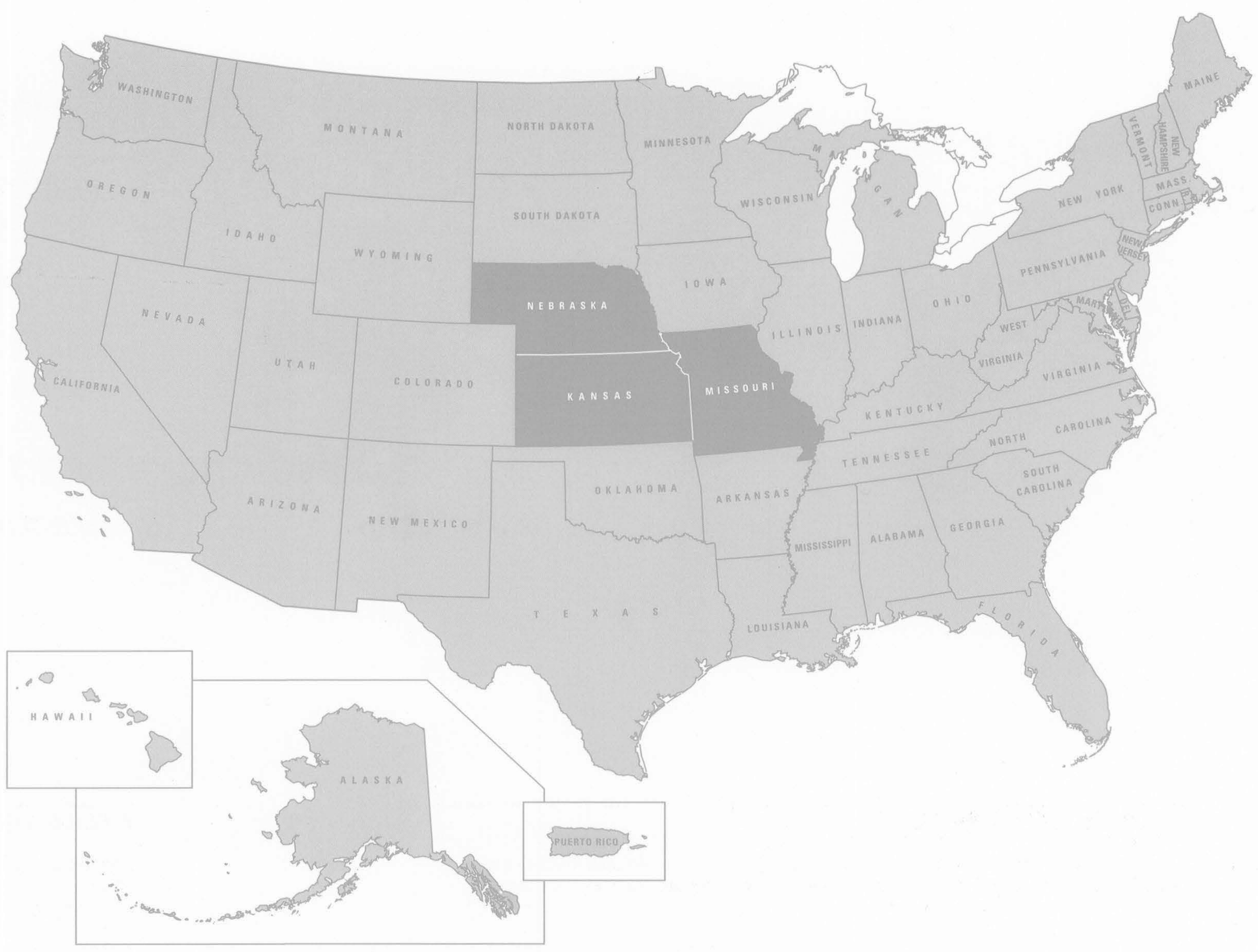
Ground Water Atlas of the United States

Segment 3

Kansas
Missouri
Nebraska



HYDROLOGIC INVESTIGATIONS ATLAS 730–D
U.S. Geological Survey

Reston, Virginia
1997

GROUND WATER ATLAS OF THE UNITED STATES
Hydrologic Investigations Atlas 730–D

FOREWORD

The Ground Water Atlas of the United States presents a comprehensive summary of the Nation's ground-water resources, and is a basic reference for the location, geography, geology, and hydrologic characteristics of the major aquifers in the Nation. The information was collected by the U.S. Geological Survey and other agencies during the course of many years of study. Results of the U.S. Geological Survey's Regional Aquifer-System Analysis Program, a systematic study of the Nation's major aquifers, were used as a major, but not exclusive, source of information for compilation of the Atlas.

The Atlas, which is designed in a graphical format that is supported by descriptive discussions, includes 13 chapters, each representing regional areas that collectively cover the 50 States and Puerto Rico. Each chapter of the Atlas presents and describes hydrogeologic and hydrologic conditions for the major aquifers in each regional area. The scale of the Atlas does not allow portrayal of minor features of the geology or hydrology of each aquifer presented, nor does it include discussion of minor aquifers. Those readers that seek detailed, local information for the aquifers will find extensive lists of references at the end of each chapter.

An introductory chapter presents an overview of ground-water conditions Nationwide and discusses the effects of human activities on water resources, including saltwater encroachment and land subsidence.

Mark Schaefer

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY
Mark Schaefer, *Acting Director*

CONVERSION FACTORS

For readers who prefer to use the International System (SI) units, rather than the inch-pound terms used in this report, the following conversion factors may be used:

Multiply inch-pound units	*By*	*To obtain metric units*
	Length	
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
billion gallons per day (Bgal/d)	3.785	million cubic meters per day (Mm^3/d)
acre-foot per year	0.00003909	cubic meter per second (m^3/s)
	Volume	
acre-foot	1,233	cubic meter (m^3)
	Transmissivity	
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
	Temperature	
degree Fahrenheit (°F)	5/9(°F – 32) = °C	degree Celsius (°C)

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

ATLAS ORGANIZATION

The Ground Water Atlas of the United States is divided into 14 chapters. Chapter A presents introductory material and nationwide summaries; chapters B through M describe all principal aquifers in a multistate segment of the conterminous United States; and chapter N describes all principal aquifers in Alaska, Hawaii, and Puerto Rico.

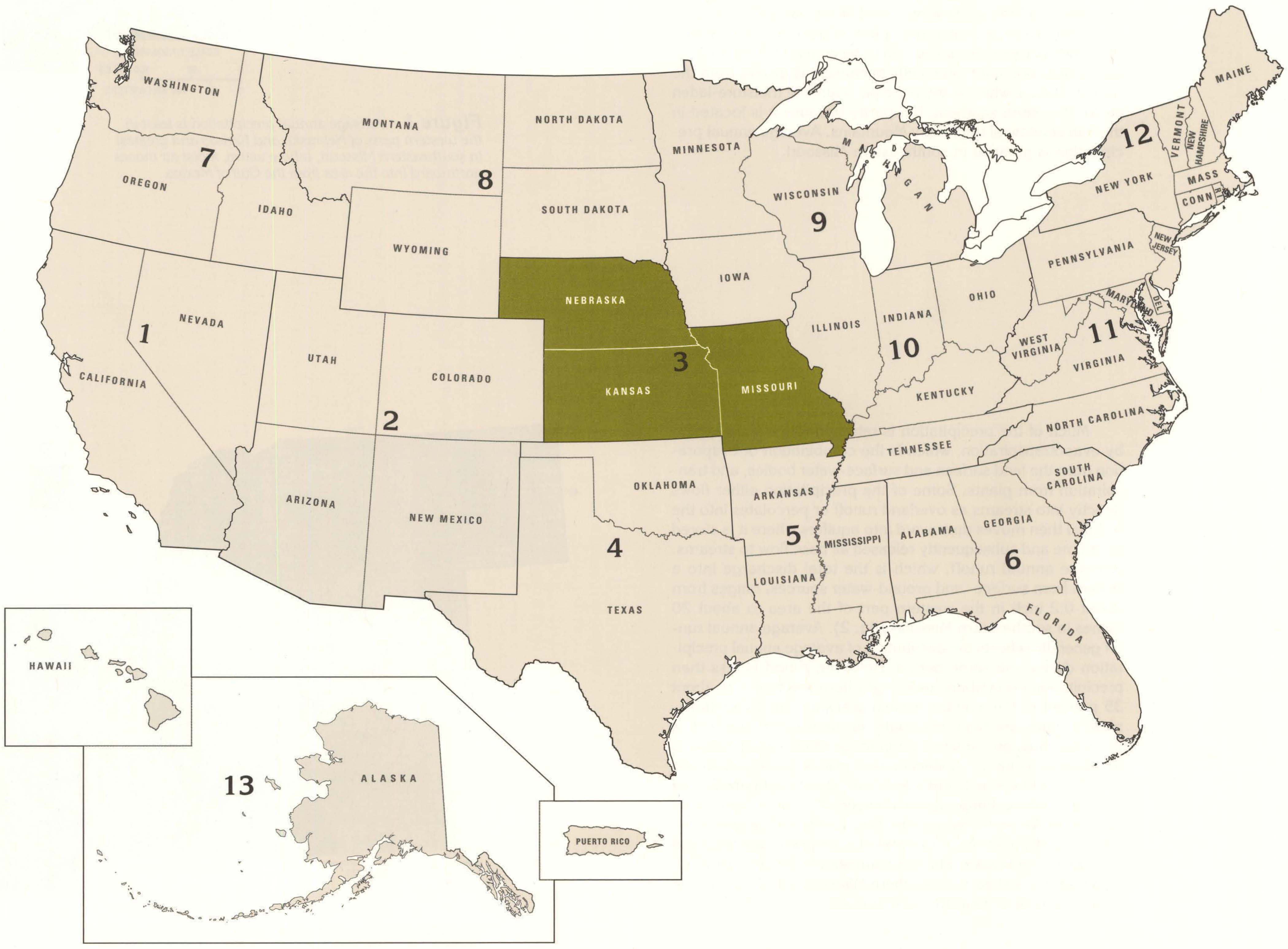
Segment Number	*Chapter content*	*Hydrologic Atlas Chapter*
—	Introductory material and nationwide summaries	730–A
1	California, Nevada	730–B
2	Arizona, Colorado, New Mexico, Utah	730–C
3	Kansas, Missouri, Nebraska	730–D
4	Oklahoma, Texas	730–E
5	Arkansas, Louisiana, Mississippi	730–F
6	Alabama, Florida, Georgia, South Carolina	730–G
7	Idaho, Oregon, Washington	730–H
8	Montana, North Dakota, South Dakota, Wyoming	730–I
9	Iowa, Michigan, Minnesota, Wisconsin	730–J
10	Illinois, Indiana, Kentucky, Ohio, Tennessee	730–K
11	Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia	730–L
12	Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont	730–M
13	Alaska, Hawaii, Puerto Rico	730–N

Ground Water Atlas of the United States

Segment 3

Kansas, Missouri, and Nebraska

By James A. Miller and Cynthia L. Appel



CONTENTS

Cartographic design and production by Loretta J. Ulibarri, Derald L. Dunagan, and Gary D. Latzke

Regional summary

INTRODUCTION

The three States—Kansas, Missouri, and Nebraska—that comprise Segment 3 of this Atlas are in the central part of the United States. The major rivers that drain these States are the Niobrara, the Platte, the Kansas, the Arkansas, and the Missouri; the Mississippi River is the eastern boundary of the area. These rivers supply water for many uses but ground water is the source of slightly more than one-half of the total water withdrawn for all uses within the three-State area. The aquifers that contain the water consist of consolidated sedimentary rocks and unconsolidated deposits that range in age from Cambrian through Quaternary. This chapter describes the geology and hydrology of each of the principal aquifers throughout the three-State area.

Some water enters Segment 3 as inflow from rivers and aquifers that cross the segment boundaries, but precipitation, as rain and snow, is the primary source of water within the area. Average annual precipitation (1951–80) increases from west to east and ranges from about 16 to 48 inches (**fig. 1**). The climate of the western one-third of Kansas and Nebraska, where the average annual precipitation generally is less than 20 inches per year, is considered to be semiarid. This area receives little precipitation chiefly because it is distant from the Gulf of Mexico, which is the principal source of moisture-laden air for the entire segment, but partly because it is located in the rain shadow of the Rocky Mountains. Average annual precipitation is greatest in southeastern Missouri.

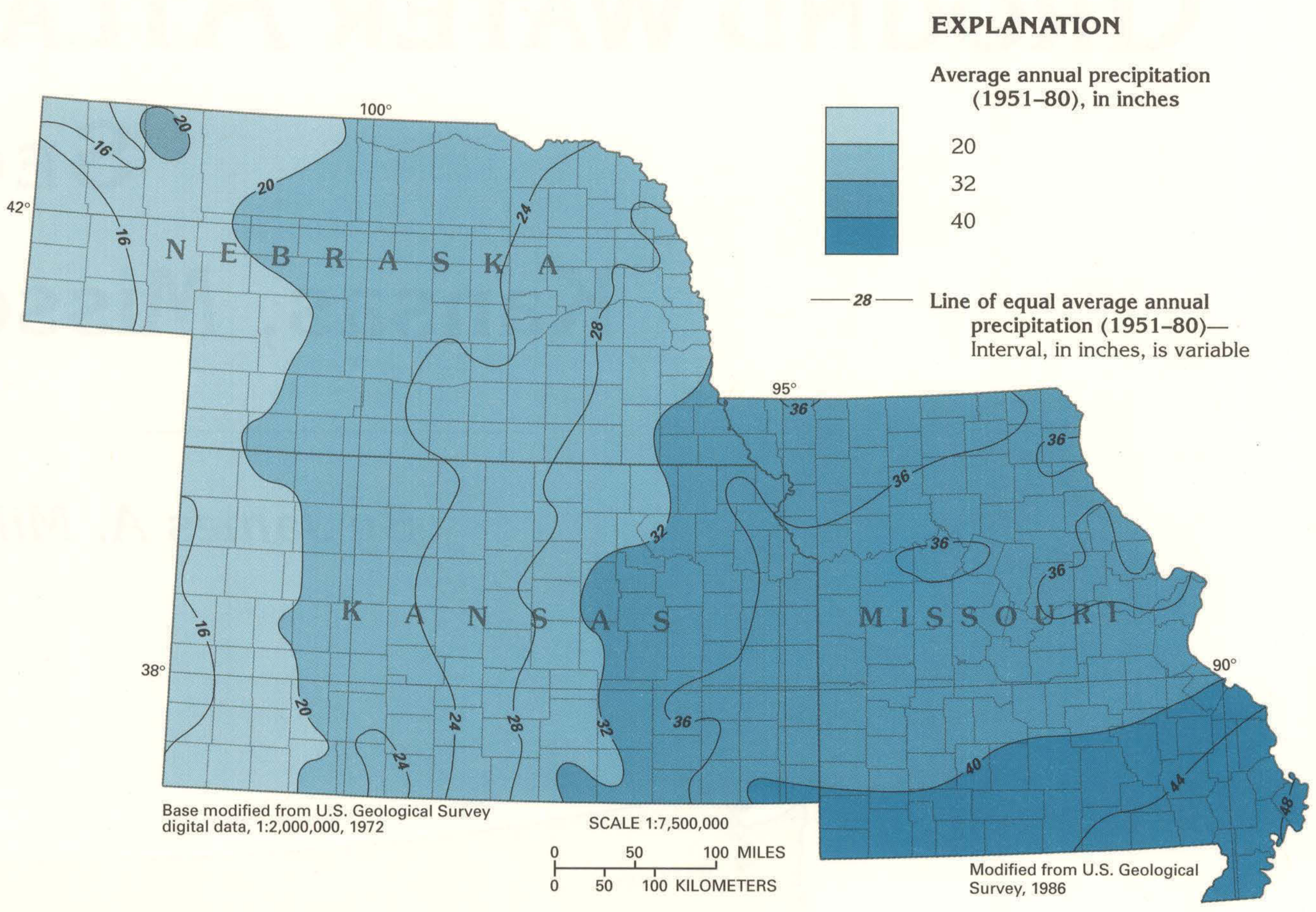


Figure 1. *Average annual precipitation is least in the western parts of Nebraska and Kansas and greatest in southeastern Missouri, where warm, moist air moves northward into the area from the Gulf of Mexico.*

Much of the precipitation is returned to the atmosphere by evapotranspiration, which is the combination of evaporation from the land surface and surface-water bodies, and transpiration from plants. Some of the precipitation either flows directly into streams as overland runoff or percolates into the soil and then moves downward into aquifers where it is stored for a time and subsequently released as base flow to streams. Average annual runoff, which is the total discharge into a stream from surface- and ground-water sources, ranges from about 0.2 inch in the western part of the area to about 20 inches in southeastern Missouri (**fig. 2**). Average annual runoff generally reflects the distribution of average annual precipitation during the same period. However, runoff is less than precipitation everywhere and ranges from less than 5 to about 35 percent of the average annual precipitation. Evapotranspiration rates are high, especially in the western one-half of the area; thus, only a small percentage of the precipitation is available to recharge aquifers in most places. Locally, however, runoff might be significantly less than shown in **figure 2**, and ground-water recharge, greater, especially where highly permeable rocks or deposits at the land surface allow precipitation to rapidly infiltrate. Examples of such places are the Sand Hills area of Nebraska, which is blanketed by permeable windblown sands, and parts of southern Missouri, where permeable limestone is at or near the land surface.

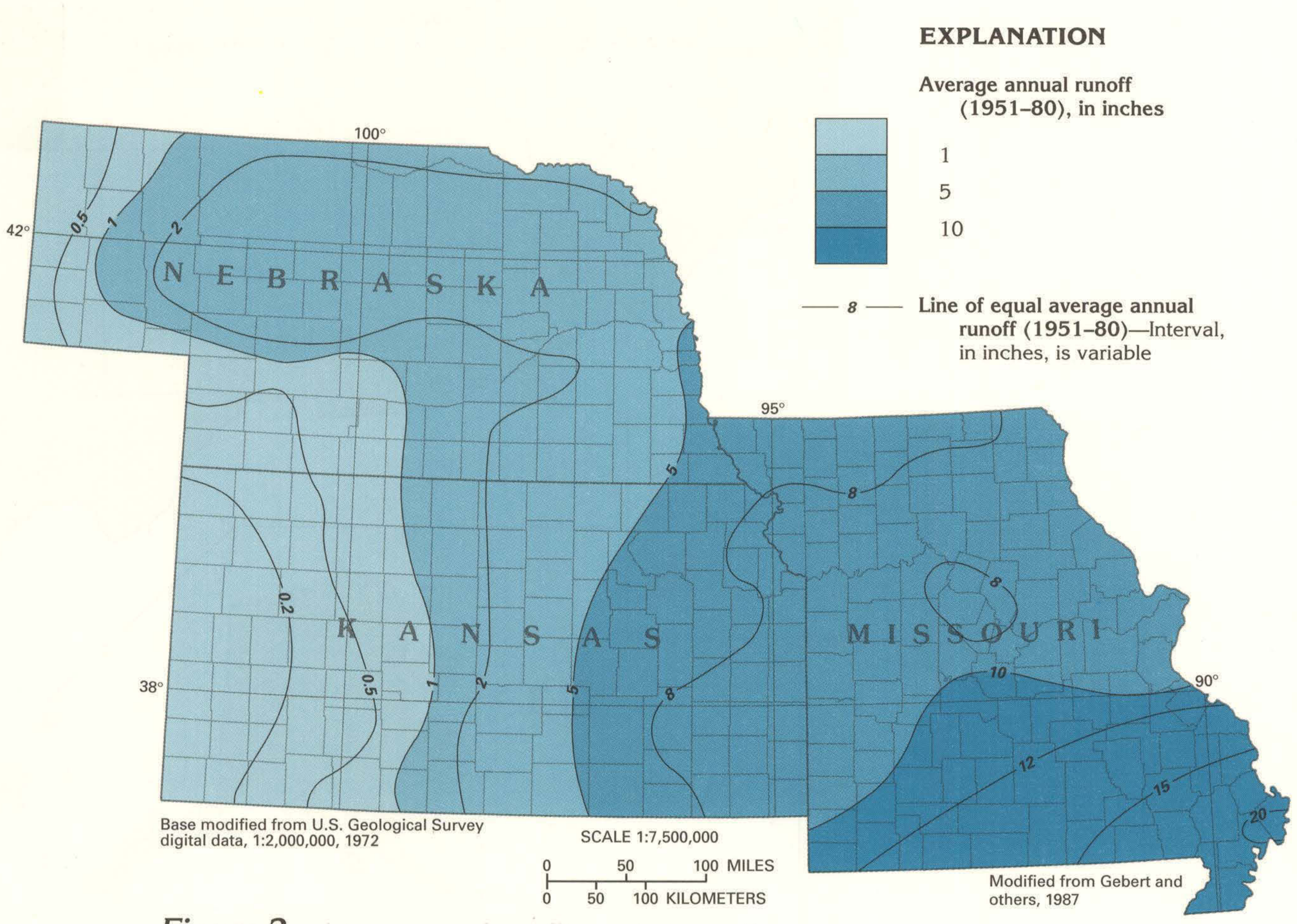


Figure 2. *Average annual runoff is greatest in southern Missouri and very small in western Kansas and Nebraska. Runoff generally is related to the amount of precipitation that falls on different parts of the segment.*

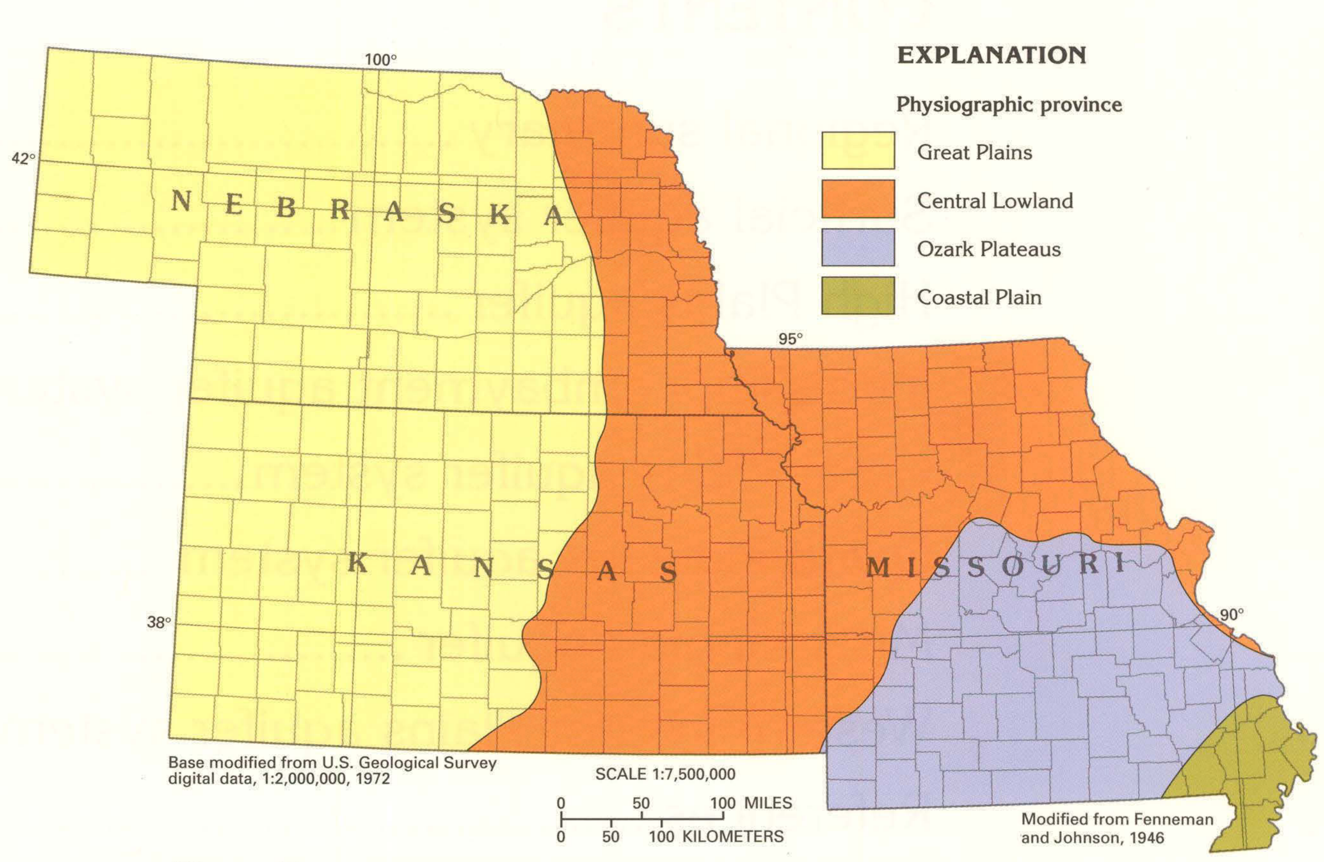


Figure 3. *Four physiographic provinces are in Segment 3. The topography of the Great Plains and the Coastal Plains Provinces is flat, the Central Lowland Province is gently rolling, and the Ozark Plateaus Province consists of a dissected plateau with some low mountains.*

The land surface of Segment 3 generally slopes gradually from west to east. In the Great Plains Physiographic Province (**fig. 3**), the altitude of the flat land surface locally is about 5,000 feet above sea level in westernmost Nebraska. By contrast, in the flat Coastal Plain Physiographic Province of eastern Missouri, the altitude is about 500 feet above sea level. The land surface is gently rolling in the Central Lowland Province except where major rivers and their tributaries are deeply incised. In the Ozark Plateaus Physiographic Province, rugged topography has developed where the underlying rocks have been uplifted and deeply eroded.

AREAL DISTRIBUTION OF AQUIFERS

The numerous aquifers within Segment 3 vary in composition. Some of the aquifers are unconsolidated sand and gravel, some are semiconsolidated sediments, and some are consolidated sandstone, limestone, or dolomite. The aquifers have been defined primarily on the basis of differences in their rock types and ground-water flow systems and secondarily by the chemical quality of water they contain. Some of the aquifers are grouped into aquifer systems. An aquifer system consists of two or more aquifers that are hydraulically connected. The flow systems of the connected aquifers function similarly, and a change in conditions in one of the aquifers affects the other aquifer or aquifers.

Seven principal aquifers or aquifer systems are at the land surface in the three-State area. The extent of those aquifers which primarily consist of unconsolidated deposits of late Quaternary age and are collectively called the surficial aquifer system is shown in **figure 4**. The remaining six aquifers and aquifer systems primarily consist of semiconsolidated to consolidated sedimentary rocks; **figure 5** shows where these aquifers are exposed or covered with only a thin blanket of soil and unconsolidated material. Some of the aquifers extend into the subsurface far beyond the areas where they are mapped in **figure 5**. One additional aquifer system, the Western Interior Plains, is present only in the subsurface and, therefore, is not shown in the figure. This aquifer system contains saline water or brine and is not as well known as the aquifers that primarily contain freshwater. In this report, the dissolved-solids concentration in ground water is used to classify the water as fresh, saline, or brine. The concentrations used to categorize the water are as follows:

	Dissolved-solids concentration, in milligrams per liter
Freshwater	less than 1,000
Slightly saline water	1,000 to 3,000
Moderately saline water	3,000 to 10,000
Very saline water	10,000 to 35,000
Brine	Greater than 35,000

Aquifers that are part of the surficial aquifer system are in all three States of Segment 3 (**fig. 4**). In this report, the surficial aquifer system is divided into the following parts: stream-valley aquifers, the Mississippi River Valley alluvial aquifer, and glacial-drift aquifers. The stream-valley aquifers are the most extensive part of the system and consist of sand and gravel deposited as alluvium in and adjacent to the channels of the larger streams in the segment. The Mississippi River Valley alluvial aquifer in southeastern Missouri also consists of alluvial sand and gravel, but these materials have been deposited as a thick, wide blanket as the channel of the Mississippi River changed its position over time. The glacial-drift aquifers consist of sand and gravel that were deposited during multiple advances of continental ice sheets from the north and northwest, primarily during the Pleistocene Epoch. Rock and soil particles were planed from the land surface as the massive sheets of ice advanced and were transported by the ice. Some of these materials were redistributed by meltwater and were deposited in preglacial channels as stratified sand and gravel that formed productive aquifers. In contrast, poorly sorted unstratified glacial deposits of clay, silt, sand, gravel, and boulders (called till) and stratified clay and silt deposited in glacial lakes have minimal permeability. Some of the glacial-drift aquifers in eastern Nebraska, northeastern Kansas, and northern Missouri are buried beneath till or glacial-lake deposits.

