

Weimer, R.J., 1970, Dakota Group stratigraphy, southern Front Range, south and middle Parks, Colorado: Mountain Geologist, v. 7, no. 3, p. 157–184.

Weiss, Emanuel, 1982a, A model for the simulation of flow of variable-density ground water in three dimensions under steady-state conditions: U.S. Geological Survey Open-File Report 82–352, 60 p.

———1982b, A computer program for calculating relative-transmissivity input arrays to aid model calibration: U.S. Geological Survey Open-File Report 82–447, 18 p.

Whittemore, D.O., Basel, C.L., Galle, O.K., and Waugh, T.C., 1981, Geochemical identification of saltwater sources in the Smoky Hill River valley, McPherson, Saline, and Dickinson Counties, Kansas: Kansas Geological Survey Open-File Report 81–6, 78 p.

Winslow, A.G., and Kister, L.R., 1956, Saline-water resources of Texas: U.S. Geological Survey Water-Supply Paper 1365, 105 p.

Young, R.G., 1970, Lower Cretaceous of Wyoming and the southern Rockies: Mountain Geologist, v. 7, no. 3, p. 105–121.

Zacharakis, T.G., and Pearl, R.H., 1982, Geothermal resource assessment of Canon City, Colorado area: Colorado Geological Survey Resource Series 20, 81 p.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1994-583-048/80009

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations, as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resource Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases that show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects, such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolor or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000, and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Books and Open-File Reports Sales, Federal Center, Box 25286, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879-1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962-1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1971-1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only.

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" are available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.—Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.

U.S. DEPARTMENT OF THE INTERIOR

MARCH 3, 1849