The High Plains aquifer (**fig. 5**), which is at the land surface in most of Nebraska and a large part of Kansas, is the most productive aquifer in the segment. This aquifer mostly consists of unconsolidated to consolidated sand and gravel of Quaternary and Tertiary to age which were deposited as a broad, thick sheet of alluvium on a wide, gentle plain by a network of branching streams whose channels migrated across the plain. Dune sand that covers an area of about 20,000 square miles in Nebraska is part of the High Plains aquifer where the sand is saturated. Where the stream-valley aquifers overlie the High Plains aquifer, they are connected hydraulically to the aquifer and are considered to be part of it.

The Mississippi embayment aquifer system in southeastern Missouri underlies and is in hydraulic connection with the Mississippi River Valley alluvial aquifer. Semiconsolidated sands of Tertiary and Cretaceous age compose the Mississippi embayment aquifer system.

The Great Plains aquifer system is exposed at the land surface in a band that extends from south-central Kansas to northeastern Nebraska (**fig. 5**). This aquifer system consists of two sandstone aquifers in Cretaceous rocks, separated by a shale confining unit. Although the Great Plains aquifer system extends in the subsurface throughout Kansas and Nebraska, it contains saline water in many places northward and westward from the area where it is exposed. A thick confining unit composed of Cretaceous shale, chalk, and limestone formations overlies the Great Plains aquifer system (**figs. 6, 7**) and separates it from the High Plains aquifer in most places.

The Ozark Plateaus aquifer system is exposed at the land surface in most of southern Missouri and in a small part of southeasternmost Kansas (**fig. 5**). This aquifer system consists of three aquifers that are separated by two confining units, all in Paleozoic rocks. The upper two aquifers are predominantly carbonate rocks, whereas the lower aquifer is predominantly sandstone. The Ozark Plateaus aquifer system extends northwestward for more than 50 miles beneath a thick confining unit called the Western Interior Plains confining unit (**fig. 6**). This confining unit extends throughout Kansas and Nebraska and consists of poorly permeable sedimentary rocks of variable composition that range in age from Jurassic through late Mississippian.

Permeable carbonate rocks that are the subsurface equivalents of the aquifers of the Ozark Plateaus aquifer system are called the Western Interior Plains aquifer system (**fig. 6**). Because this system is deeply buried everywhere, it contains saline water or brine and its hydrology, therefore, is not well known.

The Mississippian aquifer in northeastern Missouri (**fig. 5**) is in carbonate rocks that are stratigraphically equivalent to those that compose the uppermost aquifer of the Ozark Plateaus aquifer system. However, the ground-water flow systems of the two aquifers are not connected east of Boone County, Missouri, and the Mississippian aquifer is considered to be separate from the Ozark Plateaus aquifer system in this report.

The Cambrian–Ordovician aquifer is exposed in a small part of northeastern Missouri (**fig. 5**). This aquifer mostly consists of carbonate rocks and contains freshwater only in a band about 50 miles wide, which is parallel to and north of the Missouri River from Boone County eastward to the Mississippi River. The rocks that contain the Cambrian–Ordovician aquifer are stratigraphically equivalent to those that form part of the middle aquifer of the Ozark Plateaus aquifer system. The degree to which these aquifers are hydraulically connected is not precisely known, but the two aquifers are considered to be partly continuous in this report.

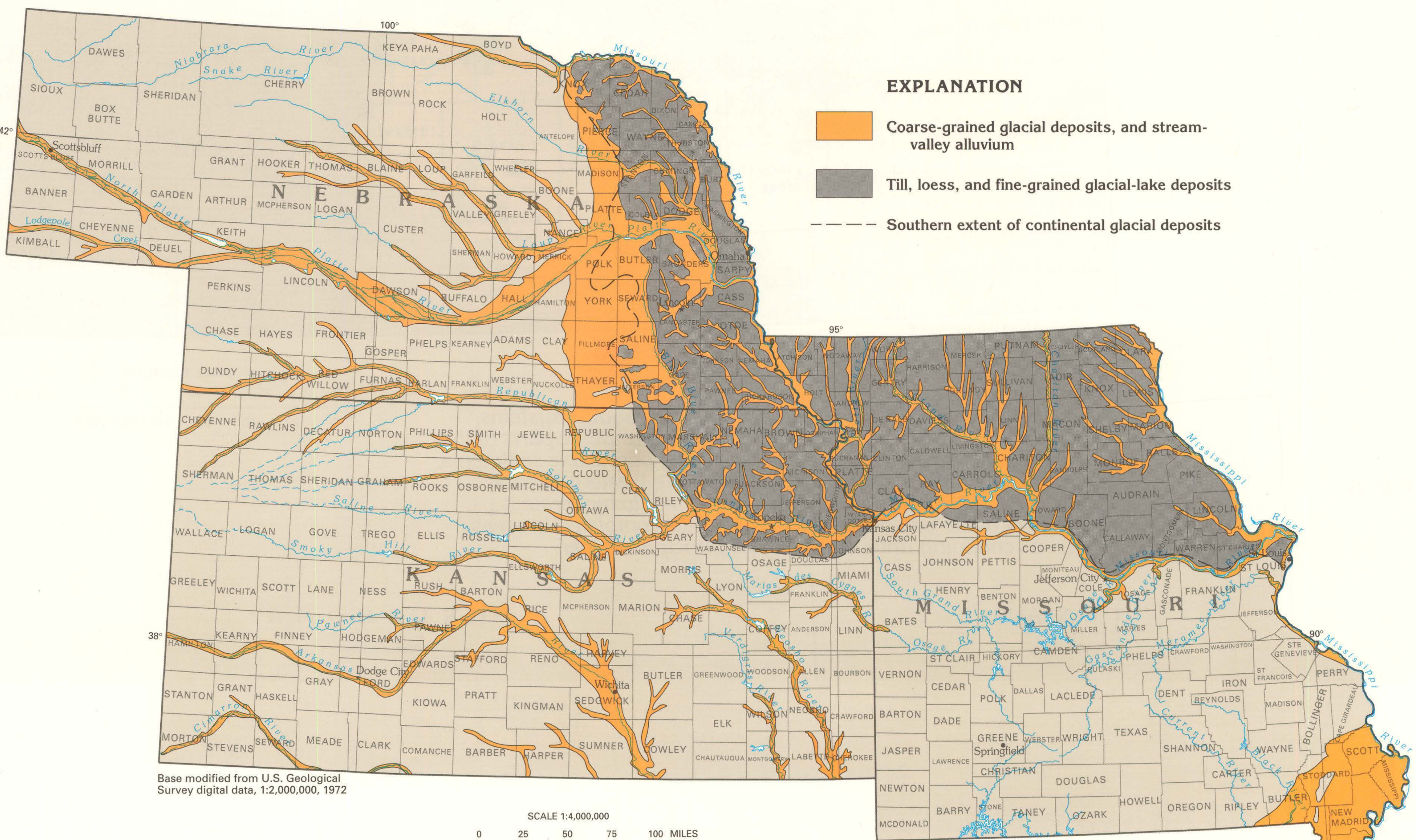


Figure 4. *Coarse-grained, unconsolidated deposits, mostly of Quaternary age, compose the surficial aquifer system and provide water for many shallow wells. Alluvium along major stream valleys, a broad blanket of alluvium in southeastern Missouri, and glacial outwash (buried in some places beneath fine-grained sediments) form productive aquifers. Till, loess, and fine-grained glacial-lake deposits are widespread in areas of the segment that were covered by continental glaciers; these deposits generally yield only small amounts of water and are not considered to be principal aquifers.*

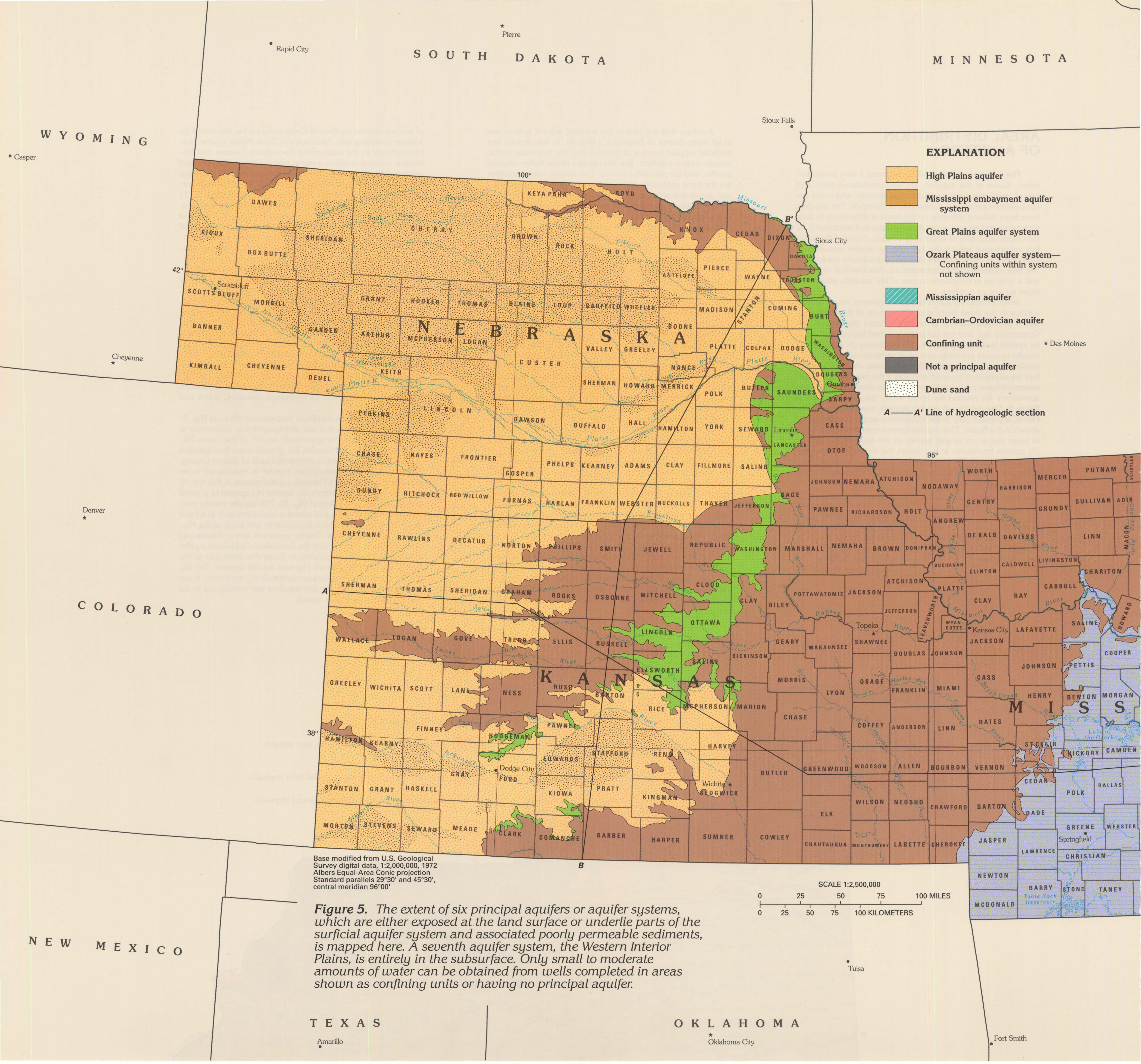


Figure 5. *The extent of six principal aquifers or aquifer systems, which are either exposed at the land surface or underlie parts of the surficial aquifer system and associated poorly permeable sediments, is mapped here. A seventh aquifer system, the Western Interior Plains, is entirely in the subsurface. Only small to moderate amounts of water can be obtained from wells completed in areas shown as confining units or having no principal aquifer.*

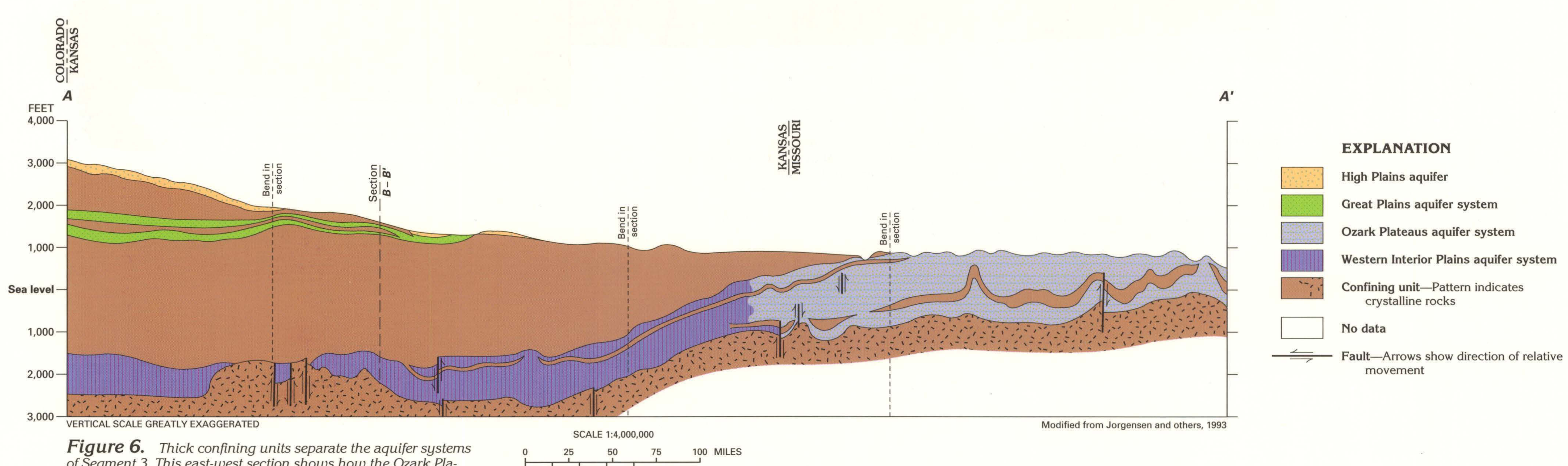
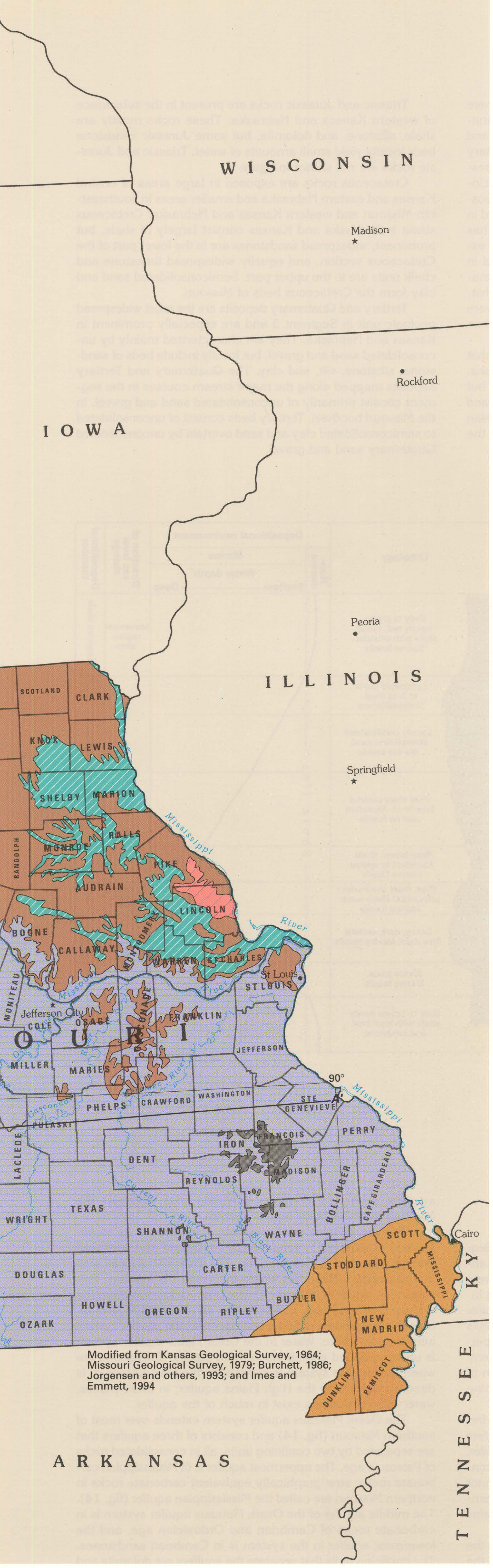


Figure 6. *Thick confining units separate the aquifer systems of Segment 3. This east-west section shows how the Ozark Plateaus aquifer system grades westward into the Western Interior Plains aquifer system, which has been locally eroded from fault blocks in central Kansas. The line of the hydrogeologic section is shown in figure 5.*



GEOLOGY

The geologic and hydrogeologic nomenclature used in this report differs from State to State because of independent geologic interpretations and varied distribution and lithology of rock units. A fairly consistent set of nomenclature, however, can be derived from the most commonly used rock names. Therefore, the nomenclature used in this report is a synthesis of that of the U.S. Geological Survey, the Kansas Geological Survey, the Missouri Department of Natural Resources, Division of Geology and Land Survey, and the Nebraska Conservation and Survey Division of the University of Nebraska. Individual sources for nomenclature are listed with each correlation chart prepared for this report.

Kansas, Missouri, and Nebraska are in part of the North American craton, which is an area that has been tectonically stable throughout most of geologic time. The area has undergone some deformation, however, as shown by faults and by upwarps and downwarps on the surface of the crystalline Precambrian rocks (**fig. 8**) that underlie Paleozoic and younger sedimentary rocks everywhere. Precambrian rocks are exposed only in the St. Francois Mountains of southeastern Missouri, where they are locally more than 1,000 feet above sea level; these rocks are buried to depths of as much as 6,000 feet below sea level in southwestern Kansas on the northern flank of the Anadarko Basin.

Because the crystalline-rock surface slopes outward in all directions from the Ozark Uplift and northward or southwestward from high areas along the Chadron Arch and the Central Kansas Uplift (**fig. 8**), the overlying sequence of sedimentary rocks slopes and thickens away from all these high areas. The greatest sedimentary rock accumulations are in the Salina Basin in south-central Nebraska and north-central Kansas and in the parts of the Mississippi Embayment and the Anadarko, the Denver, the Kennedy, and the Forest City Basins that are in Segment 3. For example, total sedimentary rock thickness in the southwestern part of the Nebraska panhandle and in southwestern Kansas along the Oklahoma State line is about 9,000 feet.

Numerous faults in the crystalline rocks of the three-State area are grouped mostly in or adjacent to the Central Kansas Uplift, the Nemaha Uplift, and the St. Francois Mountains. Vertical displacement across the faults varies from less than 100 to more than 2,500 feet. Displacement generally is greatest across some of the faults in the north-trending fault zone just east of the Nemaha Uplift. This fault zone and a second zone (**not shown in fig. 8**) that trends northeastward across the Mississippi Embayment are thought to represent zones of continental rifting that formed during Precambrian time.

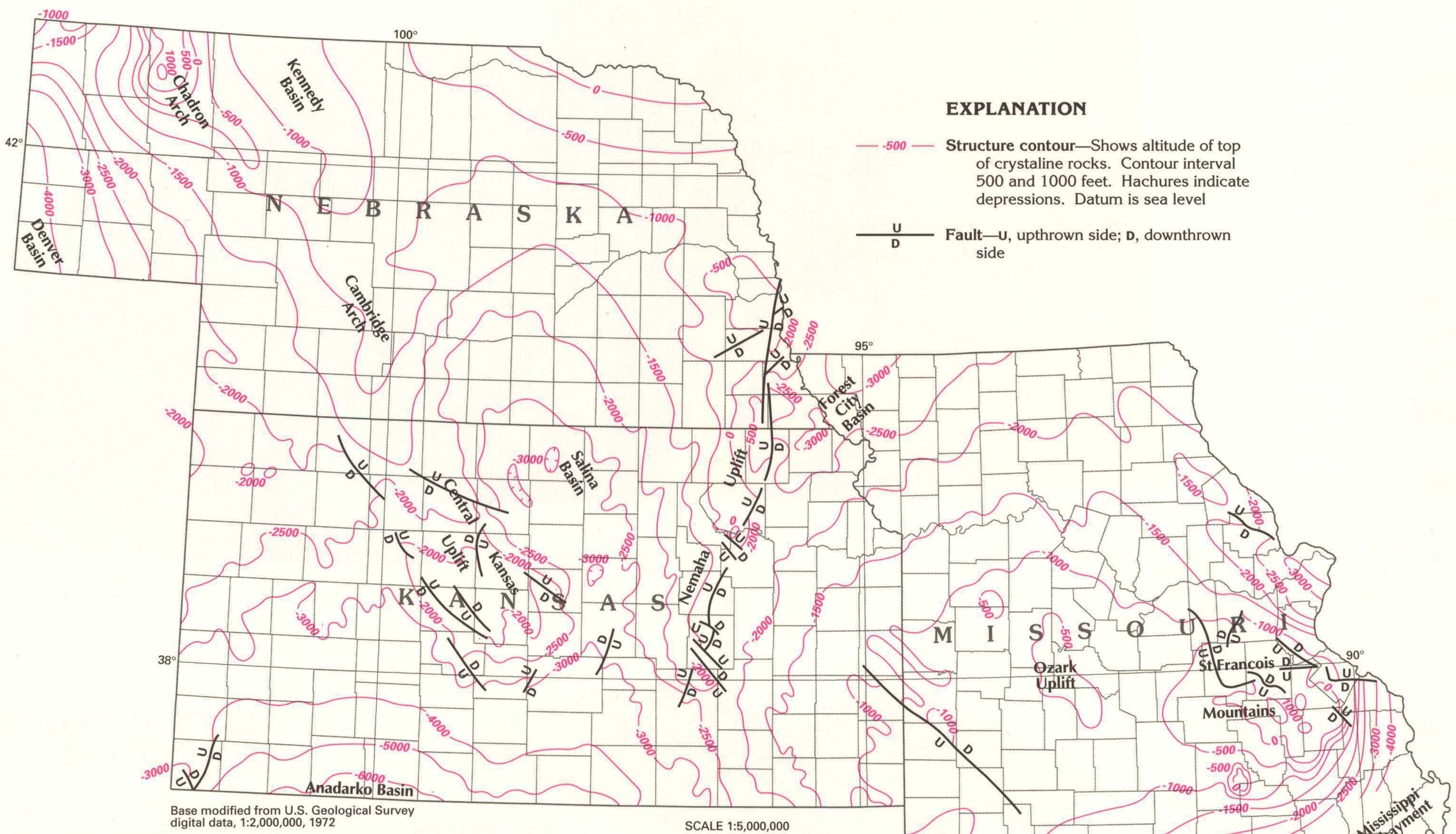


Figure 8. The crystalline-rock surface slopes from high areas, such as the Chadron Arch and the Ozark and Central Kansas Uplifts, toward the Salina Basin in north-central Kansas and other basins whose centers are outside the segment.

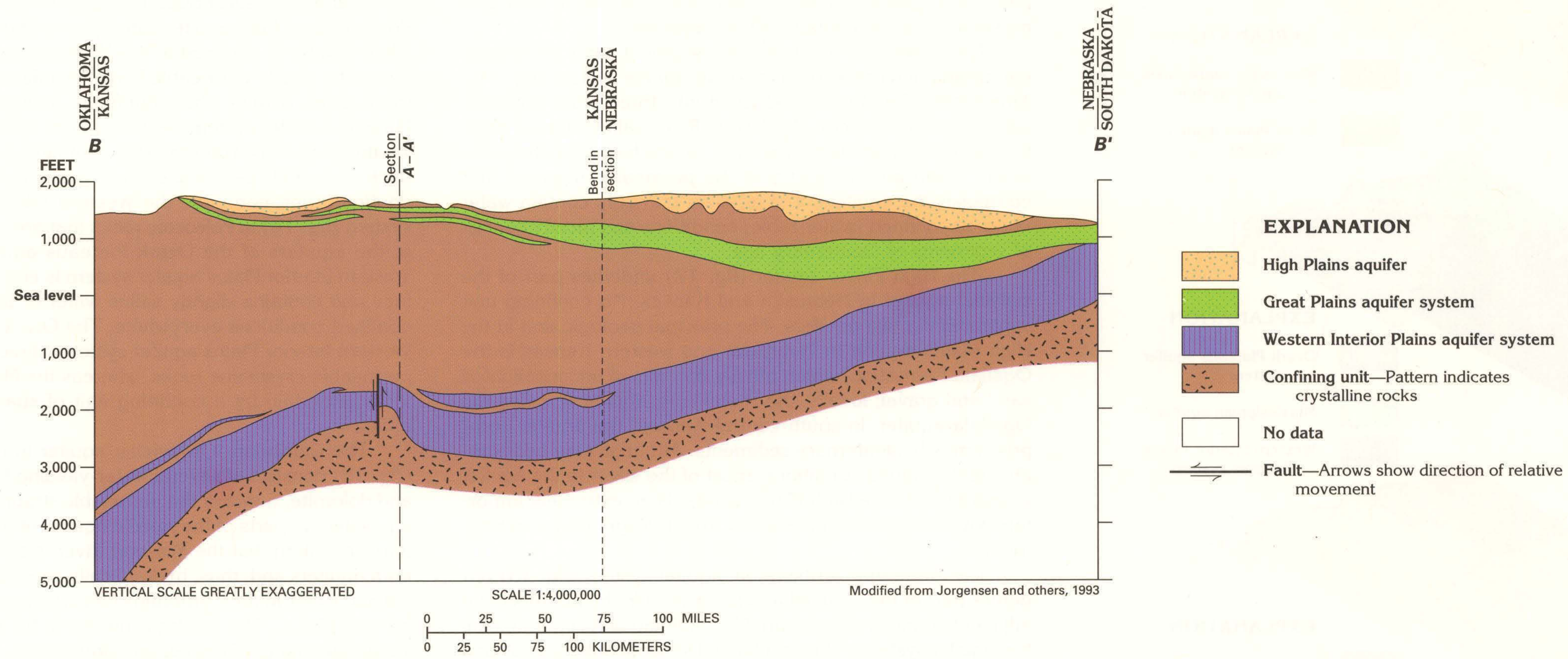


Figure 7. The thick confining unit between the Great Plains and Western Interior Plains aquifer system pinches out in northeastern Nebraska where the two aquifer systems are in hydraulic contact. The line of the hydrogeologic section is shown in figure 5.

GEOLOGY—Continued

Postdepositional erosion of the Paleozoic sedimentary-rock sequence from eastern Missouri to central Kansas and eastern Nebraska has beveled off some of the rocks. As a consequence, progressively younger rocks are exposed to the west and northwest of the Precambrian core of the St. Francois Mountains in southeastern Missouri (**fig. 9**). The glacial sediments that cover bedrock strata in eastern Nebraska, northeastern Kansas, and northern Missouri are not shown in **figure 9**, and stream-valley deposits are shown only along the major streams; the total extent of these deposits in Segment 3 is the same as that shown in **figure 4**. The widespread areas of Tertiary and Quaternary sediments in western Kansas and Nebraska are not related to erosion or beveling of rocks away from the St. Francois Mountains and the Ozark Uplift. These Tertiary and Quaternary sediments are mostly alluvium that was derived from erosion of the Rocky Mountains to the west of the segment.

Cambrian rocks are exposed in southeastern Missouri in an area that encircles the Precambrian core of the St. Francois Mountains. The basal Cambrian rocks are sandstones, and the upper parts of the Cambrian sequence are mostly dolomite.

Ordovician rocks are exposed in a large area in southern Missouri and in smaller areas in northeastern and southeastern Missouri. The thick sequence of Ordovician strata mostly consists of dolomite and limestone interbedded with minor sandstone and shale and has been divided into a large number of geologic formations.

Silurian rocks consist of a thin sequence of dolomite and limestone and are exposed only locally in southeastern and northeastern Missouri near the Mississippi River. Some studies have postulated that the Silurian Period was characterized by extensive uplift and erosion in the area of Segment 3.

Devonian rocks are exposed in scattered areas of southern, southeastern, and northern Missouri. Like the Silurian strata, Devonian rocks are thin. The lower and middle parts of the Devonian sequence are mostly limestone interbedded with minor sandstone and chert, whereas the upper part is mostly widespread shale.

Mississippian rocks crop out in a wide to narrow band that extends from southwestern Missouri to just north of the Missouri River in central Missouri and as a second, less extensive band in northeastern Missouri parallel to the Mississippi River. Mississippian strata in Segment 3 are mostly limestone (commonly cherty) but include some beds of sandstone and shale. Outliers of Mississippian rocks in southern Missouri show that these beds extended over a much larger area before most were removed by erosion.

Pennsylvanian strata crop out in large areas of eastern Kansas and western Missouri. These rocks are covered with glacial drift to the west and north of the Missouri River where they are mapped in **figure 9** as the shallowest bedrock. Pennsylvanian rocks consist of shale, sandstone, limestone, and some coal beds and were deposited in a series of sedimentary cycles, each of which represents a transgression and regression of the Pennsylvanian sea. Each cycle, known as a cyclothem (**fig. 10**), begins and ends with nonmarine shale deposits; intervening marine limestone and shale were deposited in shallow to deep water. The thick Pennsylvanian section has been divided into a large number of geologic formations, especially in Kansas where 49 formations are recognized in exposed Pennsylvanian strata and several additional formations are delineated in the subsurface. Outliers of Pennsylvanian rocks in east-central Missouri show that before they were partly eroded, these strata covered a much greater area than at present.

Permian rocks are exposed in a wide to narrow band that extends from south-central Kansas to southeastern Nebraska. Permian rocks primarily consist of shale and sandstone but also contain beds of halite (rock salt), gypsum, anhydrite, and minor limestone. Cyclic deposition is characteristic of Permian strata, but the cycles are not as numerous as those of the Pennsylvanian rocks.

Triassic and Jurassic rocks are present in the subsurface of western Kansas and Nebraska. These rocks mostly are shale, siltstone, and dolomite, but some Jurassic sandstone beds locally yield small amounts of water. Triassic and Jurassic rocks are not shown in **figure 9**.

Cretaceous rocks are exposed in large areas of central Kansas and eastern Nebraska and smaller areas in southeastern Missouri and western Kansas and Nebraska. Cretaceous strata in Nebraska and Kansas consist largely of shale, but prominent, widespread sandstones are in the lower part of the Cretaceous section, and equally widespread limestone and chalk units are in the upper part. Semiconsolidated sand and clay form the Cretaceous beds of Missouri.

Tertiary and Quaternary deposits are the most widespread geologic unit in Segment 3 and are especially prominent in Kansas and Nebraska. They are characterized mainly by unconsolidated sand and gravel, but locally include beds of sandstone, siltstone, silt, and clay. The Quaternary and Tertiary deposits mapped along the major stream courses in the segment consist primarily of unconsolidated sand and gravel. In the Missouri bootheel, Tertiary beds consist of unconsolidated to semiconsolidated clay and sand overlain by unconsolidated Quaternary sand and gravel.

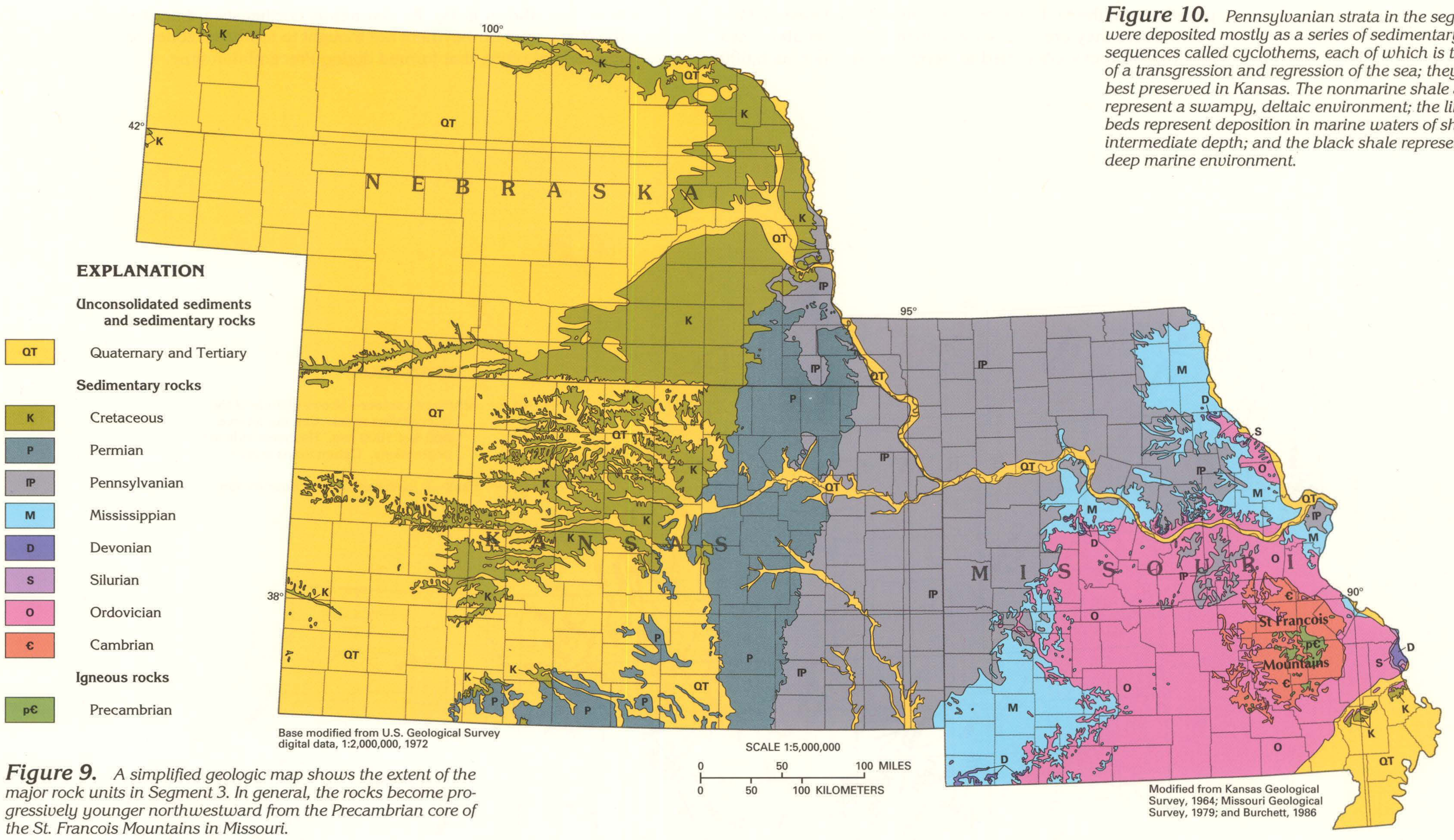


Figure 9. A simplified geologic map shows the extent of the major rock units in Segment 3. In general, the rocks become progressively younger northwestward from the Precambrian core of the St. Francois Mountains in Missouri.

Figure 10. Pennsylvanian strata in the segment were deposited mostly as a series of sedimentary sequences called cyclothems, each of which is the result of a transgression and regression of the sea; they are best preserved in Kansas. The nonmarine shale and coal represent a swampy, deltaic environment; the limestone beds represent deposition in marine waters of shallow to intermediate depth; and the black shale represents a deep marine environment.

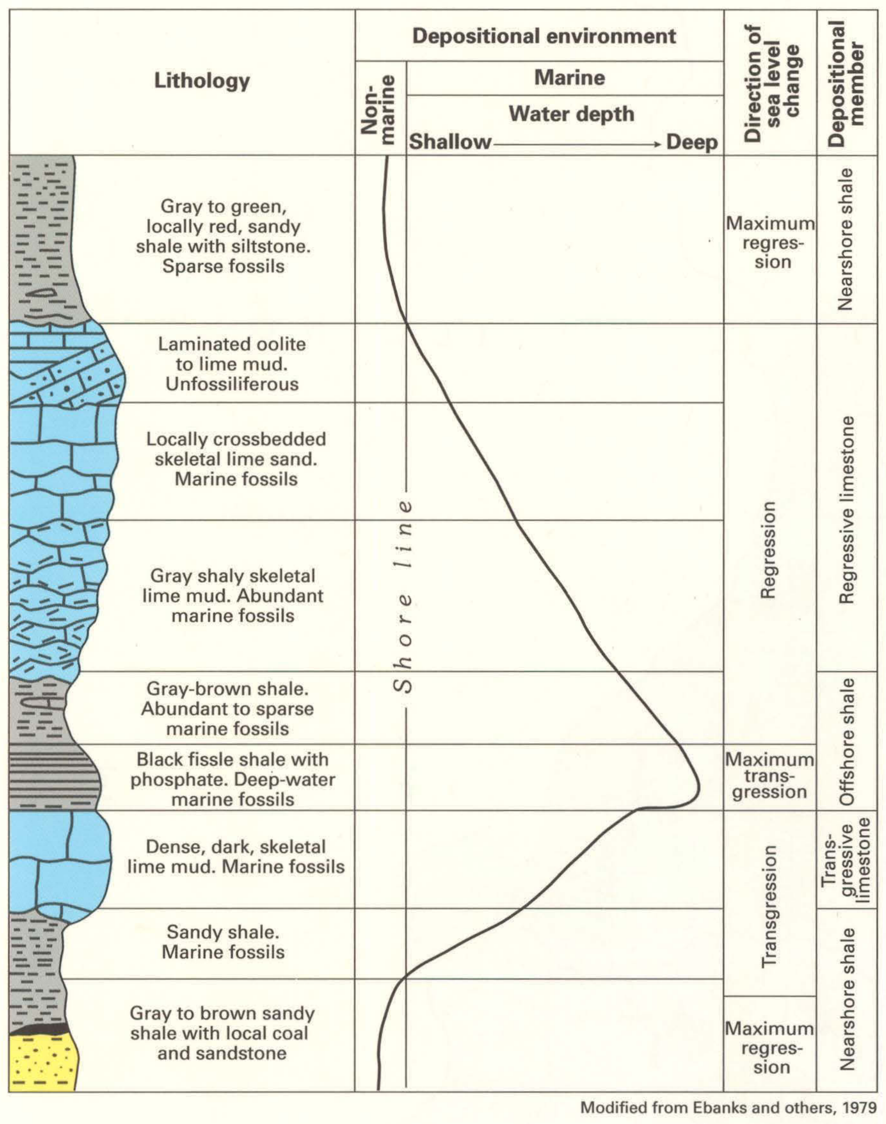


Figure 11. The surficial aquifer system consists of stream-valley aquifers along major drainages, the Mississippi River Valley alluvial aquifer in the Missouri bootheel, and glacial-drift aquifers in northern Missouri, eastern Nebraska, and northeastern Kansas. All three aquifers consist of unconsolidated deposits of sand and gravel.

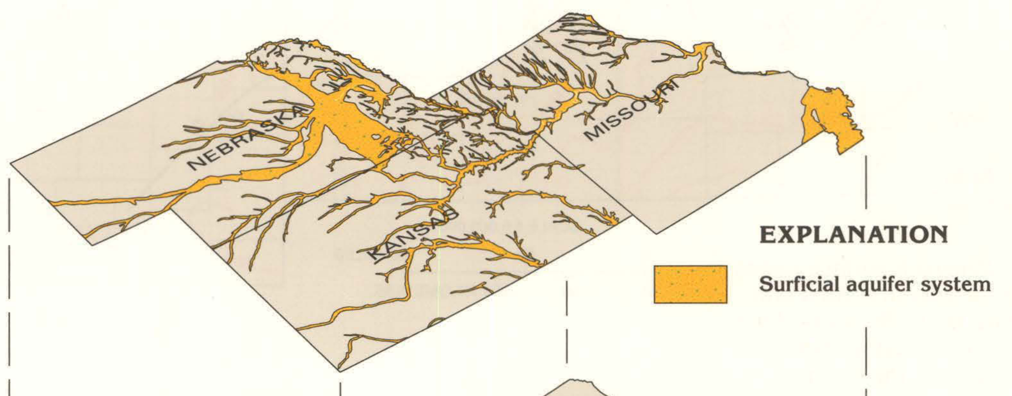


Figure 12. The High Plains aquifer primarily consists of unconsolidated sand and gravel of the Ogallala Formation in Nebraska and western Kansas and of Quaternary beds in south-central Kansas. The aquifer underlies and is hydraulically connected to parts of the surficial aquifer system in Kansas and Nebraska.

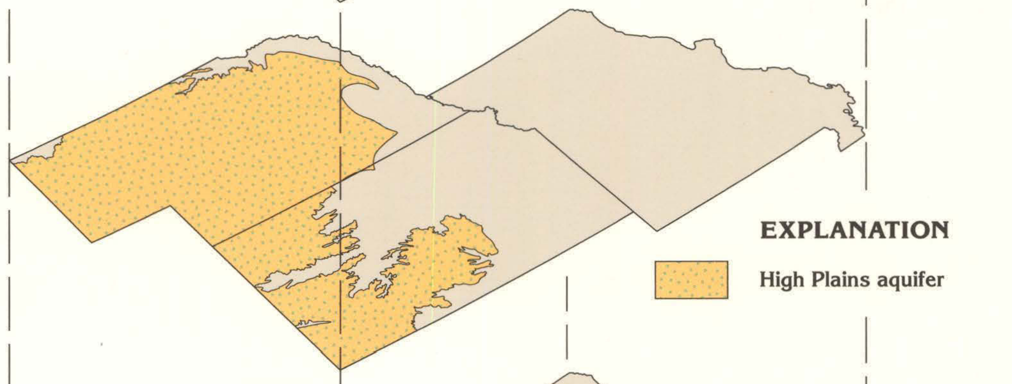


Figure 13. The Mississippi embayment aquifer system directly underlies and is hydraulically connected to the surficial aquifer system in southeastern Missouri. The Great Plains aquifer system in Kansas and Nebraska underlies much of the High Plains aquifer and is separated from parts of it by a thick confining unit of shale.

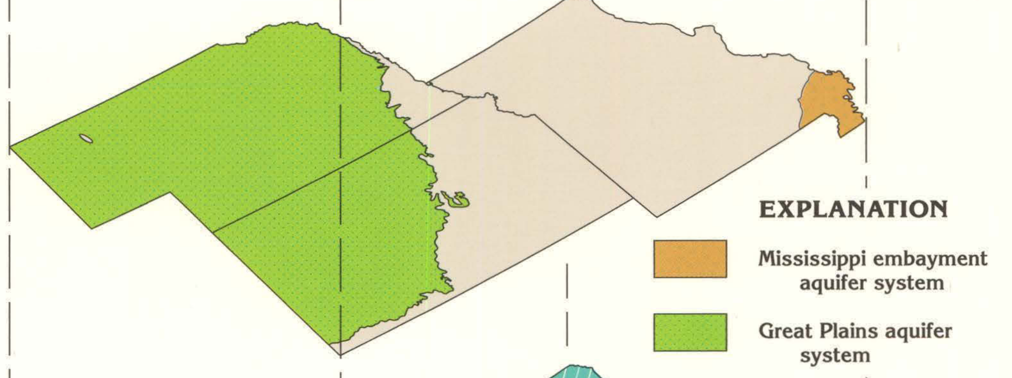


Figure 14. The Ozark Plateaus aquifer system in southern Missouri is a large freshwater system in Paleozoic rocks. Equivalent rocks of the Western Interior Plains aquifer system, however, contain no freshwater. The Mississippian aquifer of northern Missouri is in rocks equivalent to those of the upper part of the Ozark Plateaus aquifer system but has little or no hydraulic connection to that system.

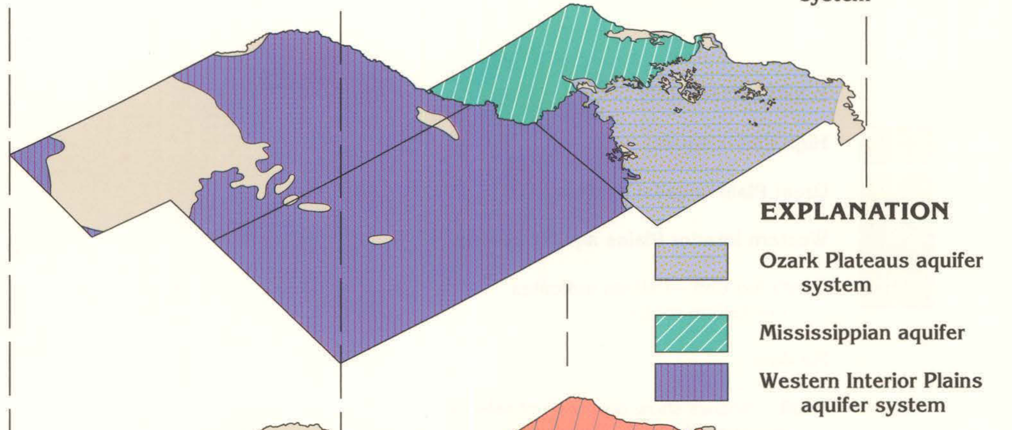
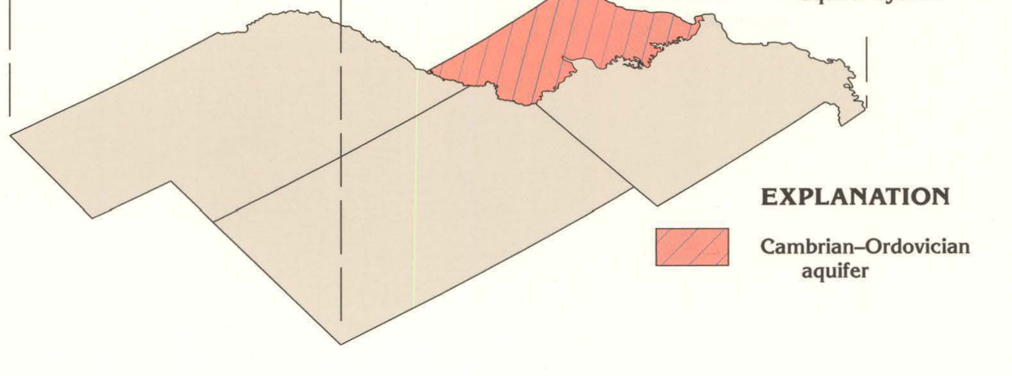


Figure 15. The Cambrian–Ordovician aquifer consists of dolomite and sandstone beds equivalent to part of the Ozark Plateaus aquifer system but is hydraulically separate from that system in some places. The aquifer is overlain and underlain by confining units.



VERTICAL SEQUENCE OF AQUIFERS

Some of the principal aquifers and aquifer systems in Segment 3 are stacked atop others. For example, in parts of Kansas and Nebraska, the High Plains aquifer overlies the Great Plains aquifer system, which, in turn, overlies the Western Interior Plains aquifer system (**fig. 7**); the aquifers and aquifer systems, however, are separated by thick shale confining units in most places. Although the confining units are poorly permeable, some water is able to move vertically through them, from one aquifer to another. Movement is in the direction of decreasing hydraulic head and is easiest where the confining units are thin, leaky, or both.

Where confining units are absent, water moves readily between aquifers. As an example, where stream-valley aquifers of the surficial aquifer system overlie the High Plains aquifer, no confining unit separates the aquifers, both of which consist of unconsolidated sand and gravel. The aquifers cannot be hydraulically distinguished from each other, and the stream-valley aquifers are considered to be part of the High Plains aquifer where the two are in contact.

The sequence of maps (**figures 11 through 15**) shows the extent of each aquifer or aquifer system. Comparison of the maps shows the places where aquifers are stacked upon each other. The vertical sequence is different from area to area, and no single location contains all the aquifers.

The uppermost aquifers in the segment are in unconsolidated sand and gravel of the surficial aquifer system (**fig. 11**). This system has been subdivided into three parts (stream-valley alluvial aquifers, Mississippi River Valley alluvial aquifer, glacial-drift aquifers), primarily on the basis of differences in the origin and geometry of the permeable material that composes the aquifers. The aquifers primarily contain water under unconfined (water-table) conditions and mostly consist of sediments of Quaternary age.

The High Plains aquifer (**fig. 12**) underlies part of the surficial aquifer in Nebraska and Kansas. No confining unit separates the two aquifers. The principal geologic unit in the High Plains aquifer in Nebraska and western Kansas is the Ogallala Formation, which mostly consists of unconsolidated sand and gravel; locally, the High Plains aquifer is called the Ogallala aquifer. In south-central Kansas, the aquifer comprises mostly Quaternary sediments. Although clay beds create local confined conditions, most of the water in the aquifer is unconfined. The High Plains aquifer is an extremely important source of water, primarily for irrigated agriculture, in Segment 3.

The Mississippi embayment aquifer system (**fig. 13**) underlies part of the surficial aquifer system in the bootheel and adjacent counties of Missouri. No confining unit separates the two aquifer systems. Unconsolidated to semiconsolidated sand aquifers, separated by clayey confining units, compose the Mississippi embayment aquifer system.

The Great Plains aquifer system extends from its southern and eastern limits continuously northward and westward through Kansas and Nebraska (**fig. 13**) except for a small area in northwestern Nebraska where the system is missing. Two sandstone aquifers in Lower Cretaceous rocks, separated by a shale confining unit, compose the aquifer system. An extremely thick shale confining unit underlies the aquifer system almost everywhere. Water in the Great Plains aquifer system is under confined conditions in most places. Exceptions are where the aquifer system is exposed at the land surface or is directly overlain by the High Plains aquifer; in these places, water-table conditions exist in much of the aquifer.

The Ozark Plateaus aquifer system extends over most of southern Missouri (**fig. 14**) and consists of three aquifers that are separated by two confining units, all in consolidated rocks of Paleozoic age. The uppermost aquifer is in Mississippian carbonate rocks; stratigraphically equivalent carbonate rocks in northern Missouri are called the Mississippian aquifer (**fig. 14**). The middle aquifer of the Ozark Plateaus aquifer system is in carbonate rocks of Cambrian and Ordovician age, and the lowermost aquifer in the system is in Cambrian sandstones. The confining units that separate the aquifers are dolomite and shale. Water in the aquifers of the Ozark Plateaus aquifer system and the Mississippian aquifer is unconfined in and just downgradient from aquifer outcrop areas but is confined elsewhere. Water is confined in the Mississippian aquifer in most places by poorly permeable Pennsylvanian strata that overlie the aquifer. A thick shale confining unit overlies the Ozark Plateaus aquifer system westward from western Missouri and southeasternmost Kansas. This confining unit is exceedingly thick and poorly permeable. Water-yielding rocks beneath the confining unit compose the Western Interior Plains aquifer system (**fig. 14**) in Paleozoic rocks that are lateral equivalents of the aquifers of the Ozark Plateaus aquifer system. The Western Interior Plains aquifer system is entirely in the subsurface and contains slightly saline water or brine that is under confined conditions everywhere. The Ozark Plateaus and the Western Interior Plains aquifer systems directly overlie poorly permeable crystalline rocks, whereas the Mississippian aquifer is underlain by a confining unit of shale and carbonate rocks.

The Cambrian–Ordovician aquifer in northern Missouri (**fig. 15**) consists of several water-yielding beds of sandstone and dolomite. Some of the permeable strata in this aquifer are equivalent to parts of the middle aquifer of the Ozark Plateaus aquifer system, but the Missouri River is a discharge area for both aquifers and, thus, hydraulically separates them in some places. Water in the Cambrian–Ordovician aquifer is confined in most places. The aquifer is underlain by a confining unit of Cambrian shale, dolomite, and limestone.

FRESH GROUND-WATER WITHDRAWALS

Ground water is the source of water supply for more than 5 million people, or almost 70 percent of the population in the three-State area (**table 1**). Public water-supply systems provide more than twice as much water as private (domestic) systems. Ground water supplies nearly 100 percent of the population in rural areas and is the source for many water-supply systems in small cities. About 86 percent of the population of Nebraska depends on ground water for supply.

Nearly 10 billion gallons per day was withdrawn from all the aquifers in Segment 3 during 1990 (**fig. 16**). About 90 percent of the total water withdrawn was used for agricultural, primarily irrigation, purposes. Withdrawals for public supply were about 6 percent of the total water withdrawn.

Total fresh ground-water withdrawals, by county, during 1990 in Kansas, Missouri, and Nebraska are shown in **figure 17**. Counties with the largest withdrawals are those in which agricultural irrigation is most intense. Some large cities located adjacent to major rivers (for example, St. Louis, Missouri) withdraw surface water for public supply, and their effect is accordingly not indicated on the map.

The total freshwater withdrawn from each principal aquifer and aquifer system in the three-State area is shown in **figure 18**. About 8,191 million gallons per day was withdrawn from the High Plains aquifer; this was about 8 times as much water as was withdrawn from the surficial aquifer system, which is the second most used source of ground water (1,037 million gallons per day). The Ozark Plateaus aquifer system supplied water at the rate of about 330 million gallons per day and is the third largest producer. Withdrawals from the Great Plains aquifer, which is the fourth largest producer in the segment, were about 133 million gallons per day. Withdrawal rates from the Mississippi embayment aquifer system were small (95 million gallons per day) because the aquifer is limited in areal extent in Segment 3 and is overlain by the productive Mississippi River Valley alluvial aquifer.

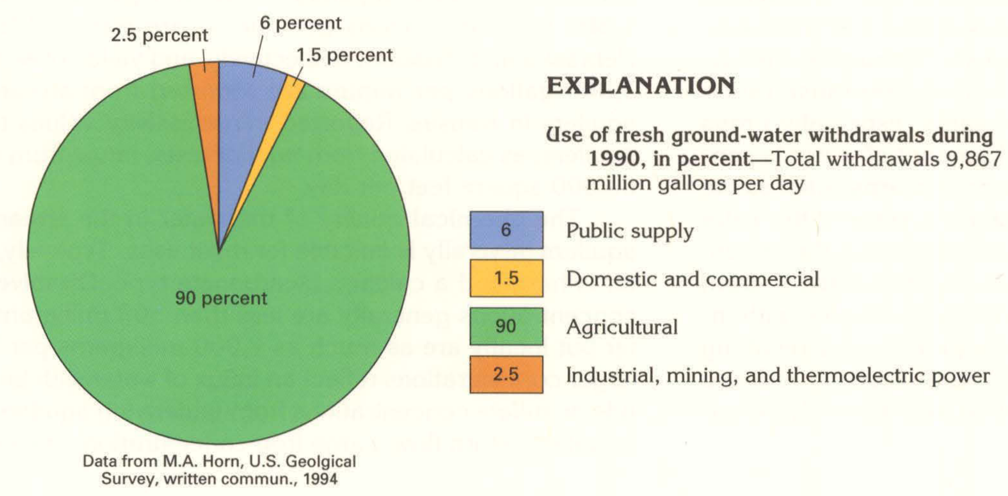


Figure 16. About 90 percent of the water withdrawn from all aquifers in the three-State area during 1990 was used for agricultural, primarily irrigation, purposes.

Table 1. During 1990, public and domestic water-supply systems provided ground water to more than 5 million people in Kansas, Missouri and Nebraska

[Modified from Solley and others, 1993]

	Population		Public water-supply systems		Domestic water-supply systems	
State	People served (thousands)	State total (percent)	People served (thousands)	Total population (percent)	People served (thousands)	Total population (percent)
Kansas	1,290	52	1,040	42	250	10
Missouri	2,530	49	1,500	29	1,030	20
Nebraska	1,353	86	975	62	378	24
Total	**5,173**		**3,515**		**1,658**	

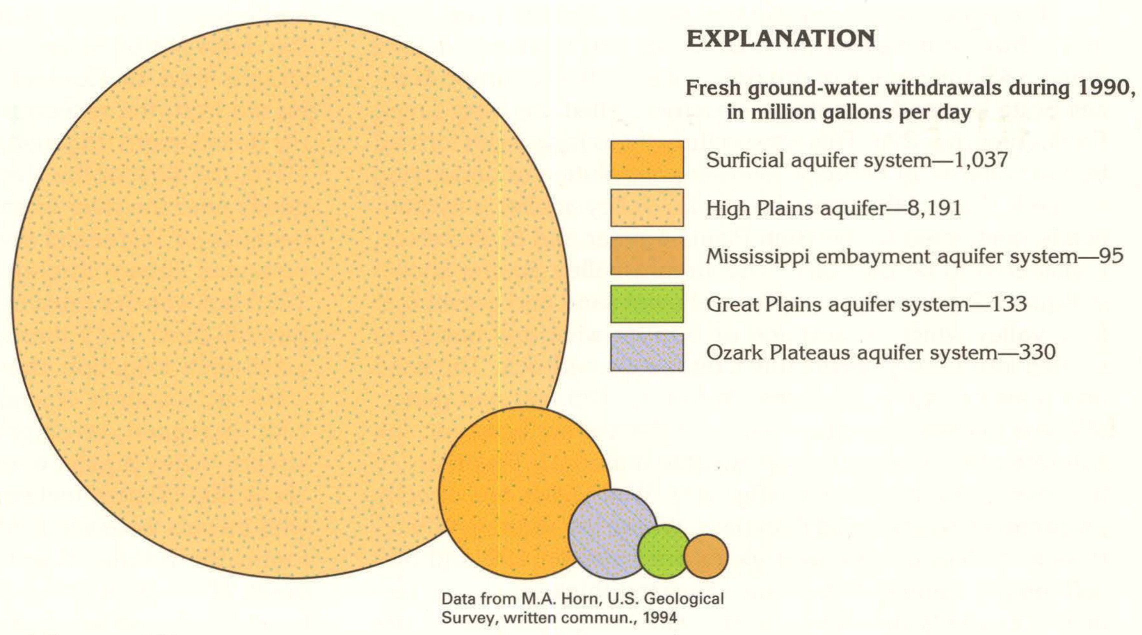


Figure 18. The High Plains aquifer was the source of about 84 percent of the total fresh ground water withdrawn from the principal aquifers in the three-State area during 1990; about 11 percent was withdrawn from the surficial aquifer system, which is the second greatest ground-water source.

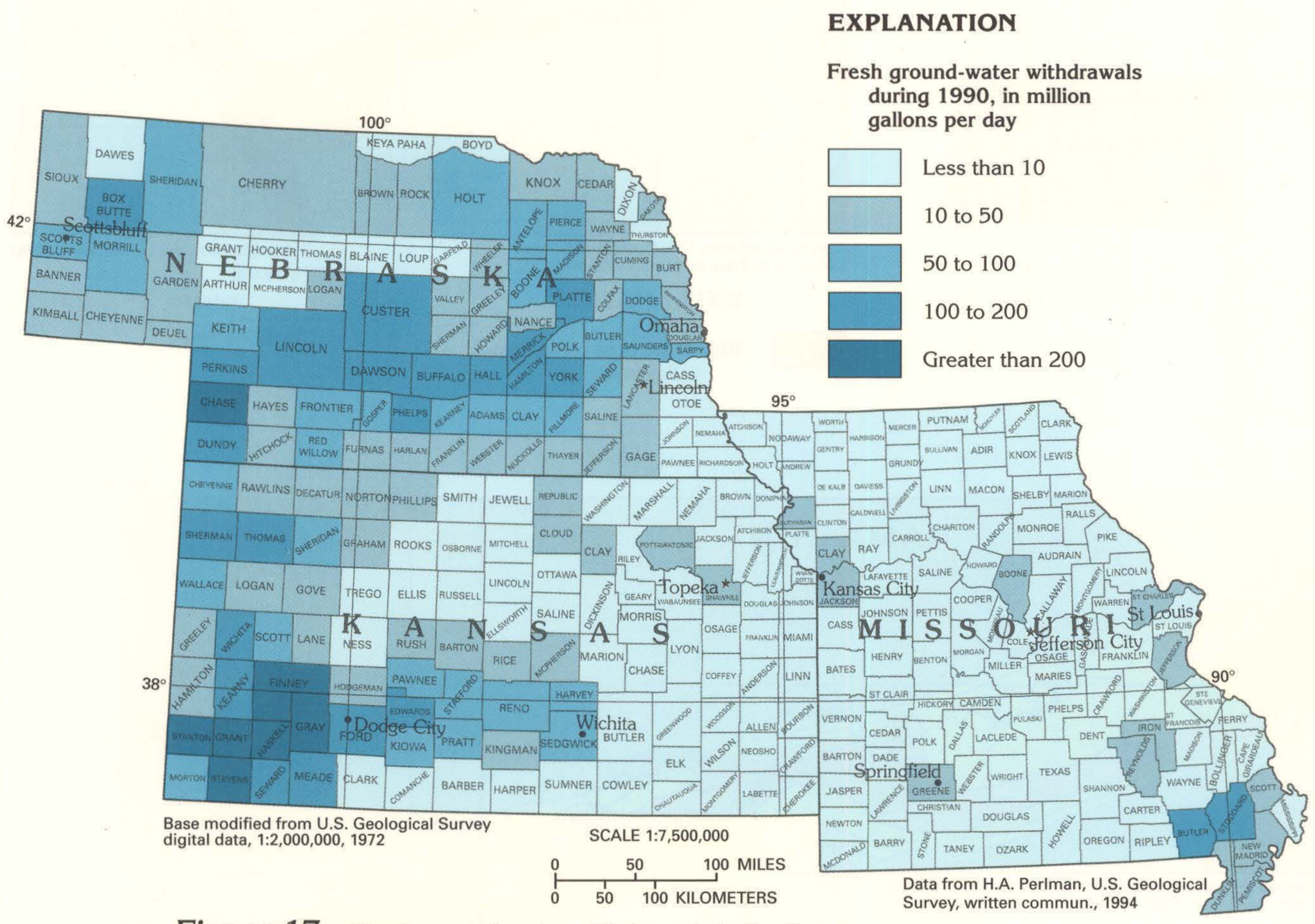


Figure 17. Fresh ground-water withdrawals in the three States are greatest in counties where the most acreage is irrigated.

Surficial aquifer system

INTRODUCTION

The surficial aquifer system in Segment 3 consists of unconsolidated sand and gravel and is divided into three parts: stream-valley aquifers, the Mississippi River Valley alluvial aquifer, and glacial-drift aquifers. These aquifers are hydraulically connected in some places. For example, many of the glacial-drift aquifers in northern Missouri, northeastern Kansas, and eastern Nebraska occupy ancient stream channels that have been eroded into bedrock. At locations where modern streams follow the ancient drainage patterns, the alluvial deposits of sand and gravel that compose a stream-valley aquifer may lie directly on glacial outwash that also consists of sand and gravel. Much of the sand and gravel of the stream-valley aquifers in Missouri and eastern Kansas and Nebraska has been reworked from older glacial-drift deposits and, therefore, may be difficult to distinguish from glacial outwash. Most of the water in the surficial aquifer system is under unconfined conditions.

STREAM-VALLEY AQUIFERS

The stream-valley aquifers of Segment 3 consist of narrow bands of fluvial and alluvial sediments which fill or partly fill the valleys of meandering to braided streams that have eroded shallow channels into glacial deposits, older unconsolidated alluvium, or bedrock. Where these streams cross the High Plains aquifer, the stream-valley aquifers are hydraulically connected to and are considered to be part of the underlying High Plains aquifer. Locally, the stream-valley aquifers are hydraulically connected to bedrock aquifers, but, in most places, they are separated from the bedrock aquifers by poorly permeable beds of clay or shale. The extent of the stream-valley aquifers is shown in **figure 19**.

The unconsolidated sand and gravel deposits that compose the stream-valley aquifers are thicker, more widespread, and more productive in the valleys of the larger rivers than those of smaller streams. In Kansas, stream-valley aquifers are along the courses of the Republican, the Kansas, the Missouri, the Solomon, the Saline, the Neosho, the Smoky Hill, the Marais des Cygnes, the Arkansas, and the Cimarron Rivers. In Missouri, the stream-valley aquifers along the Missouri and the Mississippi Rivers and their tributaries are important sources of freshwater for many communities and industries. Stream-valley aquifers occur along the Missouri, the Niobrara, the Loup, the Platte, the Republican, and the Blue Rivers in Nebraska. No comprehensive, unified study has been done for the stream-valley aquifers; accordingly, local investigations have been selected to show their hydrology. The designated boundaries **D8** and **D9** in **figure 19** are the locations of detailed studies of the stream-valley aquifers, which are described in the following sections of this report.

The stream-valley aquifers consist mostly of sand and gravel of Holocene age but locally include sediments of Pleistocene age. The average thickness of the aquifers is about 90 to 100 feet, but locally they are as much as 160 feet thick. However, the average thickness of saturated alluvial material is less and generally ranges from 50 to 80 feet; the thicker saturated sections yield more water to wells.

Most of the water in the stream-valley aquifers is under unconfined, or water-table, conditions. Locally, where coarse-grained aquifer sediments are capped by poorly permeable silt or clay, confined (artesian) conditions exist. The stream-valley aquifers are in direct hydraulic connection with the adjacent streams and water levels in the aquifers are, therefore, closely related to river levels (**fig. 20**). Aquifer and river water levels rise following precipitation events; the rise in the water level of the river precedes that in the aquifer.

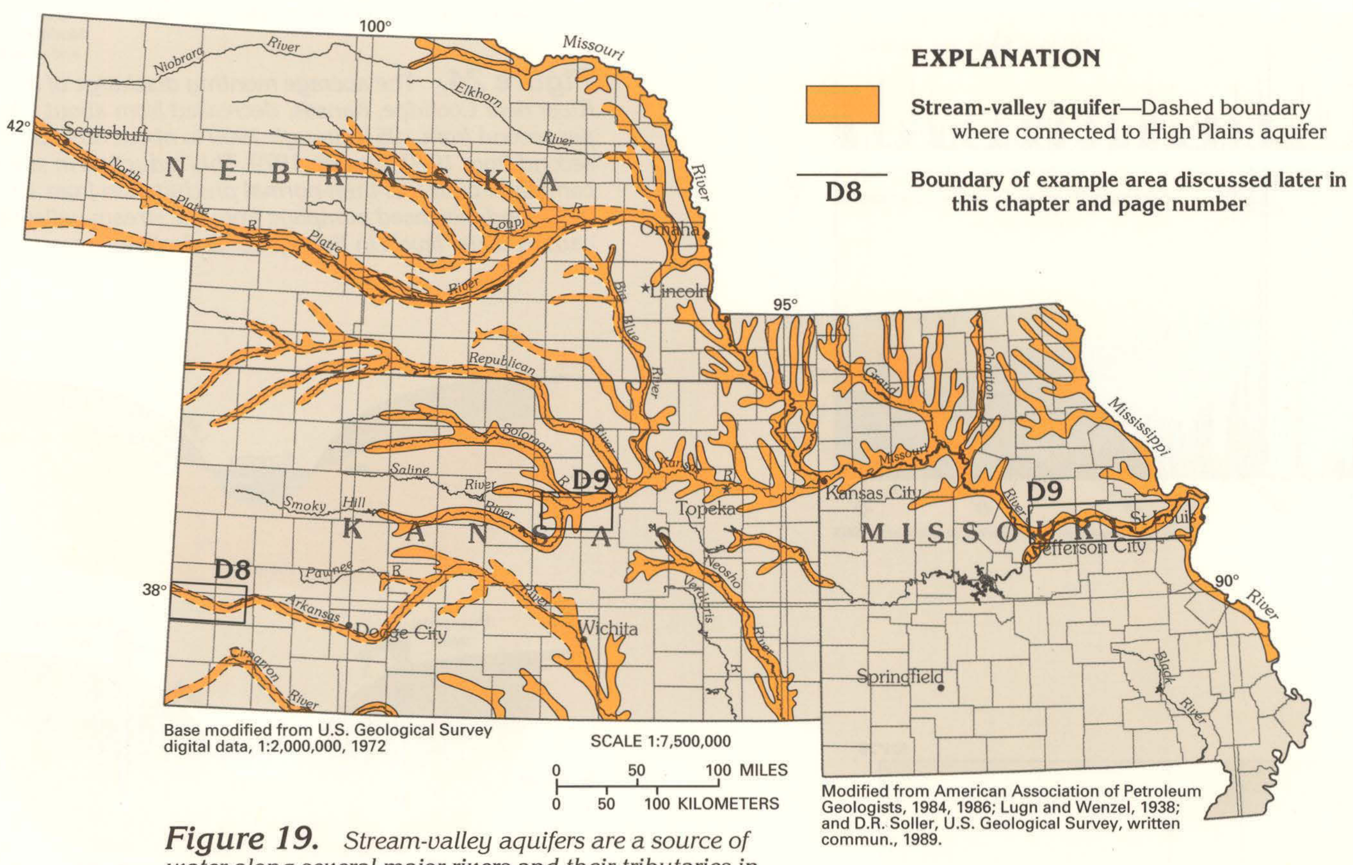


Figure 19. Stream-valley aquifers are a source of water along several major rivers and their tributaries in Segment 3. The dashed lines show where these aquifers are hydraulically connected to the underlying High Plain aquifer.

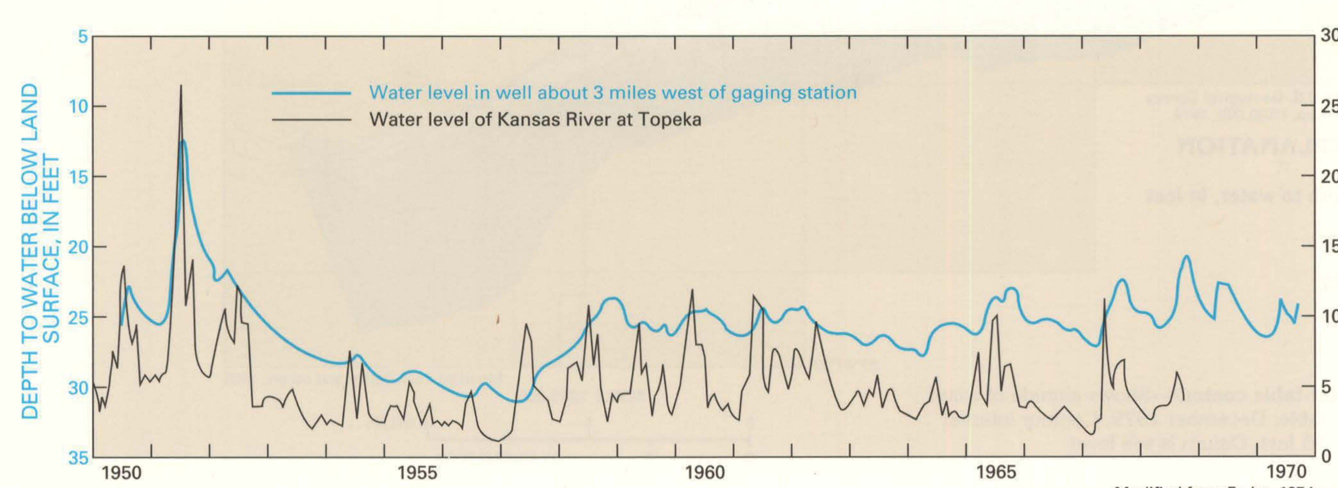


Figure 20. The water level in a well completed in the stream valley aquifer near Topeka, Kansas, rises and falls in response to rises and falls in the level of the nearby Kansas River. Water levels in the aquifer and the stream rise after periods of heavy rainfall.

STREAM-VALLEY AQUIFERS—Continued

Recharge to a typical stream-valley aquifer is by precipitation that falls directly on the aquifer, seepage through the beds of streams and of reservoirs and canals constructed in the stream valleys, downward percolation of applied irrigation water (**fig. 21**), and ground-water inflow from underlying, permeable bedrock. The aquifer discharges by leakage to streams and canals, pumpage from wells, and evapotranspiration (evaporation plus transpiration by plants, especially crops during the growing season). A small amount of water is consumed by crops. Along reaches of some streams, such as the Arkansas, the Smoky Hill, and the Solomon, some of the water potentially available to recharge the aquifer from the stream is diverted by networks of canals and irrigation ditches, from which evaporation occurs. Such diversions, coupled with intense irrigation pumpage from the aquifer and a resulting decrease in base flow to the stream, have severely reduced streamflow. In some cases, streams that were formerly perennial are now dry most of the year.

The stream-valley aquifers are reliable sources of ground water because of the coarse-grained nature and high permeability of the aquifer material. Yields that range from 100 to 1,000 gallons per minute commonly are reported for wells completed in these aquifers; maximum yields of more than 1,500 to 2,500 gallons per minute are reported locally in Nebraska and Missouri, respectively, and yields of as much as 3,000 gallons per minute are reported from stream-valley aquifers in Kansas. Reported transmissivity values for these aquifers, as calculated from aquifer tests, range from 8,000 to 80,000 square feet per day.

The chemical quality of the water in the stream-valley aquifers generally is suitable for most uses. Typically, the water is hard and a calcium bicarbonate type. Dissolved-solids concentrations generally are less than 500 milligrams per liter but locally are as much as 7,000 milligrams per liter; the larger concentrations reflect an influx of water with large chloride or sulfate concentrations from underlying aquifers or from irrigation return flow. Large iron concentrations are common.

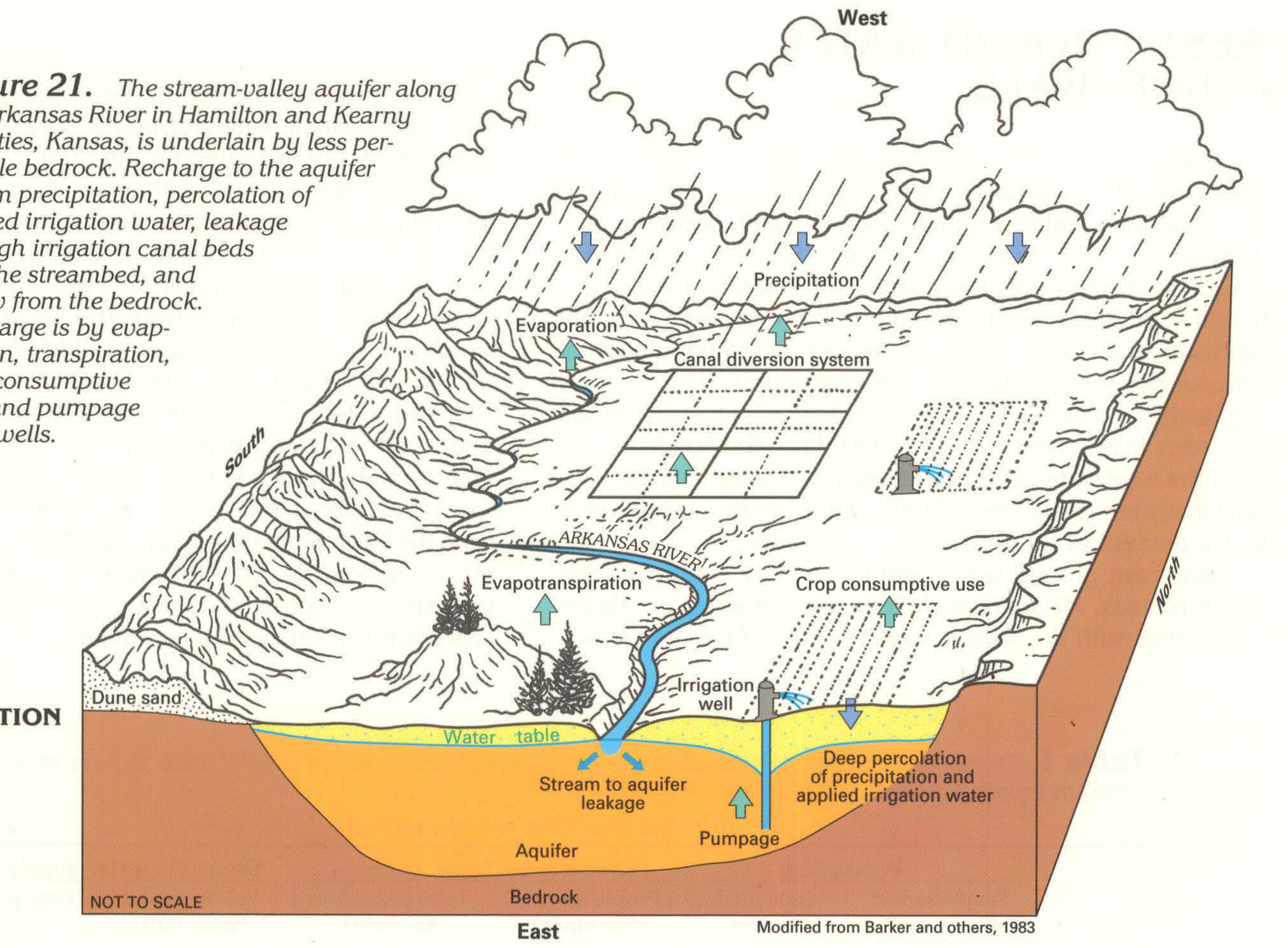


Figure 21. The stream-valley aquifer along the Arkansas River in Hamilton and Kearny Counties, Kansas, is underlain by less permeable bedrock. Recharge to the aquifer is from precipitation, percolation of applied irrigation water, leakage through irrigation canal beds and the streambed, and inflow from the bedrock. Discharge is by evaporation, transpiration, crop consumptive use, and pumpage from wells.

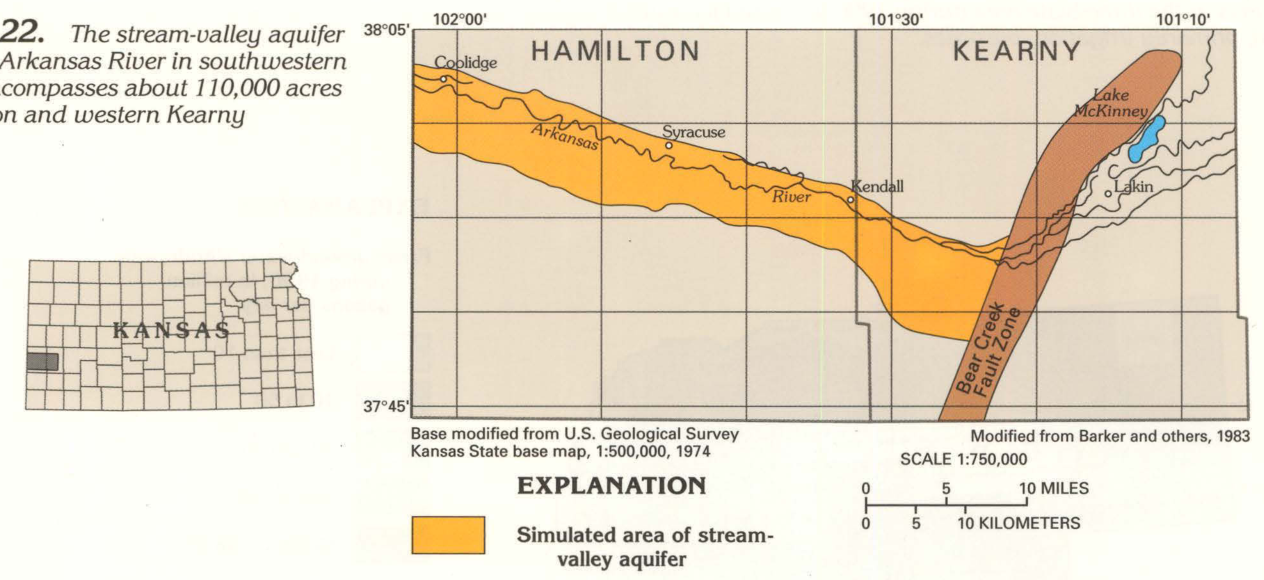


Figure 22. The stream-valley aquifer along the Arkansas River in southwestern Kansas encompasses about 110,000 acres in Hamilton and western Kearny Counties.

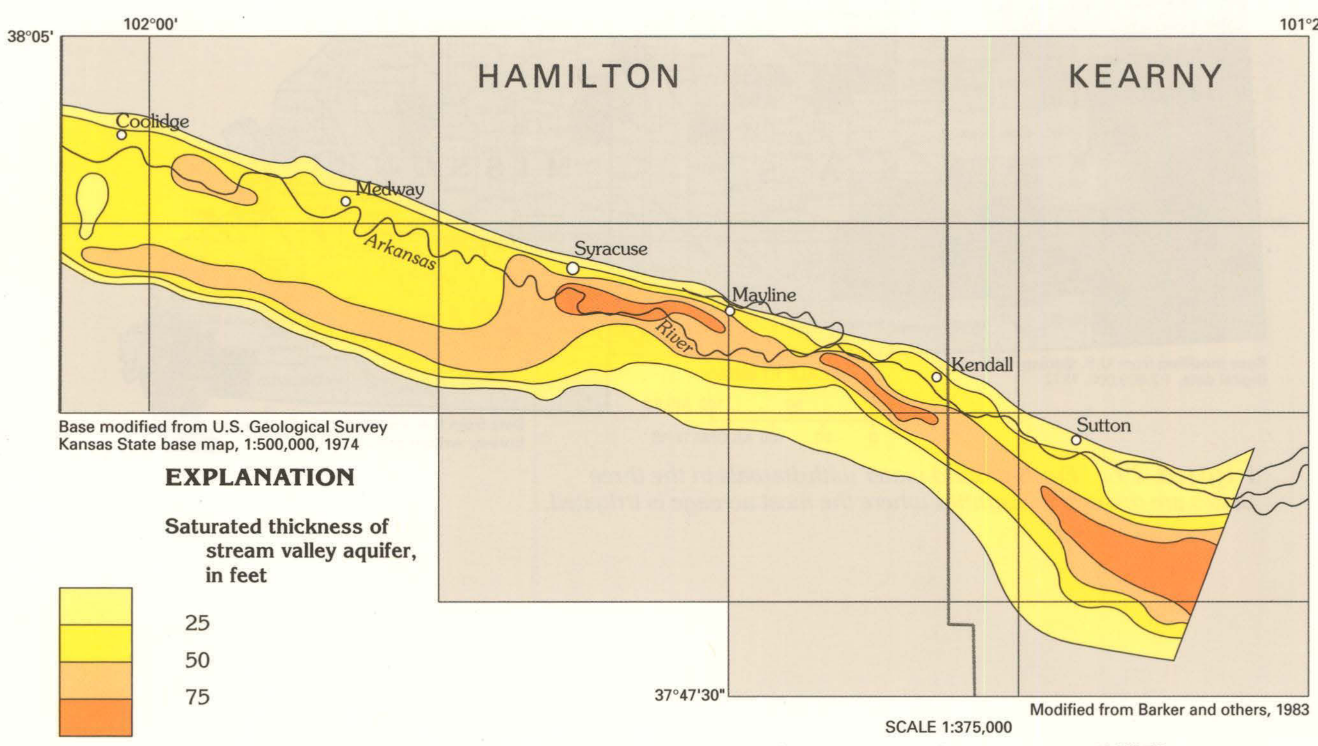


Figure 23. The saturated thickness of the stream-valley aquifer ranged from 0 feet along the edges of the stream valley to more than 75 feet near the center of the valley in 1979. Well yields are greatest where the saturated thickness is greatest.

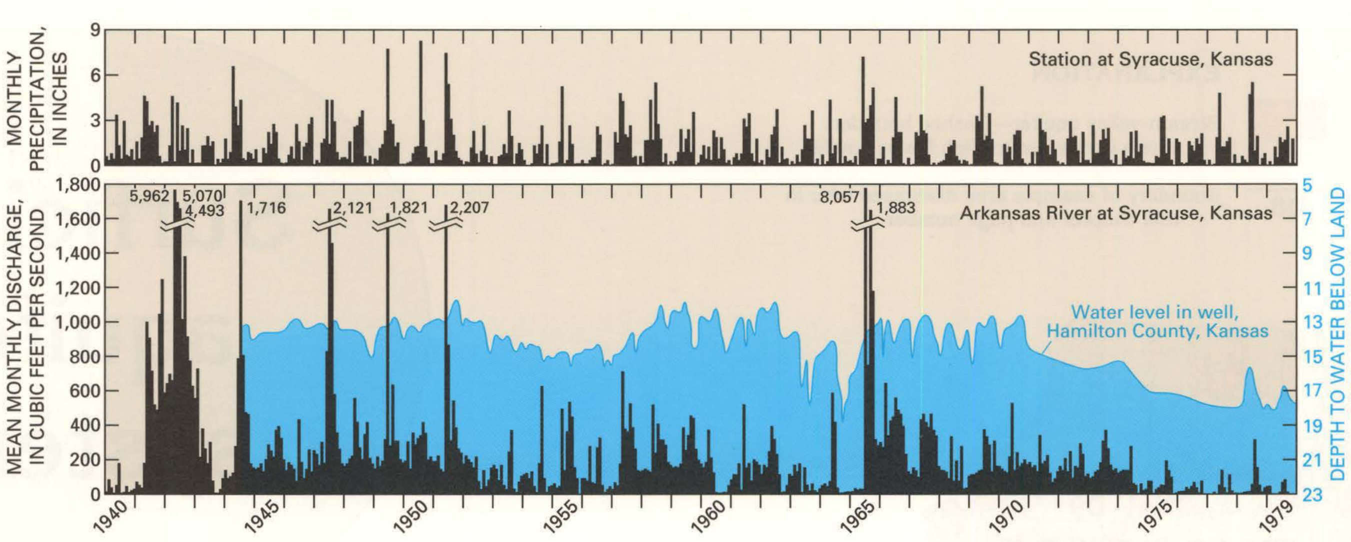


Figure 25. Water levels in wells completed in the stream-valley aquifer declined during the 1970's in response to decreases in precipitation and in the discharge of the Arkansas River from Colorado and an increase in ground-water withdrawals.

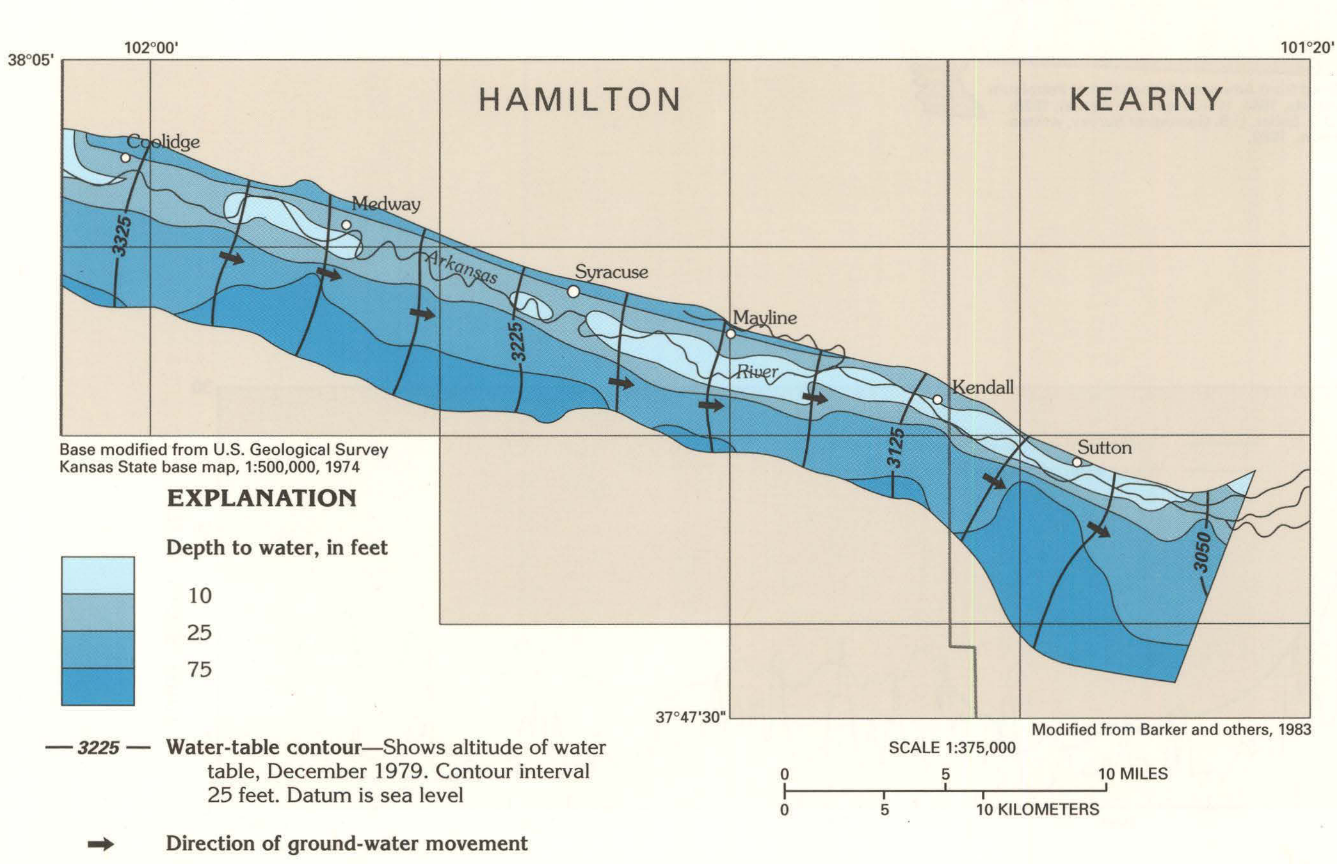


Figure 26. Ground-water movement in the stream-valley aquifer parallels the direction of streamflow. The depth to the water table of the aquifer ranges from 0 feet at the river edge to more than 75 feet near the southern boundary of the stream valley.

Arkansas River Valley, Southwestern Kansas

The stream-valley aquifer that borders the Arkansas River in southwestern Kansas (area **D8** in **fig. 19**) has been studied along a 48-mile reach of the river between the Colorado-Kansas State line and a geologic structure called the Bear Creek Fault Zone (**fig. 22**). This zone is thought to have been formed by the collapse of bedrock following dissolution of underlying salt beds. East of this zone the stream-valley aquifer is hydraulically connected to the High Plains aquifer and is, therefore, considered to be part of it. The stream-valley aquifer shown in **figure 22** primarily comprises alluvial sand and gravel that fill a valley which is as much as 5 miles wide and has been eroded into poorly permeable Cretaceous bedrock. The sand and gravel range in thickness from 0 to 125 feet and generally are thickest near the center of the valley; however, the saturated thickness of this permeable material is less than 75 feet except in small areas (**fig. 23**). Well yields are directly proportional to saturated thickness. Where the saturated thickness is 25 feet or less, well yields are between 100 and 500 gallons per minute, but where saturated thickness is 75 feet or more, yields that range from 1,000 to 3,000 gallons per minute have been reported.

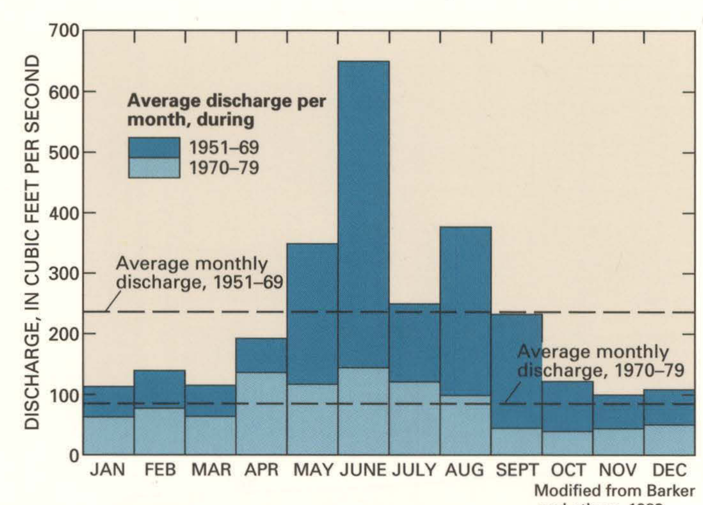


Figure 24. The average monthly discharge of the Arkansas River near Coolidge, Kansas, decreased from about 230 cubic feet per second from 1951 through 1969 to about 85 cubic feet per second from 1970 through 1979. This reduction in streamflow, combined with less-than-normal precipitation from 1970 through 1979, and increased pumpage from the stream-valley aquifer caused water levels in the aquifer to decline.

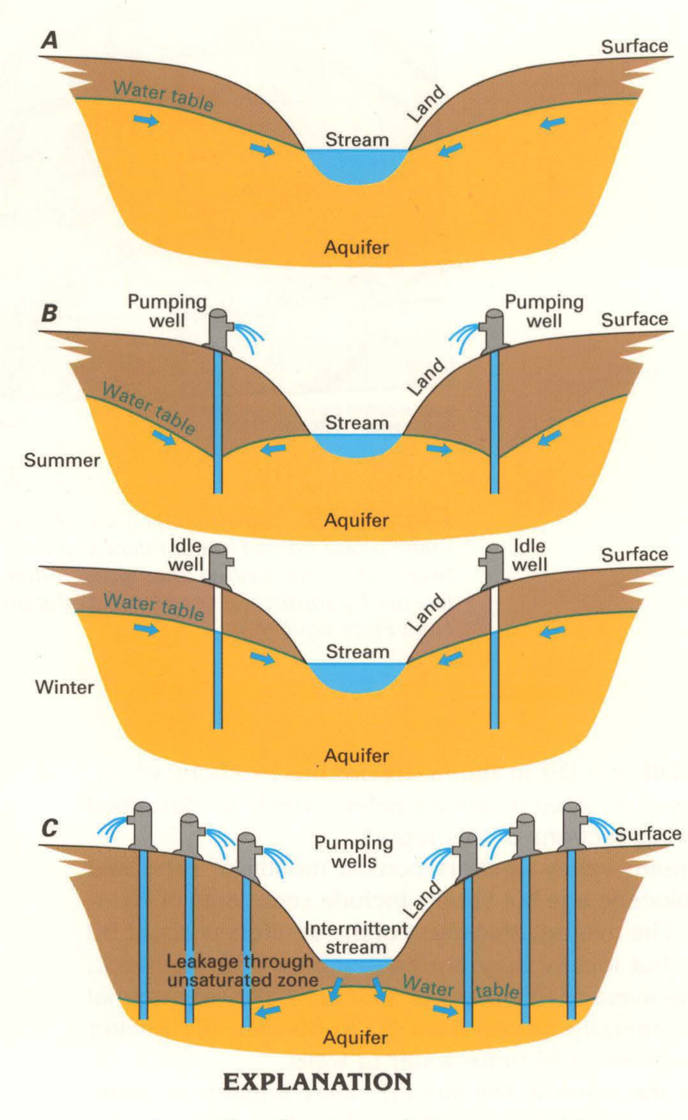


*Figure 27. Before pumping began (**A**), water moved to the stream from the stream-valley aquifer. Withdrawals for irrigation lower the aquifer's water table in the summer growing season (**B**) and reverse this movement; in winter, the water table rises. Increased withdrawals may lower the regional water table below stream level (**C**), the stream contains water only after rainfall events, and pumping might capture most or all of the streamflow.*

The Arkansas River and the stream-valley aquifer are hydraulically connected and water moves freely from the aquifer into the stream or from the stream into the aquifer, depending upon the relative position of the water levels in the stream and aquifer. The flow of the Arkansas River is impounded by the John Martin Reservoir in Colorado, about 50 miles upstream from the Colorado-Kansas State line, and water is released from the reservoir during the growing season to supply downstream irrigation ditches and canals. Beginning about 1970, the flow of the river was insufficient to meet irrigation needs near the river in southwestern Kansas (**fig. 24**), partly because of increased diversions upstream. The river was a perennial stream throughout the studied 48-mile reach until 1975 but was dry most of the year east of (downstream from) Kendall from 1975 through 1980. Accordingly, farmers who used ditch irrigation changed from surface water to ground water as a source of irrigation supply; this change, coupled with increased development, caused withdrawals from the stream-valley aquifer to more than triple between 1970, when about 20,000 acre-feet per year was pumped, and 1979, when withdrawals were about 65,000 acre-feet per year. (One acre-foot is the volume of water that will cover 1 acre of land to a depth of 1 foot, or about 43,560 cubic feet of water.) The combination of decreased streamflow from Colorado, less-than-normal precipitation, and increased pumpage caused water levels in the aquifer to decline 4 feet in the western part of Hamilton County (**fig. 25**) and more than 25 feet in Kearny County.

Water in the stream-valley aquifer moves from west to east (**fig. 26**) and follows the eastward slope of the topography of the valley floor. Movement of the water in the aquifer is nearly parallel to streamflow. In places, the altitude of the water table is below the altitude of the stream, and the contours show a slight "v" that points in a downstream direction (for example, the area near Medway). In other places, the contours "v" slightly upstream (for example, near Mayline), which indicates the aquifer is discharging to the stream. The lack of sharp, well-defined "v" points on the contours indicates good hydraulic connection between the stream and the aquifer. The depth to the water table also is shown in **figure 26**. The water table is nearest to land surface near the river and is deepest near the edge of the valley.

Water levels in the stream-valley aquifer and in the streams to which it is connected vary seasonally in response to pumping from the aquifer. The effects of pumping are summarized in **figure 27**. Before withdrawals began, the water table in the aquifer was above the water level in the stream, and the aquifer discharged to the stream as shown in **figure 27A**. Wells installed to provide irrigation supplies can greatly lower the water table in the aquifer, especially during the summer, when crop growth rate is highest and water demands are greatest. At such times, ground-water movement can be reversed from that before pumping began (**fig. 27B**), and water can move from the stream to recharge the aquifer. When irrigation pumping ceases during the winter months, movement of water from the aquifer to the stream is reestablished; however, water levels may not recover fully to those before pumping began. If pumping is greatly increased (**fig. 27C**), however, then the regional water table may decline to a level below the streambed; the stream will flow only after periods of heavy rainfall and will lose water to the aquifer during all seasons. This condition exists along some reaches of the Arkansas River in Kansas.

The hydrographs in **figure 28** show the response of the water level in a well 100 feet from the Arkansas River near Kendall to changes in the river stage. From 1979 through 1981, the water level in the aquifer near the river was generally below or at the same level as the river stage. Thus, the river is a losing stream here and contributes water to the aquifer. The hydrograph shows that the river ceased to flow for several months in late 1979; thus, the aquifer received no recharge from the stream.

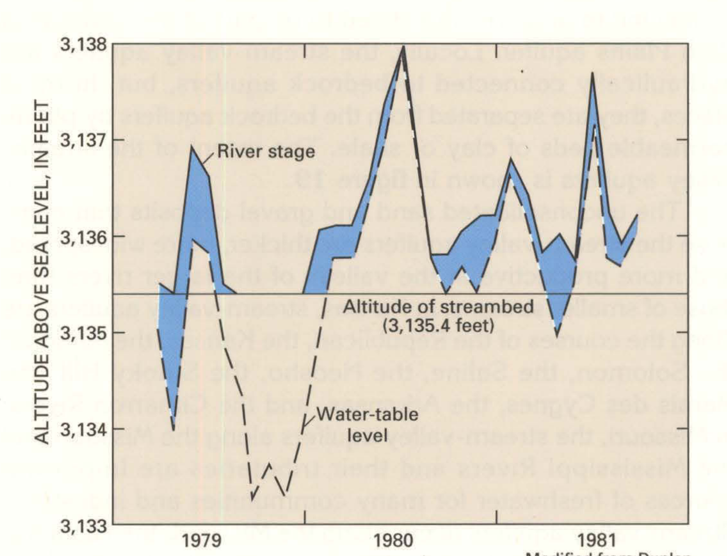


Figure 28. During periods of low river stage, the Arkansas River near Kendall, Kansas loses water by seepage to the stream-valley aquifer, as shown by the blue area.

Smoky Hill, Saline, and Solomon River Valleys, Central Kansas

The stream-valley aquifer along parts of the Smoky Hill, the Saline, and the Solomon Rivers (area **D9** in **fig. 19**) ranges in width from about 3 to 5 miles (**fig. 29**). The lower two-thirds of the aquifer generally consists of coarse-grained alluvial deposits, whereas the upper third is finer grained material. The uplands adjacent to the rivers are underlain by sandstone, shale, and limestone of Cretaceous to Permian age (**fig. 29**), all of which are less permeable than the alluvium. Locally, the stream-valley alluvium is bordered by Quaternary dune sands and poorly sorted terrace deposits that are mostly unsaturated and not part of the stream-valley aquifer. Shale beds underlie the stream-valley aquifer and form a confining unit that separates the aquifer from permeable beds in the Hutchinson Salt Member of the Wellington Formation of Permian age.

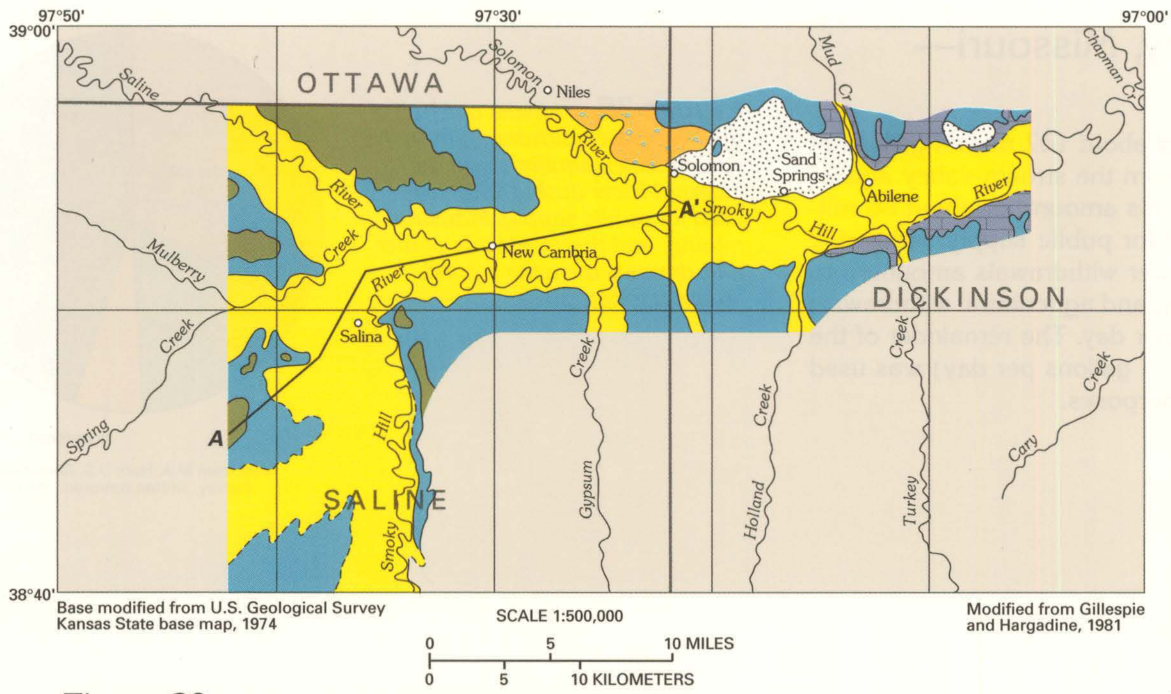
Wells completed in the coarse-grained, lower part of the stream-valley aquifer commonly yield from 200 to 900 gallons per minute. Transmissivity values determined from aquifer tests in this part of the alluvium range from 8,000 to 13,000 feet squared per day. The water in the aquifer generally is unconfined. The stream-valley aquifer is in direct hydraulic contact with the three rivers and discharges water to them.

The stream-valley aquifer mostly contains freshwater in its upper 35 to 50 feet in the area shown in **figure 29**. Below the freshwater from Salina eastward, the aquifer contains saline water, some of which discharges to some reaches of the rivers. During a period of stable base flow in 1976–77, the chloride concentration in water from the Smoky Hill River increased about 800 milligrams per liter in the reach of the river between New Cambria and Sand Springs. In the same period, an increase in chloride concentration of about 550 milligrams per liter was observed in water from the Solomon River in the reach between Niles and Solomon. Chloride concentrations as large as 73,000 milligrams per liter have been reported in water from the lower part of the stream-valley aquifer. Withdrawals from the aquifer in this part of central Kansas are small because of the poor quality of the water.

The source of the saline water and brine in the stream-valley aquifer is the Hutchinson Salt Member of the Wellington Formation (**fig. 30**). Fresh ground water from the alluvial aquifer has circulated downward and dissolved some of the salt and evaporite beds in the Hutchinson Salt Member and the unnamed lower member of the Wellington Formation. Where this dissolution locally has increased the porosity and permeability of the Wellington, the formation is called the Wellington aquifer. Collapse structures have formed in the shale confining unit that separates the Wellington and the stream-valley aquifers and allow brine to move upward from the Wellington aquifer (**fig. 30**) to the stream-valley aquifer. The brine is diluted as it mixes with freshwater and moves through the stream-valley aquifer to discharge into the Smoky Hill and the Solomon Rivers.

Water in the stream-valley and the Wellington aquifers generally moves from west to east, parallel to the direction of flow of the Smoky Hill, the Solomon, and the Saline Rivers (**fig. 31**). From Salina westward, the water table in the stream-valley aquifer is higher than the potentiometric surface of the Wellington aquifer, which indicates that water moves downward from the alluvial material into the Wellington aquifer. As the water moves eastward through the Wellington aquifer, it partially dissolves rock salt and evaporite minerals in the Wellington Formation; as a result, the chloride and the dissolved-solids concentrations in the water increase. East of the confluence of the Saline River and Mulberry Creek, the potentiometric surface of the Wellington aquifer is higher than the water table in the stream-valley aquifer, and the poor-quality water moves upward into the stream-valley aquifer. This water subsequently discharges into the Smoky Hill and the Solomon Rivers as base flow. During periods of low rainfall, when most of the flow in these rivers is derived from ground-water discharge, the water in the rivers is unusable. Concentrations of chloride and dissolved solids in the river water decrease as rainfall increases and the water is diluted by surface runoff.

Saline springs and seeps occur to the south in Oklahoma and Texas where circulating ground water brings to the surface saline water derived from the partial dissolution of salt beds in the manner described above. The saline water there contains tritium, a radioactive isotope of hydrogen that originates chiefly as a product of hydrogen bomb explosions. The concentrations of tritium in water from the salt springs and seeps show that the saline water has moved from recharge to discharge areas in less than 40 years. Ground-water circulation in the Smoky Hill-Solomon-Saline River Valley area may be equally rapid.



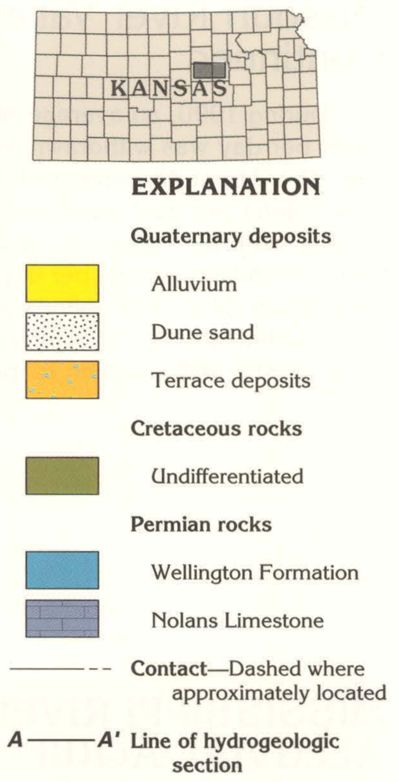


Figure 29. *The stream-valley aquifer along the Smoky Hill, the Saline, and the Solomon Rivers in central Kansas consists of Quaternary alluvium that is confined to channels that have been eroded into bedrock of Cretaceous and Permian age. Local terrace and dune-sand deposits are not part of the aquifer.*

Figure 30. *A generalized hydrogeologic section shows that the shale confining unit that separates the Wellington and stream-valley aquifers has collapsed in places where circulating freshwater has partially dissolved rock salt and evaporites from the Hutchinson Salt Member of the Wellington Formation. The water transports the dissolved minerals upward through the stream-valley aquifer and into the streams. The line of the section is shown in figure 29.*

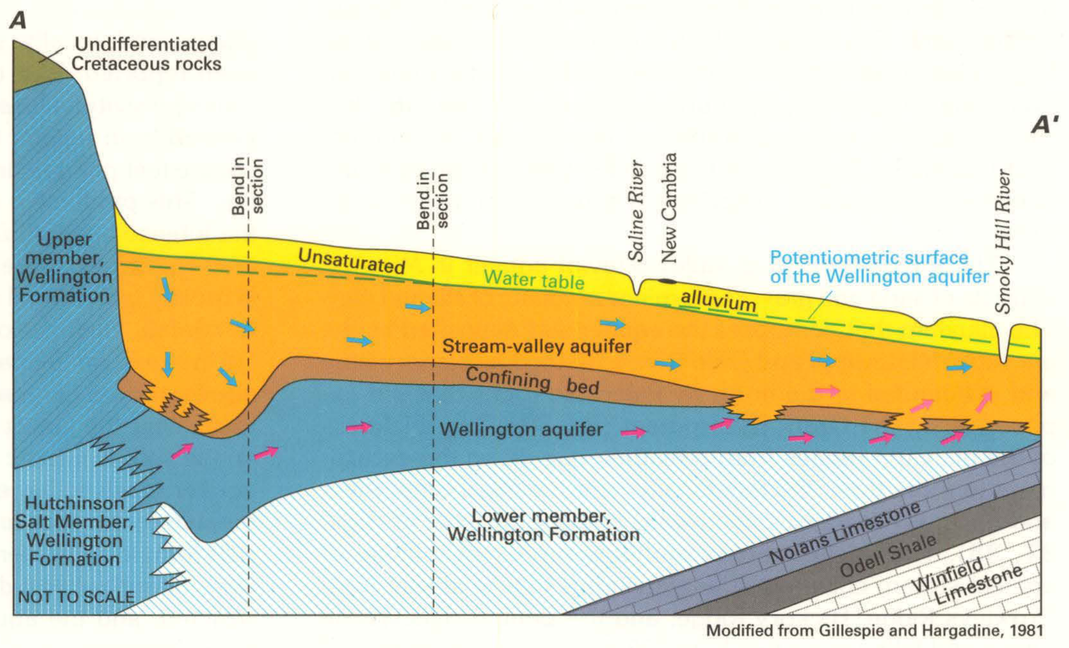
EXPLANATION

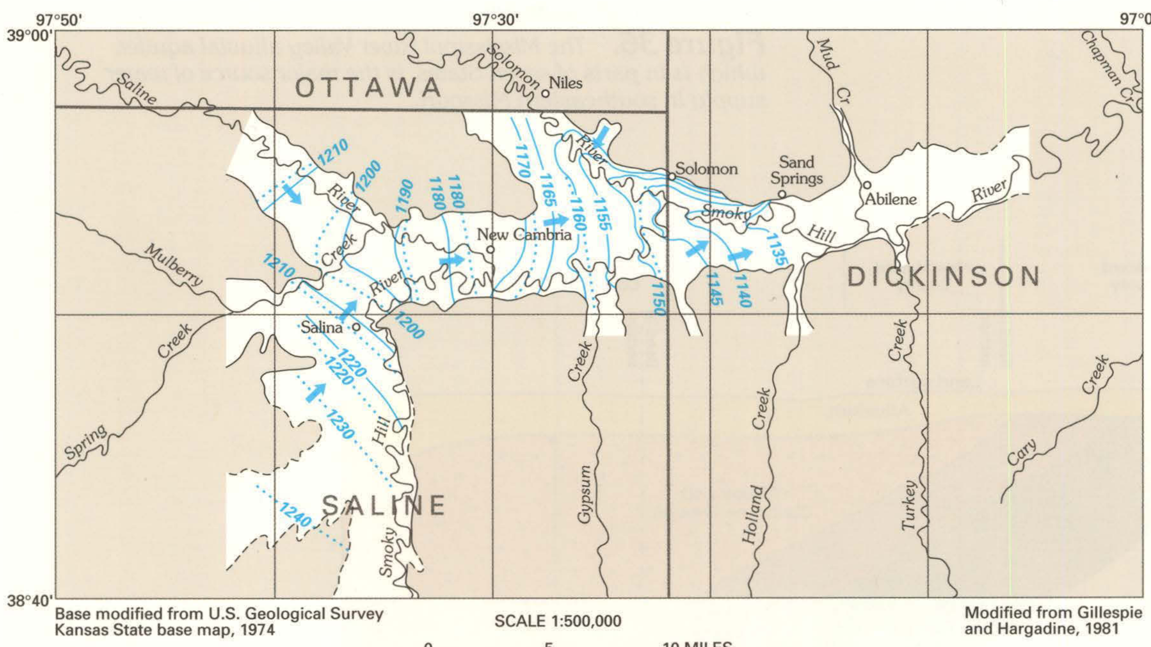
Direction of flow

Freshwater

Saline water

Brine





EXPLANATION

—1200— **Water-table contour**—Shows altitude of water table in stream-valley aquifer, April, 1977. Dashed where approximately located. Contour interval 5 and 10 feet. Datum is sea level

····1200···· **Potentiometric contour**—Shows altitude at which water would have stood in tightly cased wells in the Wellington aquifer, April 1977. Contour interval 10 feet. Datum is sea level

Direction of ground-water movement

Figure 31. *Ground water in the Wellington and the stream-valley aquifers moves eastward. West of the junction of the Saline River and Mulberry Creek, water moves downward into the Wellington aquifer from the stream-valley aquifer; east of this area, the direction of vertical movement is reversed.*

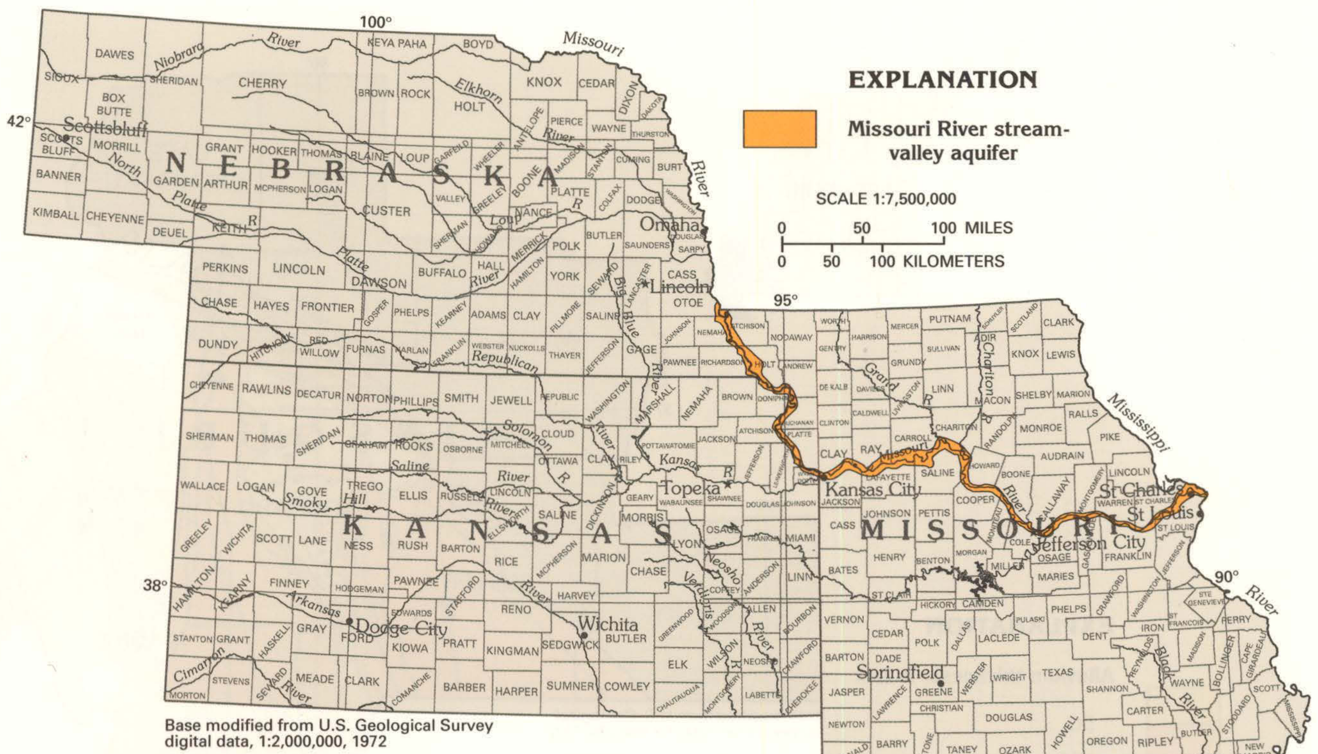


Figure 32. *The stream-valley aquifer along the Missouri River is an important source of water for industries and several cities in northwestern and central Missouri.*

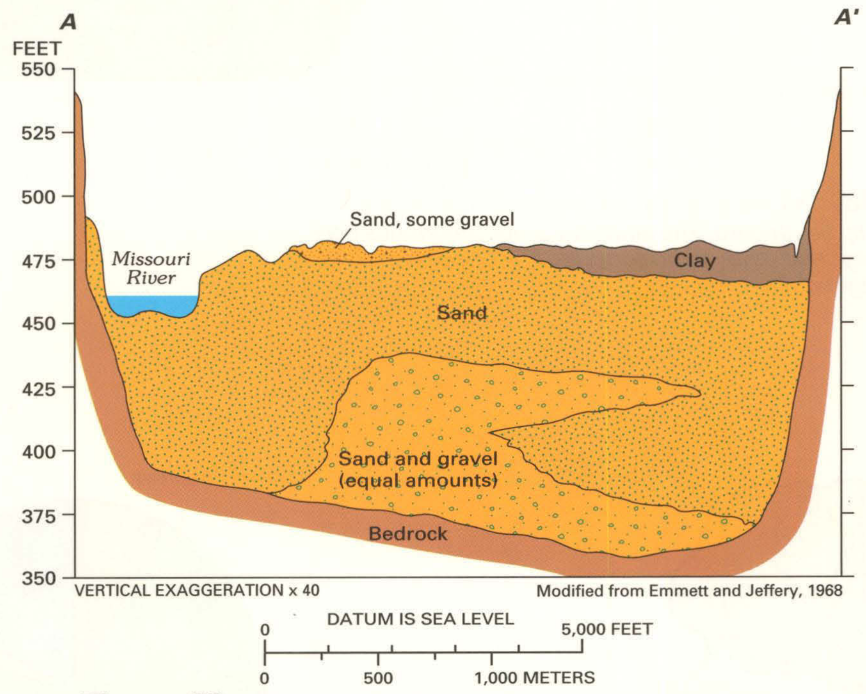


Figure 33. *The stream-valley aquifer consists of coarse-grained alluvium in the lower part, overlain by finer grained sediments that locally are confining units. The aquifer partially fills a channel that has been incised into bedrock and averages about 90 feet in thickness. The line of the hydrogeologic section is shown in figure 34.*

Missouri River Valley, Missouri

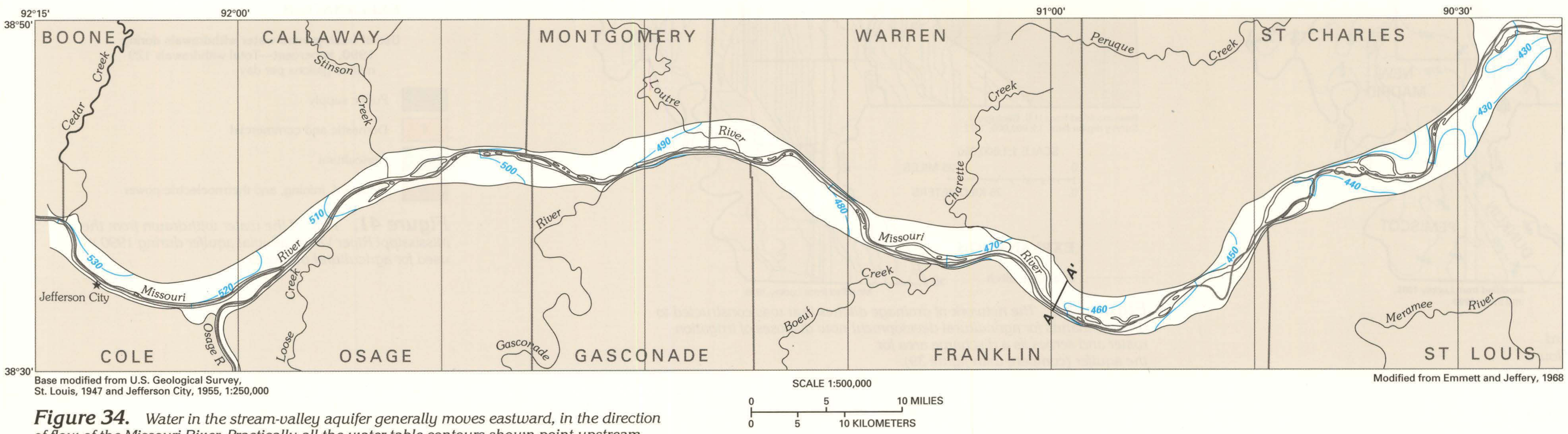
Alluvial deposits along the Missouri River form an important stream-valley aquifer from the Iowa-Missouri State line to the junction of the Missouri and the Mississippi Rivers (**fig. 32**); small areas of similar deposits in eastern Nebraska compose local aquifers. The deposits partly fill an entrenched bedrock valley that ranges from about 2 to 10 miles wide. In many places in northern Missouri, the bedrock contains slightly saline to saline water, and the stream-valley aquifers, along with aquifers in glacial drift, are the only sources of fresh ground water. The part of the stream-valley aquifer along the Missouri River between St. Charles and Jefferson City, Missouri (area **D9** in **fig. 19**) is described below.

The stream-valley aquifer consists of clay, silt, sand, and gravel. Gravel and sand generally are most common in the lower parts of the aquifer (**fig. 33**). Poorly permeable silt and clay are prominent in the upper part of the aquifer and locally create confined conditions. Sandstone, limestone, dolomite, and shale of Pennsylvanian and Mississippian age mostly compose the bedrock that underlies the stream-valley aquifer in western Missouri. From the Howard–Boone County line eastward, the bedrock consists of Ordovician limestone and dolomite. In upland areas, glacial deposits overlie the bedrock and locally are hydraulically connected to the stream-valley aquifer.

The alluvial material of the stream-valley aquifer averages about 90 feet in thickness but is locally as much as 160 feet thick. The saturated thickness of the aquifer averages about 80 feet. Reported yields of wells completed in the aquifer range from less than 100 to about 3,000 gallons per minute.

Recharge to the stream-valley aquifer is by infiltration of precipitation, seepage of water from the Missouri River to the aquifer during periods of high streamflow, and inflow from bedrock aquifers. Discharge from the aquifer is by evapotranspiration, withdrawals by wells, and seepage to the Missouri River during periods of low streamflow. The general direction of water movement in the stream-valley aquifer is downstream and toward the river (**fig. 34**).

Water in the stream-valley aquifer is a calcium bicarbonate type and is characterized by excessive iron content and hardness; in many places, the water is softened before use. Dissolved-solids concentrations in water from the aquifer range from about 250 to 1,500 milligrams per liter and are largest in areas where saline water leaks upward from bedrock and is diluted by mixing with freshwater.



EXPLANATION

Limit of stream-valley aquifer

—430— **Water-table contour**—Shows altitude of water table in stream-valley aquifer, December 1966. Contour interval 10 feet. Datum is sea level

A——A' Line of hydrogeologic section

Figure 34. *Water in the stream-valley aquifer generally moves eastward, in the direction of flow of the Missouri River. Practically all the water-table contours shown point upstream where they cross the river, which indicates that the aquifer is discharging to the river.*

Missouri River Valley, Missouri—Continued

During 1990, an average of about 147 million gallons of water per day was withdrawn from the stream-valley aquifer (**fig. 35**). About 45 percent of this amount, or about 66 million gallons per day, was used for public supply. Industrial, mining, and thermoelectric power withdrawals amounted to about 48 million gallons per day, and agricultural withdrawals were about 24 million gallons per day. The remainder of the water withdrawn (about 9 million gallons per day) was used for domestic and commercial purposes.

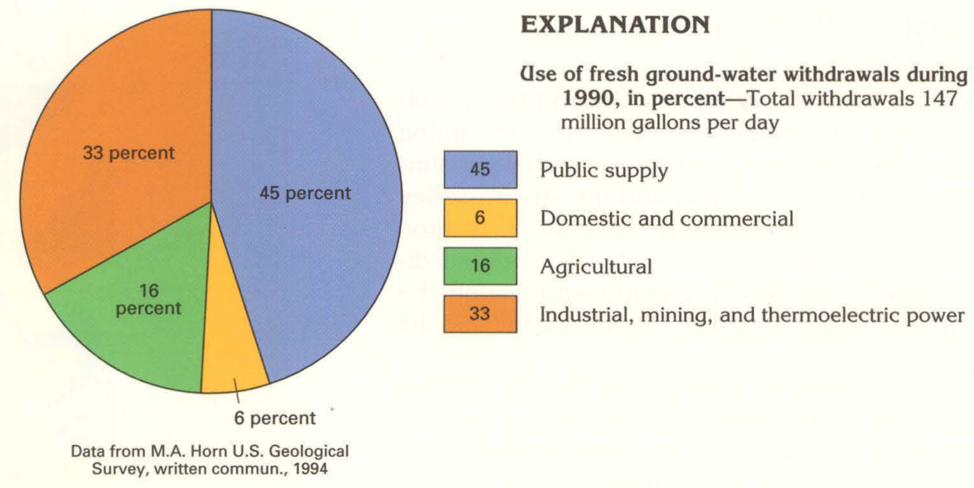


Figure 35. Almost one-half of the freshwater withdrawn from the stream-valley aquifer along the Missouri River during 1990 was used for public supply. Industrial, mining, and thermoelectric power withdrawals were the second largest use category.

MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER

Alluvial material adjacent to the Mississippi River forms an important aquifer in the northern part of the Mississippi Embayment. This aquifer, which is called the Mississippi River Valley alluvial aquifer, is in parts of Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee (**fig. 36**). It is most extensive, and is described in more detail, in Segment 5 of this Atlas. The part of the aquifer that is located in the bootheel of Missouri is the principal source of irrigation water there.

The Mississippi River Valley alluvial aquifer in Missouri consists of sand and gravel with minor amounts of silt and clay. The alluvium that composes the aquifer was deposited by the ancestral Mississippi and Ohio Rivers during Quaternary time and is bounded to the north by Paleozoic rocks that are exposed along the Ozark Escarpment (**fig. 37**). The thickness of the alluvium ranges from a featheredge along the escarpment to more than 250 feet locally near the Mississippi River and generally increases southward and southeastward (**figs. 37, 38**). The thickest areas probably represent infilling of ancient stream channels. The alluvium is thin or absent from Crowleys Ridge, Hickory Ridge, and the Benton Hills. These ridges and hills rise as much as 250 feet above the surface of the surrounding alluvial plain and are underlain by rocks of early Tertiary, Cretaceous, and Paleozoic age.

The coarse-grained sediments of the Mississippi River Valley alluvial aquifer are highly permeable. Wells completed in the aquifer will yield 1,000 gallons per minute in most places, and, locally, yields of 3,000 gallons per minute have been reported. Well depths commonly are 100 feet or less. Transmissivity values for the alluvial aquifer, which were calculated from aquifer test data, range from 15,000 to 54,000 square feet per day and average about 40,000 square feet per day. This productive aquifer is the major source of water for the intense agricultural development in the area.

The water in the Mississippi River Valley alluvial aquifer is mostly unconfined and water levels rise rapidly in response to rainfall. Near major streams, aquifer water levels rise and fall in response to changes in stream water levels. Water in the aquifer moves generally southward from topographically high areas near the Ozark Escarpment (**fig. 39**). Local high areas on the potentiometric surface represent sandy ridges where the aquifer receives larger amounts of recharge. The poorly permeable rocks that underlie Crowleys Ridge and the Benton Hills form local barriers to ground-water flow. An extensive network of agricultural drainage ditches (**fig. 40**) has been constructed, and the aquifer discharges to these ditches and to major streams.

The chemical quality of the water in the Mississippi River Valley alluvial aquifer generally meets the standards recommended for public water supplies by the U.S. Environmental Protection Agency; locally, excessive concentrations of iron and manganese have been reported. Iron concentrations in water from the aquifer locally are as much as 35 milligrams per liter and average about 4.3 milligrams per liter; manganese concentrations locally are as much as 2.0 milligrams per liter and average 0.46 milligram per liter. The water is a calcium-magnesium bicarbonate type, generally hard, and has small dissolved-solids concentrations (averaging 240 milligrams per liter). Locally, the water in the aquifer contains traces of pesticides and nutrients as a result of downward leakance of irrigation water from fields that have been treated with chemicals for insect control or with fertilizer.

Withdrawals of freshwater from the Mississippi River Valley alluvial aquifer totaled 129 million gallons per day during 1990 (**fig. 41**). About 92 million gallons per day was withdrawn for agricultural purposes, which is the principal water use. About 22 million gallons per day was withdrawn for public supply, and about 10 million gallons per day was pumped for industrial, mining, and thermoelectric power uses. Withdrawals for domestic and commercial uses were about 5 million gallons per day.

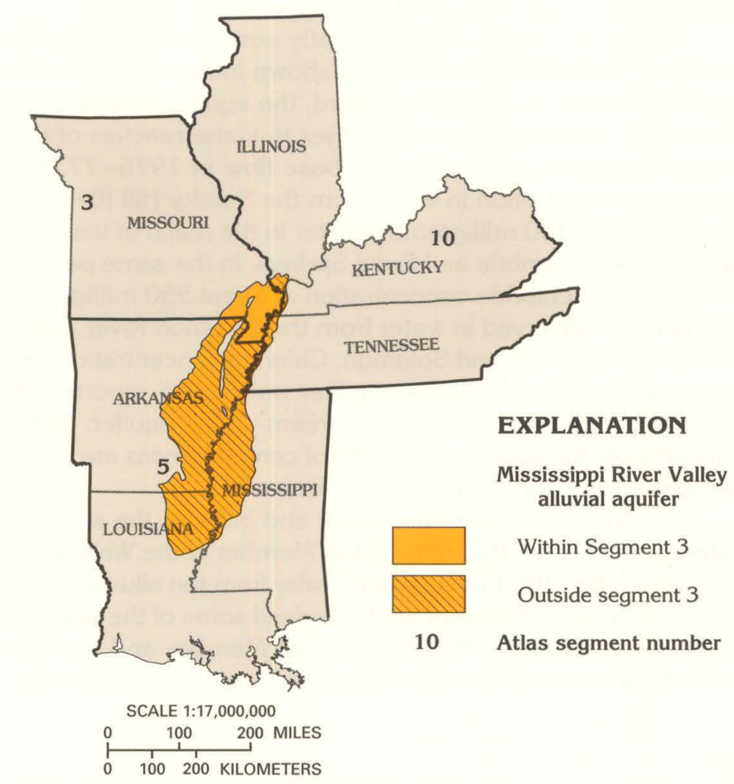


Figure 36. The Mississippi River Valley alluvial aquifer, which is in parts of seven States, is the major source of water supply in southeastern Missouri.

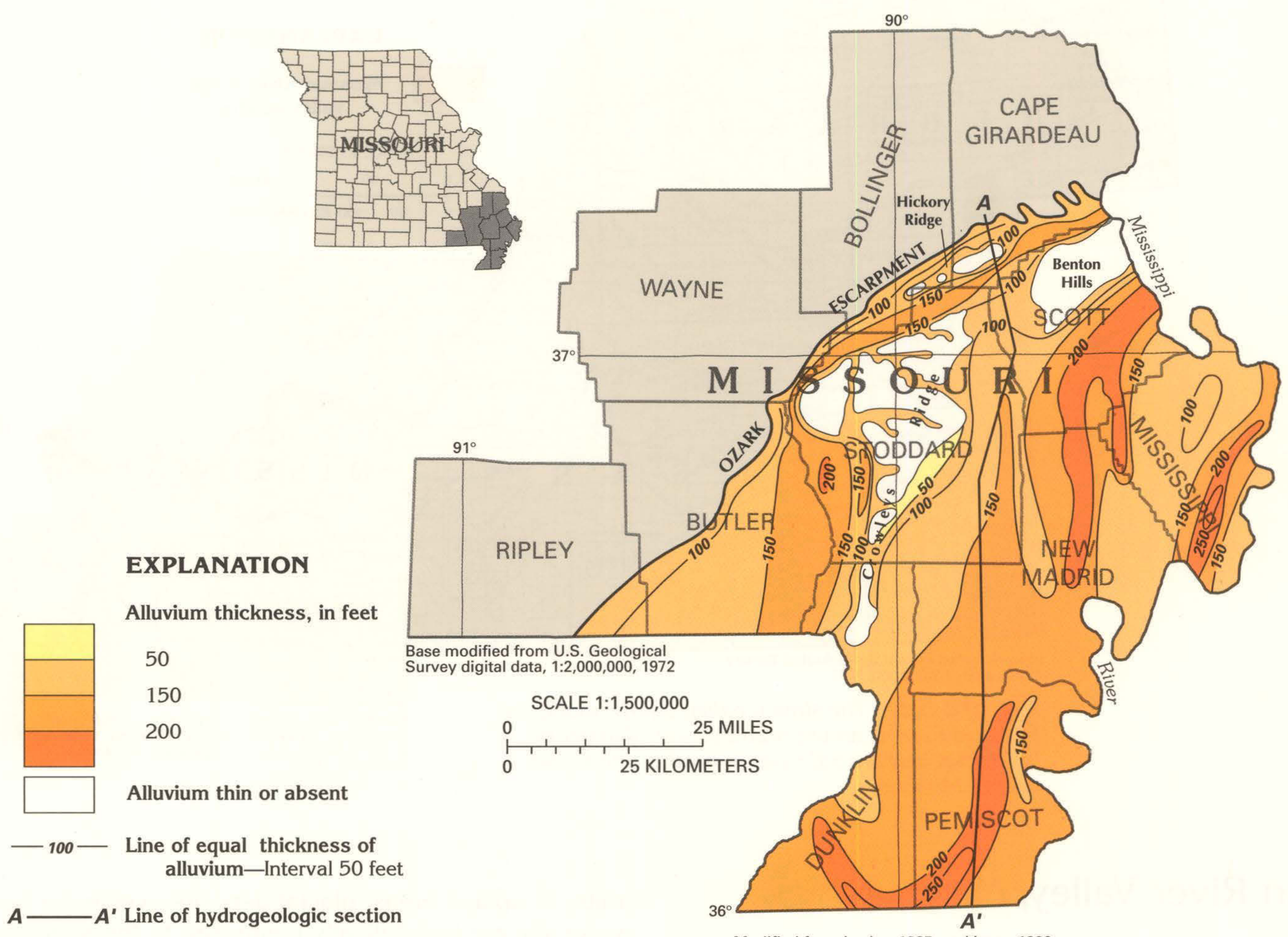


Figure 37. The alluvium that composes the Mississippi River Valley alluvial aquifer thickens southward and southeastward from the Ozark Escarpment. Ridges and hills mark places where older rocks are thinly covered or protrude through the cover of alluvium.

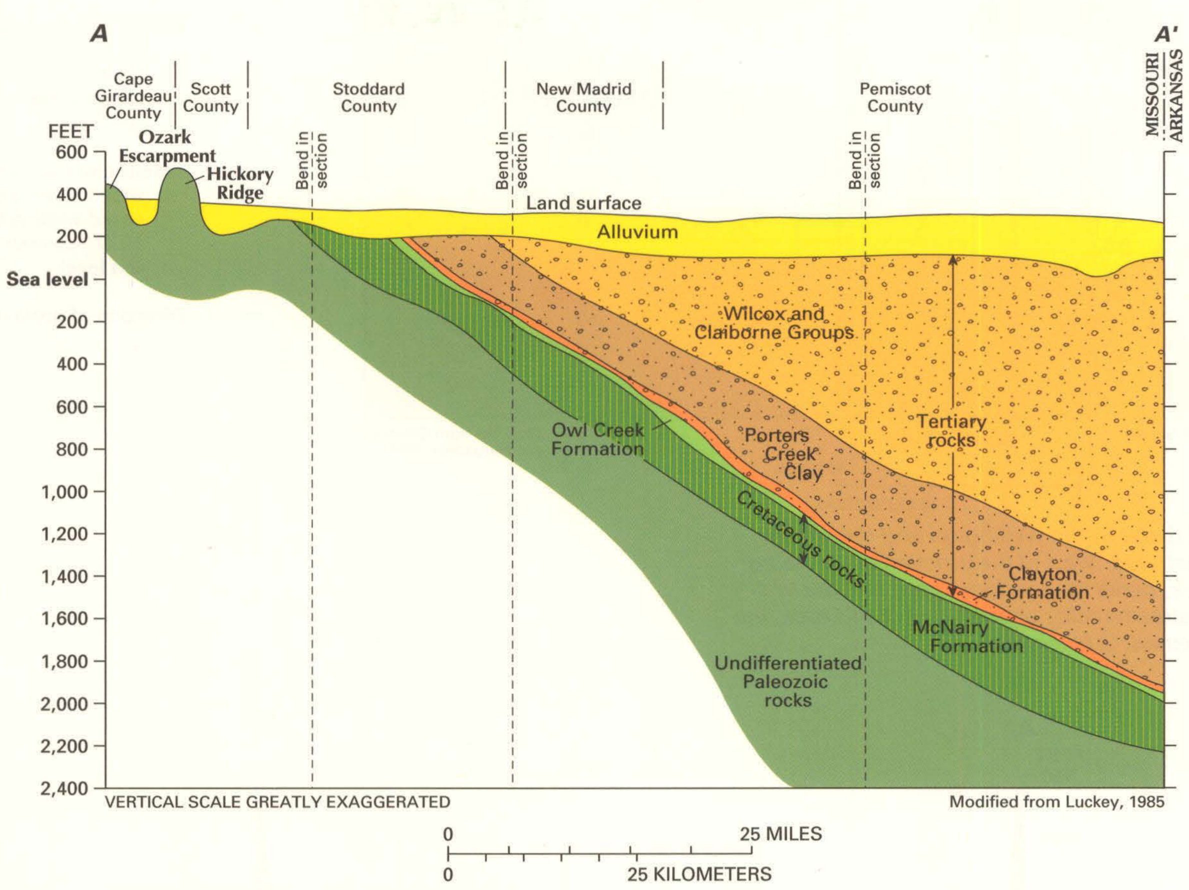


Figure 38. As much as 250 feet of alluvium blankets older rocks that dip southward. The alluvium is not continuous over Hickory Ridge and other bedrock ridges. The line of section is shown on figure 37.

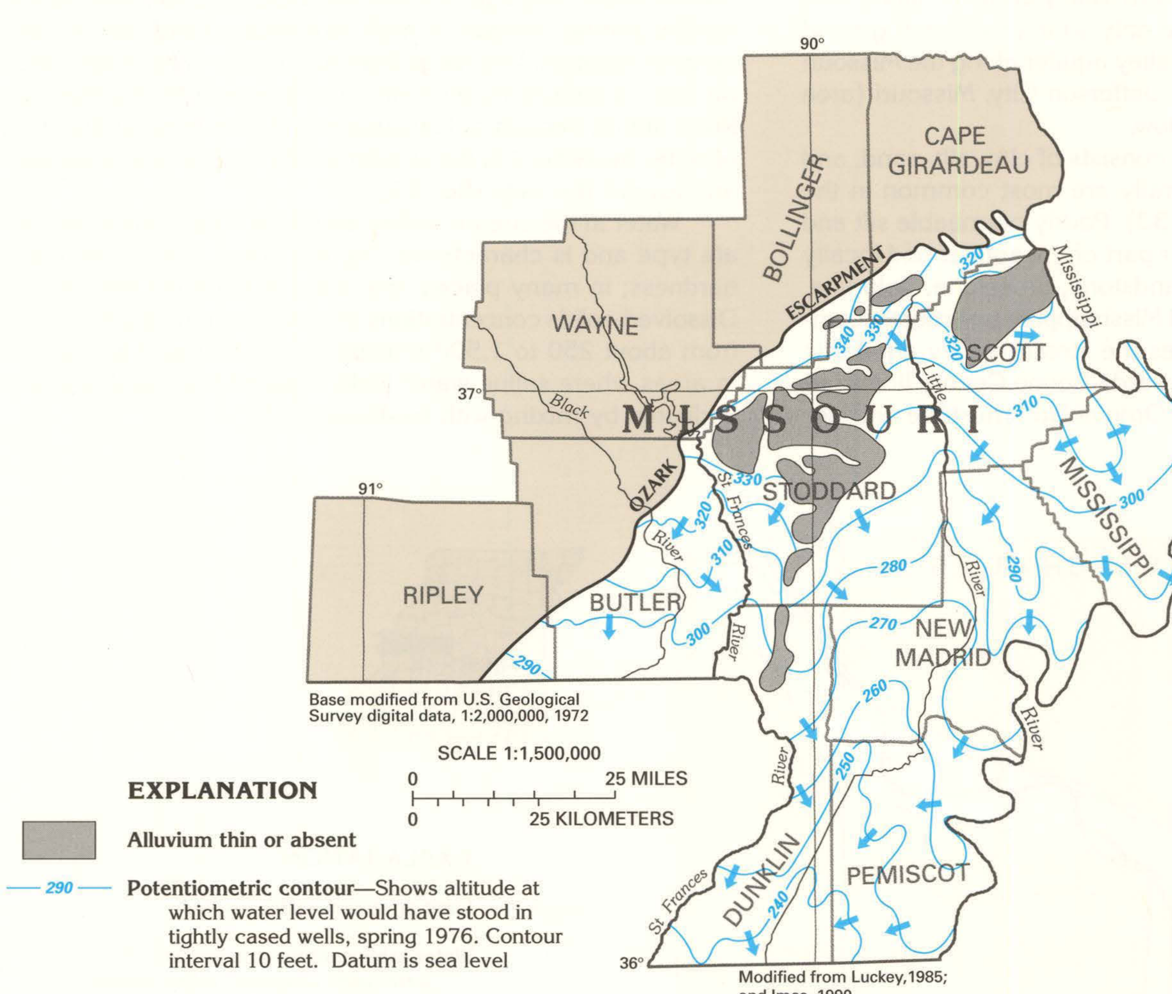


Figure 39. Water in the aquifer moves generally southward from topographically high areas near the Ozark Escarpment. Flow is complex around the poorly permeable rocks of the ridges in the northern part of the area.

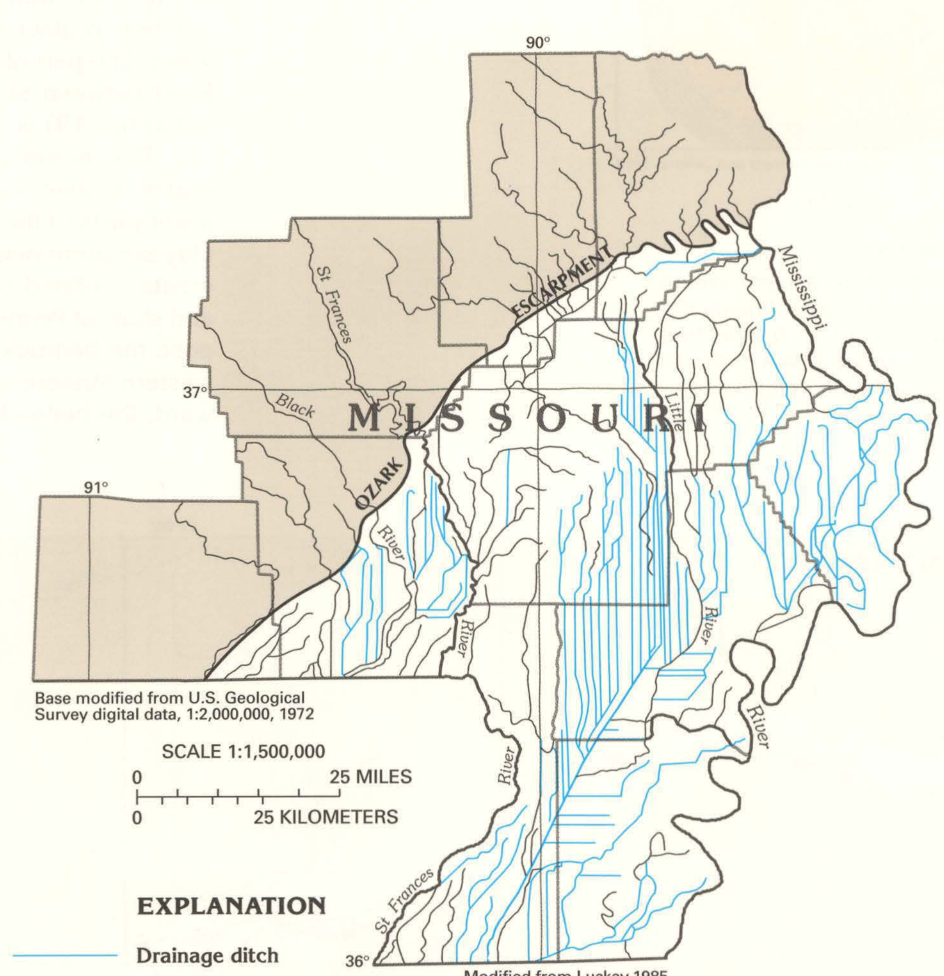


Figure 40. The network of drainage ditches that was constructed to drain wetlands for agricultural development now disposes of irrigation water and serves as a discharge area for the aquifer (compare with figure 39).

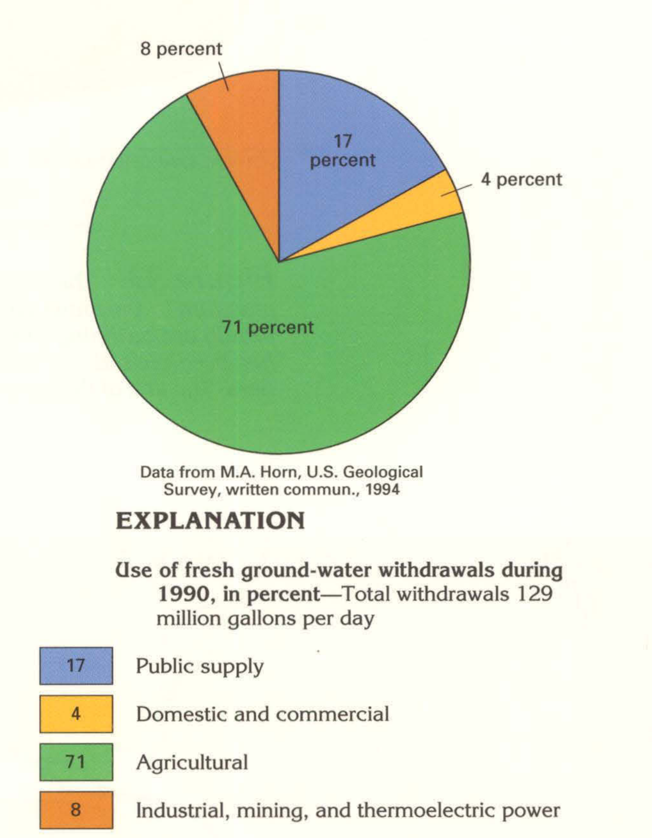


Figure 41. Most of the water withdrawn from the Mississippi River Valley alluvial aquifer during 1990 was used for agricultural purposes.

GLACIAL-DRIFT AQUIFERS

The maximum southern extent of glacial ice and glacial-drift deposits was about the present location of the Missouri River in Missouri and just south of the Kansas River in northeastern Kansas. The glacial deposits in Segment 3 are pre-Illinoian and, thus, are older than deposits in States to the north and east of the segment. Some of the drift in Segment 3 might be of late Pliocene age, whereas most glacial deposits in North America are considered to be Pleistocene. Although deposits of glacial drift extend over wide areas, most were laid down directly by the ice; are fine grained, poorly sorted, or both; and, therefore, yield only small amounts of water to wells.

The thickness of glacial drift generally is 100 to 200 feet but locally is greater than 300 feet in eastern Missouri and 400 feet in western Missouri and northeastern Kansas. In southeastern Nebraska, local drift thicknesses of more than 350 feet have been reported. Meltwater created an extensive stream network in front of the advancing ice (**fig. 42**), and the streams deposited gravel, sand, and finer sediments as alluvium along the courses of preglacial bedrock valleys.

Complex interbedding of fine- and coarse-grained material is characteristic of the glacial deposits (**fig. 43**). The lenslike shape of some of the beds is the result of meandering of the meltwater streams across their valley floors and of periodic changes in stream-channel locations. However, in parts of Missouri, the glacial-drift aquifers are not complexly interbedded. For example, in the Grand River Valley of Daviess County, Missouri, the basal part of the deposits that fill glacial stream channels is coarse grained, and the upper part generally consists of poorly permeable silt, clay, or till (**fig. 44**). Such aquifers are called buried channel or buried valley aquifers and contain water under confined or semiconfined conditions. Not all the drift consists of sand and gravel, (**shown in figures 43 and 44**), and not all is saturated. Water generally is obtained from sand beds that range from 20 to 40 feet in thickness.

Yields of wells completed in the glacial-drift aquifers are highly variable and range from less than 10 to about 1,000 gallons per minute. Large diameter wells that penetrate several thick, saturated, highly permeable sand beds yield the most water. Even in places where wells penetrate only one thin sand bed in the glacial-drift deposits, yields are generally larger than those of wells completed in the underlying bedrock. Transmissivity values that range from 200 to 13,000 feet squared per day have been reported from aquifer tests in glacial-drift aquifers in Kansas. The larger transmissivity values represent places where several thick sand beds were encountered by wells; the smaller values indicate that thin sand beds with low permeability were penetrated.

Movement of water in the glacial-drift aquifers is from recharge areas to discharge areas along major modern streams. Much of the water moves along short flow paths to the nearest surface-water body, where it discharges. Some water follows longer flow paths and discharges to regional drains. A small amount of the water percolates downward and enters underlying bedrock aquifers.

The complex interbedding of permeable and poorly permeable sediments in the glacial- drift aquifers results in a large number of local confining units. Accordingly, water in these aquifers is under unconfined conditions in some places and confined conditions in other places. Where several sand and clay beds are stacked, water levels in each of the stacked sand beds may be different. The potentiometric surface of the glacial-drift aquifers is, therefore, a composite surface and shows only the general configuration of water levels. The influence of topography on water levels in these aquifers is shown by a map of their potentiometric surface in Missouri (**fig. 45**). Topographically high areas in Clinton and Sullivan Counties, for example, stand out clearly. The low water levels parallel to the courses of the Missouri and the Mississippi Rivers and some of their tributaries show that the aquifer discharges water to these streams.

The chemical quality of the water in the glacial-drift aquifers generally is suitable for most uses. The water is hard and commonly is a calcium bicarbonate type although in many places in Missouri and locally in Kansas, it is a sodium sulfate type. Dissolved-solids concentrations in water from these aquifers usually are less than 500 milligrams per liter but exceed 3,900 milligrams per liter in places. Sulfate concentrations ordinarily are 250 milligrams per liter or less except locally in Kansas and in Missouri; concentrations of sulfate as great as 2,150 milligrams per liter have been reported in Missouri. The source of the sulfate is dissolution of gypsum in the underlying bedrock in areas where the hydraulic head in the bedrock is greater than that in the glacial-drift aquifers; this condition allows the high-sulfate water to leak upward. Locally, concentrations of as much as 30 milligrams per liter of iron have been reported in Missouri. Nitrate concentrations that are greater than 45 milligrams per liter have been reported in water from these aquifers in Kansas, which probably reflects local contamination from agricultural sources or human wastes.

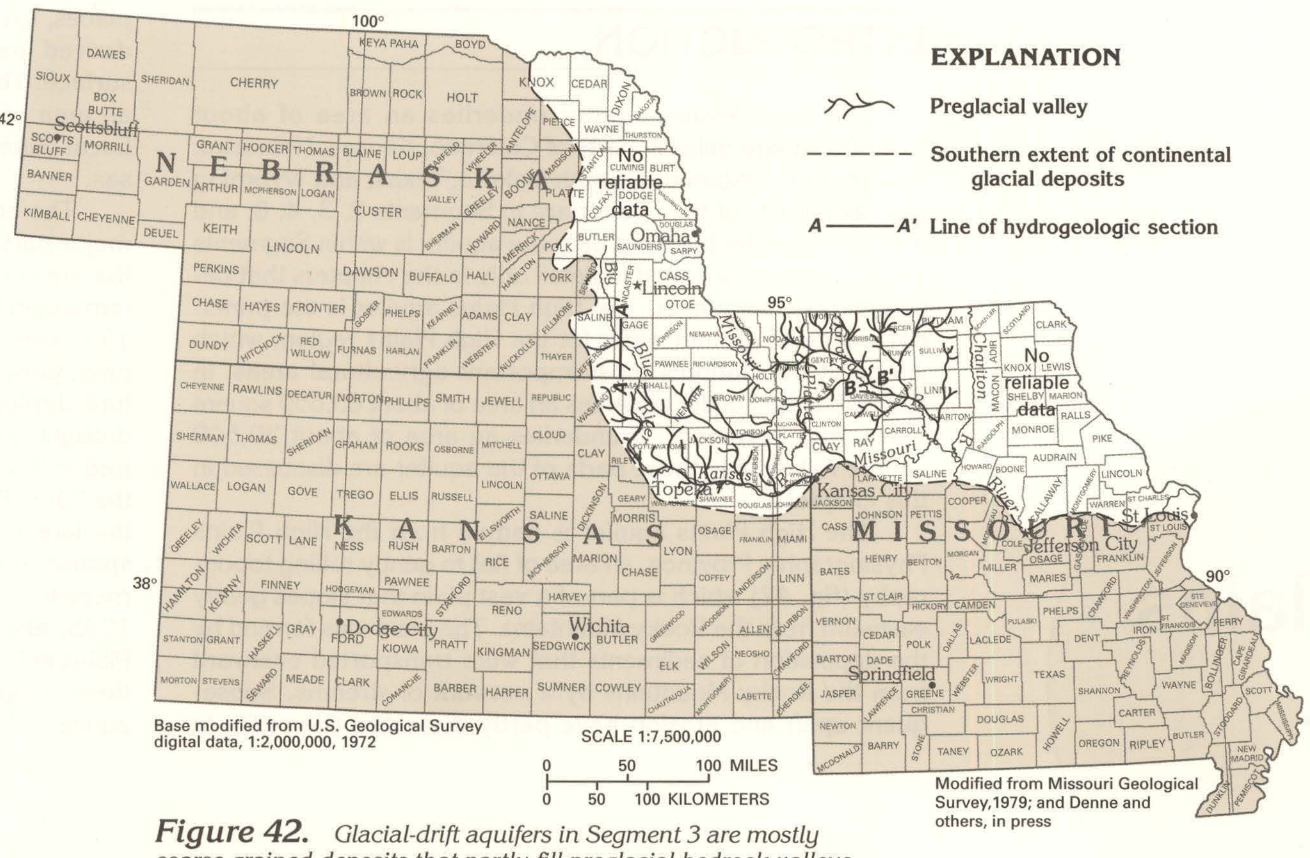


Figure 42. Glacial-drift aquifers in Segment 3 are mostly coarse-grained deposits that partly fill preglacial bedrock valleys. The courses of these channels generally do not coincide with those of modern streams.

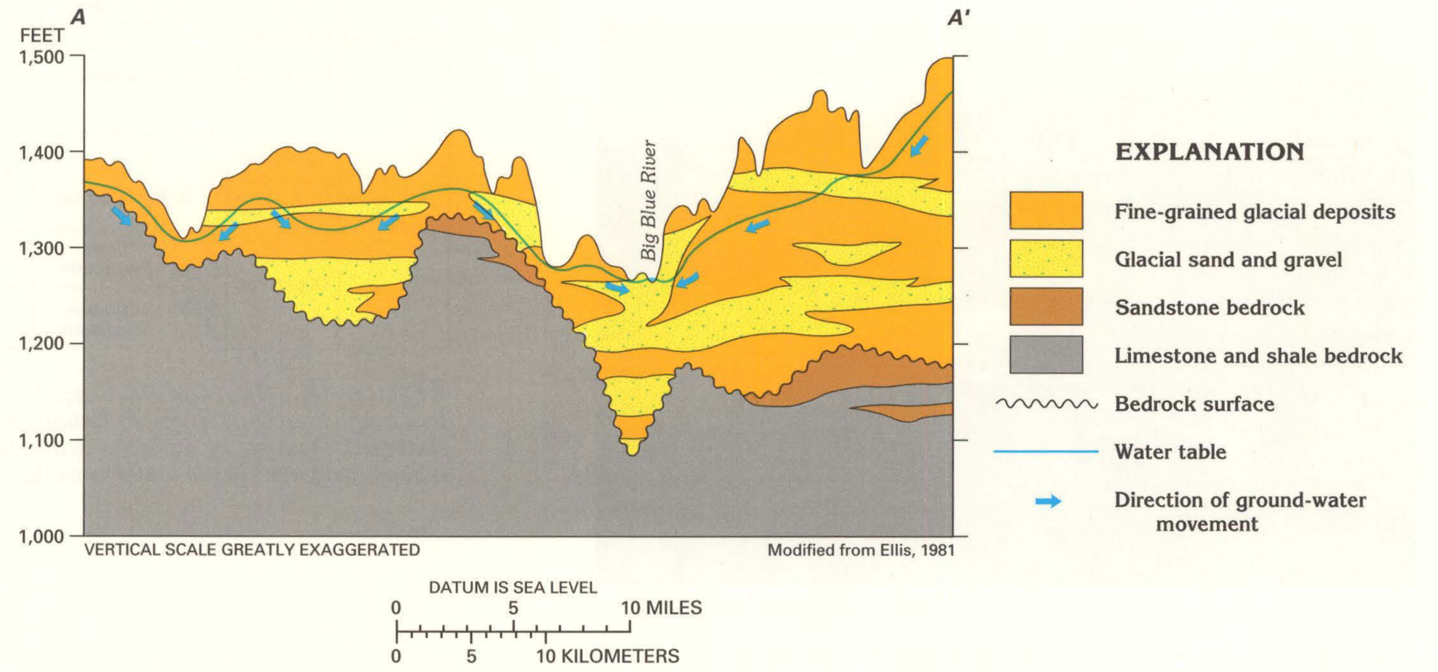


Figure 43. Complex interbedding of coarse- and fine-grained materials characterizes the glacial-drift aquifers. Changes in the courses of meltwater streams are largely responsible for the lens-shaped, discontinuous nature of the beds of sand and clay. The line of the hydrogeologic section is shown in figure 42.

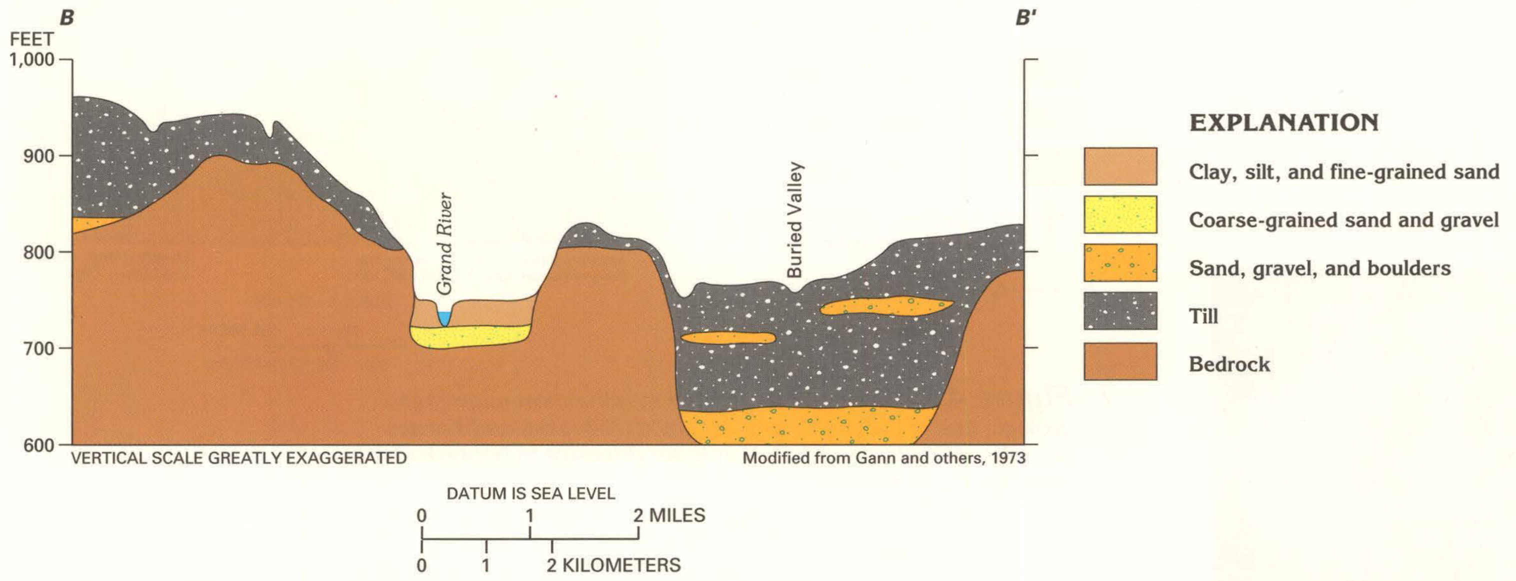


Figure 44. In Missouri, sand and gravel commonly are at the base of the glacial channel-fill deposits and are covered by clay and silt. The cover of fine-grained material creates confined conditions for the water in the coarse-grained sediments. The line of the hydrogeologic section is shown in figure 42.

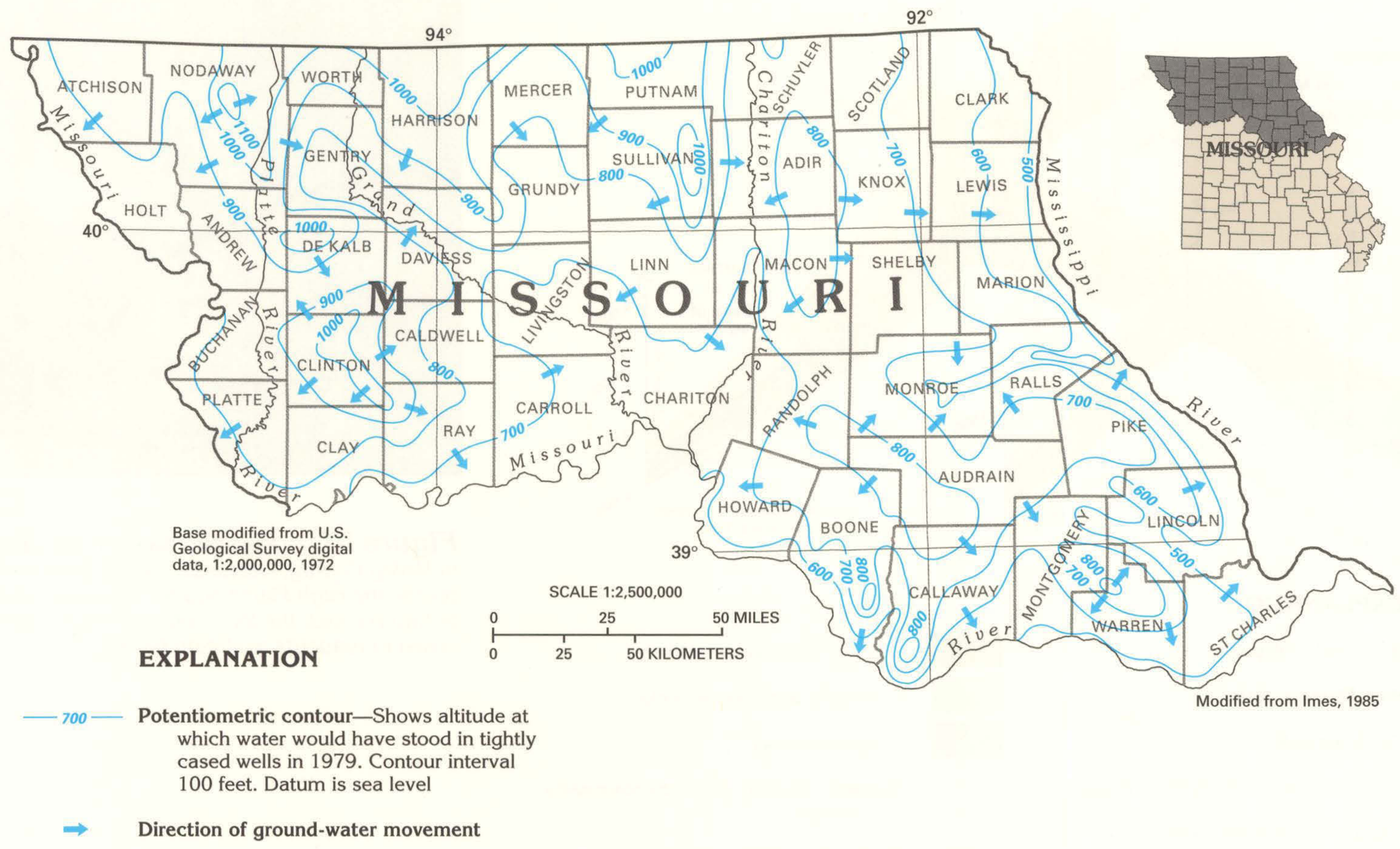


Figure 45. Most of the water in the glacial-drift aquifers in Missouri moves from topographically high areas toward major modern streams.

High Plains aquifer

INTRODUCTION

The High Plains aquifer underlies an area of about 174,000 square miles in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (**fig. 46**). Parts of the aquifer are in Segments 2, 3, 4, 8, and 9 of this Atlas; for the most part, the aquifer is within Segments 3 and 4 and is discussed in detail only in the chapters that describe those segments. The High Plains aquifer is the principal source of ground water for the High Plains region, which is one of the Nation's most important agricultural areas. In Nebraska, the aquifer underlies an area of about 63,650 square miles, and in Kansas, it underlies an area of about 30,500 square miles; only these parts of the aquifer are discussed in this chapter.

The High Plains aquifer is named from the High Plains Physiographic Province, an area of flat to gently rolling topography (**fig. 47**) which is part of a vast plain that slopes gently eastward from the Rocky Mountains. The plain was formed by the deposition of sediments that were transported eastward from the Rocky Mountains by a network of streams. Subsequent uplift and erosion have partly dissected the plain. In places, extensive areas of windblown silt and sand that were derived from channel deposits of the streams are at the land surface. The windblown sand deposits form dunes that cover an area of about 20,000 square miles in central Nebraska. Local dune sands also are common in parts of southern Kansas.

The economy of the High Plains area, which provides a major part of the food supply of the Nation, is dependent on the successful growing of crops. The prevailing method of farming in the High Plains before the drought of 1930 through 1939 was dryland farming. By the 1930's, continuous cropping, primarily by repeatedly planting the cropland in wheat, had depleted the humus that bound the soil. During the drought, the wind blew away much of the remaining pulverized soil as huge clouds of dust, and the area was known as the "Dust Bowl." Ground-water irrigation, which had begun in the late 1800's, was greatly intensified in the 1940's in response to the drought. A second surge in irrigation development followed a severe drought during the 1950's. During 1985, about 10.5 million acres were irrigated on the High Plains in Nebraska and Kansas. Most of the water that supplies these irrigation needs was withdrawn from the High Plains aquifer.

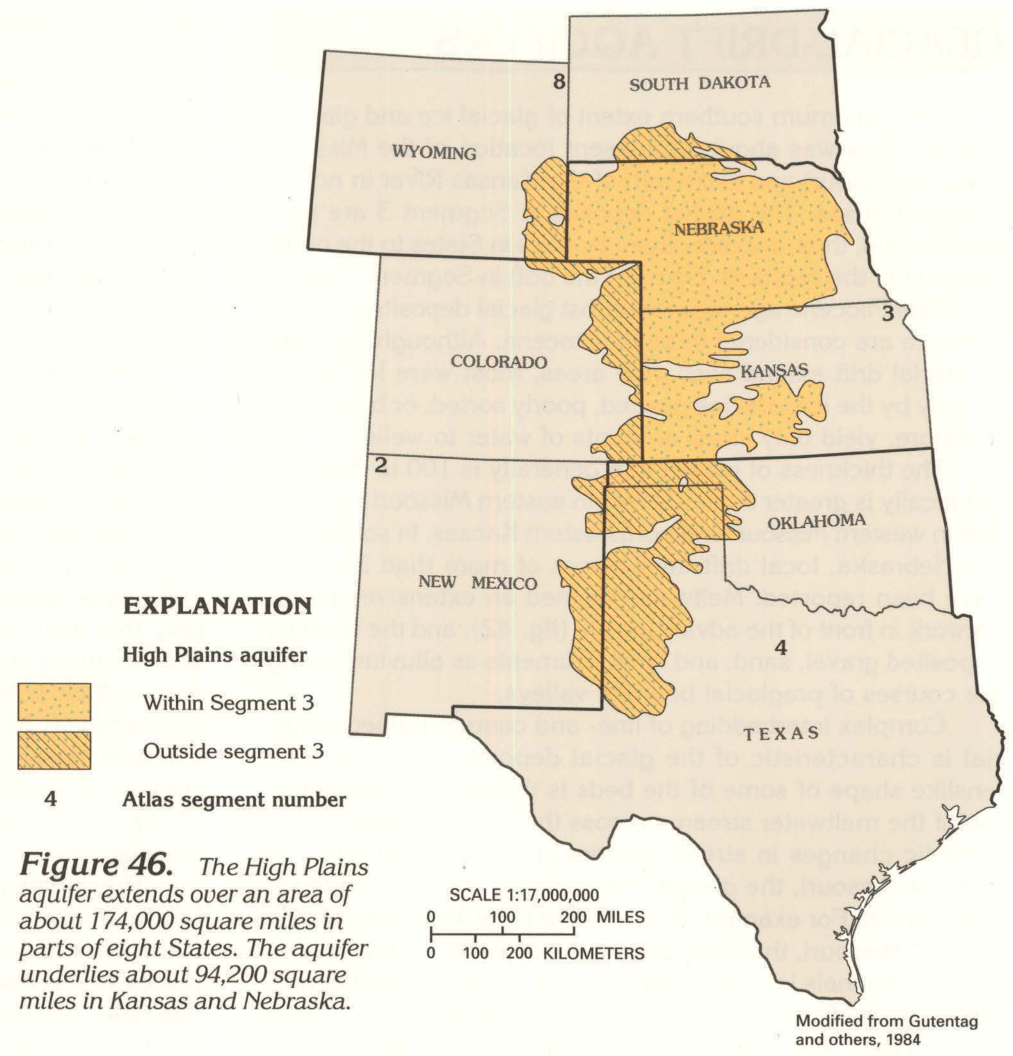


Figure 46. The High Plains aquifer extends over an area of about 174,000 square miles in parts of eight States. The aquifer underlies about 94,200 square miles in Kansas and Nebraska.

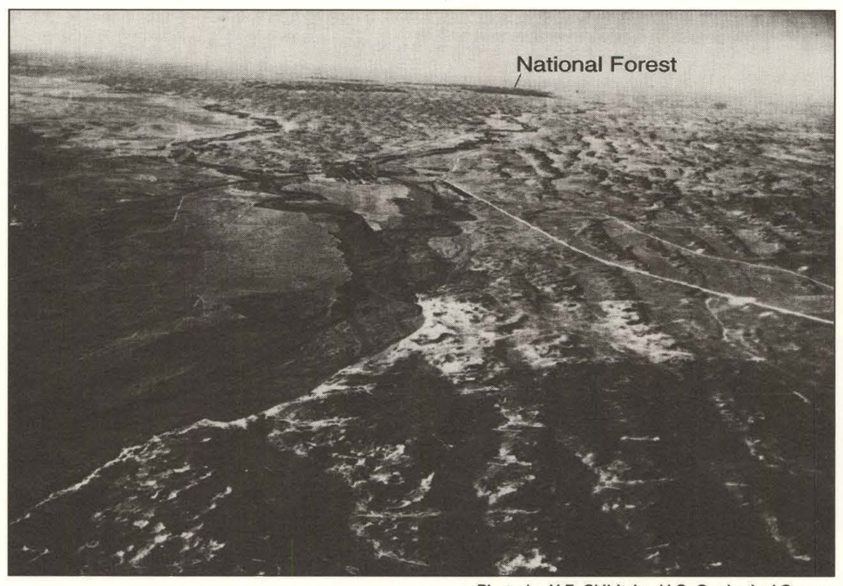


Photo by H.E. Skibitzke, U.S. Geological Survey. Reproduced from Keech and Bentall, 1988

Figure 47. The High Plains Physiographic Province is characterized by flat to gently rolling terrain like that shown in the left foreground. Sand dunes, such as those in Blaine County, Nebraska, in the right of the photograph, form low hills that are 100 to 300 feet high.

System	Series	Geologic unit		Lithology	Hydrogeologic unit
Quaternary	Holocene and Pleistocene	Valley-fill deposits and dune sand		Gravel, sand, silt, and clay. Dune sands prominent in Nebraska	High Plains aquifer
	Pleistocene	Alluvial deposits		Gravel, sand, silt, and clay. Locally cemented	
Tertiary	Miocene	Ogallala Formation		Unconsolidated, poorly sorted gravel, sand, silt, and clay	
		Arikaree Group		Sandstone, fine-to very fine-grained. Local beds of volcanic ash, siltstone, claystone, and marl	
	Oligocene	White River Group	Brule Formation	Siltstone with sandstone as beds and channel deposits	
			Chadron Formation	Clay and silt	Confining unit

Modified from Gutentag and others, 1984

Figure 48. The High Plains aquifer consists of geologic units that range from Quaternary to Tertiary in age. Where they are saturated, Quaternary dune sands and the Miocene Ogallala Formation yield most of the water to wells.

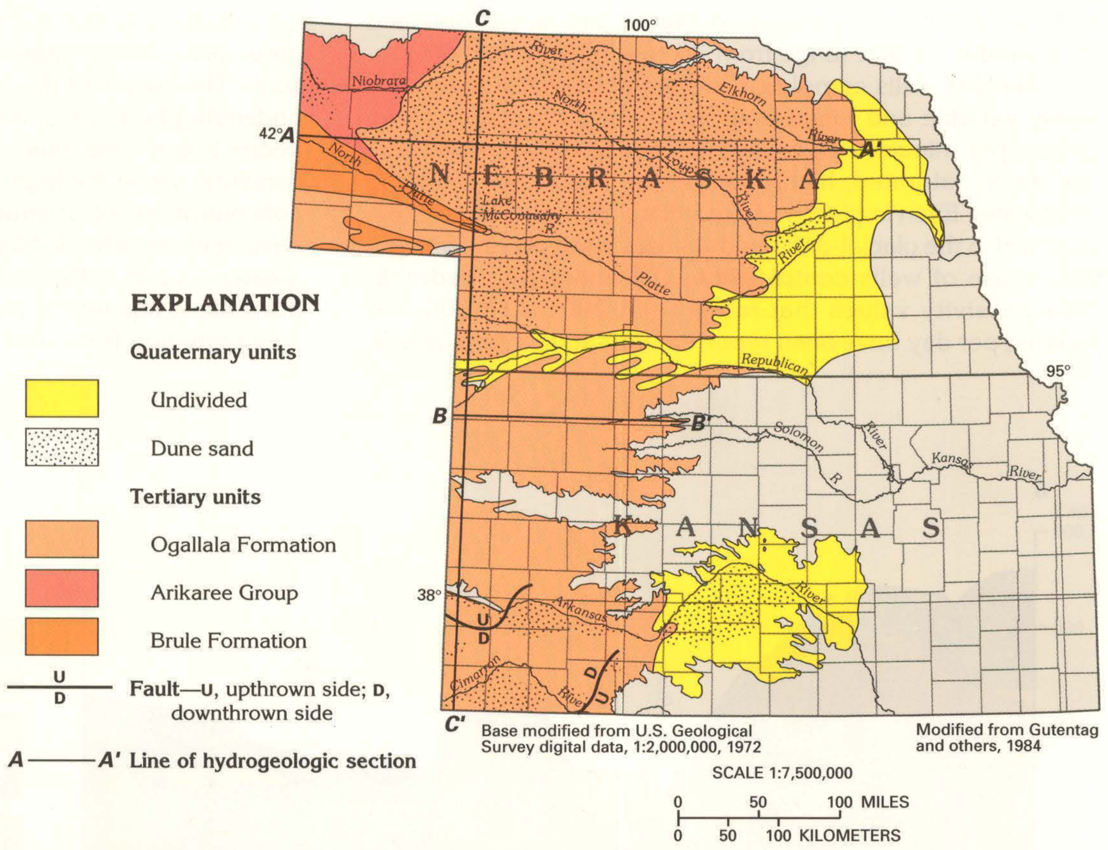


Figure 49. The Ogallala Formation is the most widespread geologic unit of the High Plains aquifer in Nebraska and Kansas. Deposits of Quaternary dune sands are extensive in Nebraska and occur locally in Kansas.

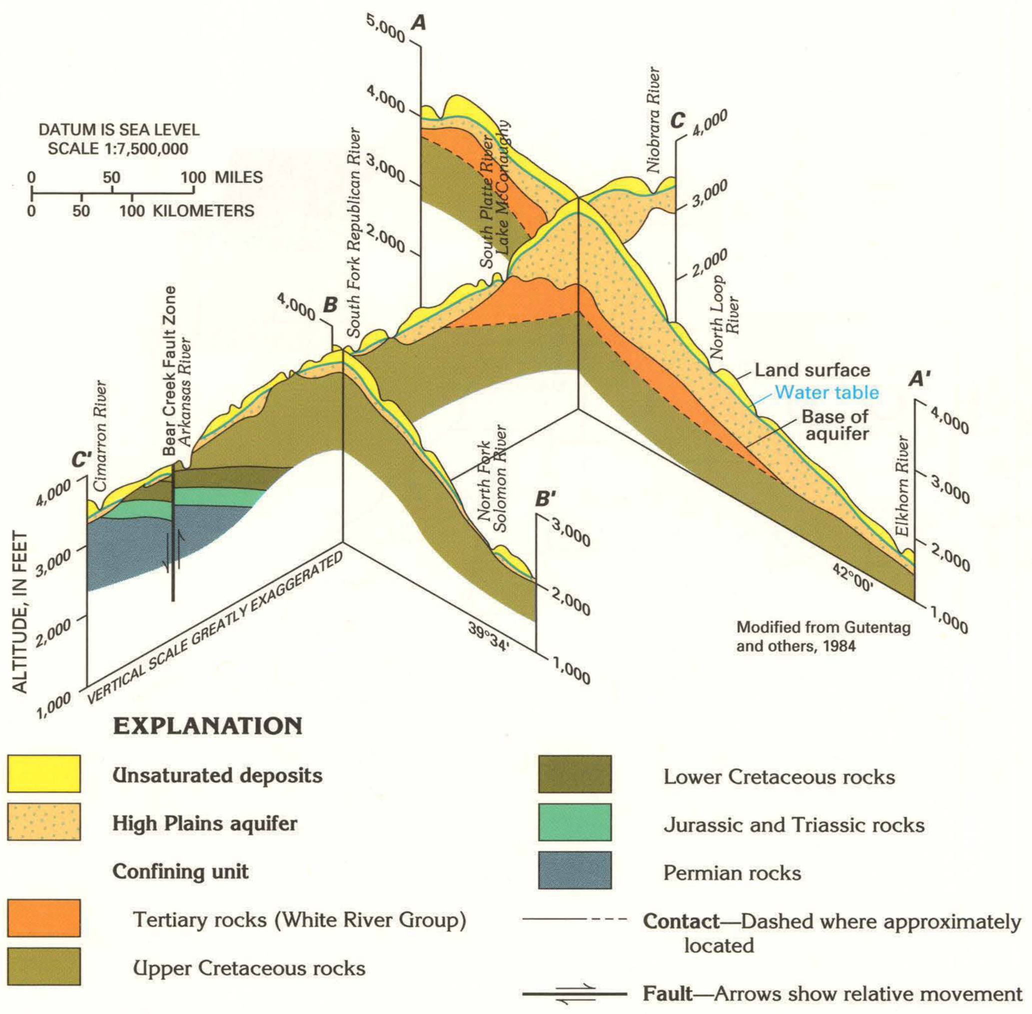


Figure 50. The High Plains aquifer is as much as 1,000 feet thick in north-central Nebraska but thins to the south and east. The aquifer overlies rocks of Late Cretaceous age in Kansas, where it generally is less than 250 feet thick. The lines of hydrogeologic section are shown in figure 49.

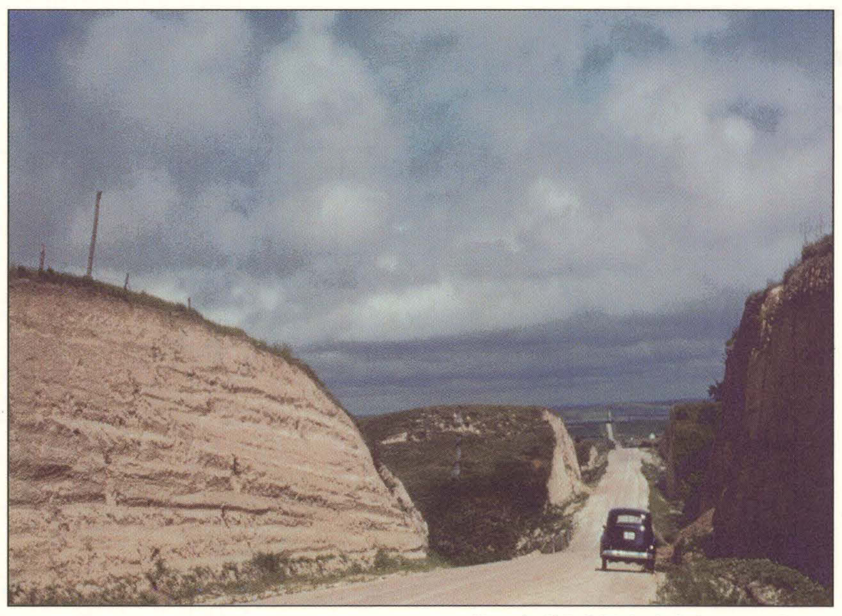


Photo by H.E. Skibitzke, U.S. Geological Survey. Reproduced from Keech and Bentall, 1988

Figure 51. Deposits of loess, or windblown silt, such as these in Valley County, Nebraska, locally form confining units where they overlie the High Plains aquifer. Because the silt is angular and tightly packed, the loess will maintain a vertical face where it is exposed in roadcuts or stream banks.

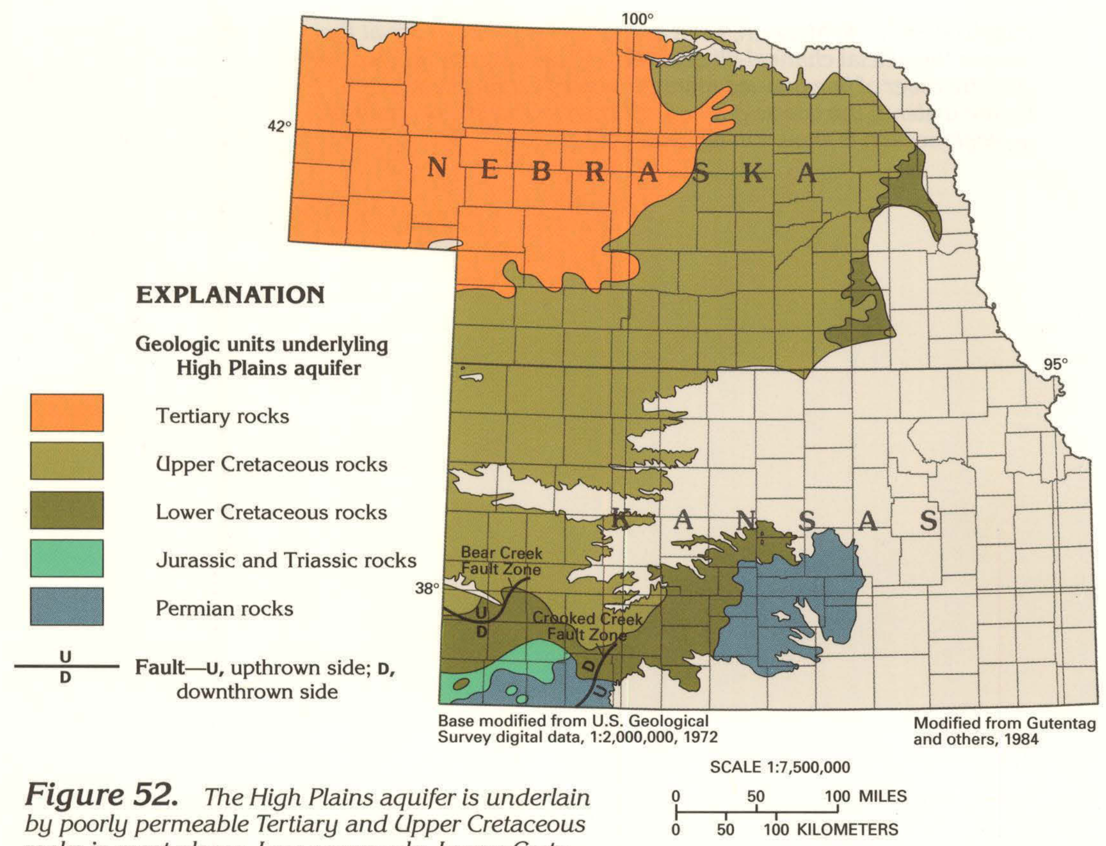


Figure 52. The High Plains aquifer is underlain by poorly permeable Tertiary and Upper Cretaceous rocks in most places. Less commonly, Lower Cretaceous, Jurassic, Triassic, and Permian rocks form the base of the aquifer.

HYDROGEOLOGIC UNITS

The High Plains aquifer consists of all or parts of several geologic units of Quaternary and Tertiary age. The stratigraphic column in **figure 48** shows the formation name, generalized rock type, thickness, and age of the geologic units that compose the aquifer. The Brule Formation of Oligocene age is the oldest geologic unit included in the aquifer. The Brule Formation is the upper unit of the White River Group and is primarily massive siltstone with beds and channel deposits of sandstone. Locally, the Brule includes lenticular beds of volcanic ash, clay, and fine sand. The Brule underlies much of western Nebraska and is included in the aquifer only where it has been fractured or where the formation contains solution openings. Such secondary porosity and permeability are developed only where the Brule crops out or is near the land surface (**fig. 49**).

The Arikaree Group of Miocene and Oligocene age overlies the Brule Formation and consists primarily of massive, very fine to fine-grained sandstone. Locally, the Arikaree includes beds of volcanic ash, siltstone, claystone, and marl. The Arikaree Group crops out in western Nebraska and pinches out to the south and east as does the White River Group, which includes the Brule Formation (**fig. 50**). The maximum thickness of the Arikaree is about 1,000 feet in western Nebraska.

The Ogallala Formation of Miocene age is the principal geologic unit included in the High Plains aquifer and is at the land surface throughout most of the extent of the aquifer (**fig. 49**). The Ogallala consists of unconsolidated gravel, sand, silt, and clay. Locally, it also includes caliche, which is a hard deposit of calcium carbonate that precipitated when part of the ground water that moved through the formation evaporated. The Ogallala Formation was deposited by an extensive eastward-flowing system of braided streams that drained the eastern slopes of the Rocky Mountains during late Tertiary time. The location of the stream system migrated during a long period of time, and the Ogallala Formation was deposited over about 134,000 square miles in eastern Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming.

Unconsolidated deposits of Quaternary age overlie the Ogallala Formation. These Quaternary deposits consist of gravel, sand, silt, and clay, much of which is reworked material that was derived from the Ogallala Formation. Where these unconsolidated deposits are saturated, such as in southeastern Nebraska and south-central Kansas, they compose part of the High Plains aquifer (**fig. 49**). Deposits of loess (**fig. 51**) overlie the Ogallala Formation or the unconsolidated Quaternary sediments in some locations. The loess was deposited as windblown material and consists mostly of silt with small quantities of very fine-grained sand and clay. Where the loess is thick, it forms the upper confining unit of the High Plains aquifer. Dune sands of Quaternary age compose part of the aquifer where they are saturated. The dune sands are most extensive in west-central Nebraska where they cover about 20,000 square miles (**fig. 49**) and attain a maximum thickness of about 300 feet. Saturated dune sands also are part of the High Plains aquifer south of the Arkansas River in southwest and south-central Kansas. The dune sands are highly porous and, therefore, quickly absorb rainfall that recharges the High Plains aquifer. Valley-fill deposits along the channels of streams, such as the Platte and the Arkansas Rivers, also are considered to be part of the aquifer where they are hydraulically connected to it. In such places, the valley-fill deposits directly link the streams to the High Plains aquifer and allow water to move freely between the aquifer and the streams.

The High Plains aquifer is underlain by rocks that range in age from Tertiary to Permian. Rocks of Permian age directly underlie parts of the aquifer in southern Kansas (**fig. 52**). These rocks are predominantly red shale, siltstone, sandstone, gypsum, anhydrite, and dolomite and locally include limestone and halite (rock salt) as beds or disseminated grains. Partial dissolution of salt and evaporite minerals by circulating ground water has adversely affected the chemical quality of water in the High Plains aquifer where Permian rocks that contain salt beds or saline water are in hydraulic connection with the aquifer. The dissolution of salt beds also has resulted in collapse structures and faulting in the overlying deposits. The Bear Creek and the Crooked Creek Fault Zones in southwestern Kansas (**fig. 52**) are collapse structures that have formed as a result of partial dissolution of salt beds.

Rocks of Jurassic and Triassic age directly underlie the High Plains aquifer in small parts of southwestern Kansas and western Nebraska. These rocks consist primarily of shale and sandstone, and some of the sandstone beds are permeable enough to yield water to wells. Some irrigation wells in southwestern Kansas withdraw water from the High Plains aquifer and the rocks of Jurassic and Triassic age. For the most part, however, the Jurassic and Triassic rocks have low permeability.

Lower Cretaceous rocks directly underlie the High Plains aquifer in parts of southern Kansas and eastern Nebraska (**fig. 52**). These rocks are primarily shale and sandstone. The hydraulic properties of the sandstones are highly variable, but Lower Cretaceous rocks provide water for irrigation and other uses in parts of Kansas and Nebraska.

Upper Cretaceous rocks directly underlie the High Plains aquifer in large parts of Nebraska and Kansas. These rocks consist primarily of shale, chalk, limestone, and sandstone of which only the chalk (where it is fractured, contains solution openings, or both) yields quantities of water large enough for irrigation purposes. Elsewhere, Upper Cretaceous rocks have little permeability.

The Chadron Formation that is part of the White River Group of Tertiary age (**fig. 48**) directly underlies the High Plains aquifer in most of western Nebraska (**fig. 52**). The Chadron Formation is predominantly clay and silt, both with minimal permeability. The Brule Formation, which also is part of the White River Group, is predominantly siltstone but locally is fractured. Where it contains fracture or solution permeability, the Brule Formation is considered to be part of the High Plains aquifer.

GROUND-WATER HYDROLOGY

Depth to Water

The depth to water in a particular area is the difference between the altitude of land surface and the altitude of the water table. The generalized depth to water in the High Plains aquifer in 1980 is shown in **figure 53**. In most places, the water levels shown are lower than those that existed before widespread irrigation withdrawals began. The depth to water in the High Plains aquifer is less than 100 feet in about one-half of the area of the aquifer and less than 200 feet in most of Nebraska and Kansas. The depth to water generally is less near the Platte and the Arkansas Rivers than in areas farther from the rivers because the rivers are hydraulically connected to the aquifer through the stream valley aquifers that parallel the rivers. The water table is between 200 and 300 feet below the land surface in parts of western and southwestern Nebraska and in parts of southwestern Kansas. The depth to water is as much as 400 feet below the surface in a small area in southwestern Kansas where development of the aquifer began earlier than in most parts of Kansas; consequently, water-level declines are greater.

Ground-Water Flow

Water in the High Plains aquifer generally is under unconfined, or water-table, conditions. Locally, water levels in wells completed in some parts of the aquifer may rise slightly above the regional water table because of artesian pressure created by local confining beds. The altitude and configuration of the water table of the High Plains aquifer are shown in **figure 54**. The configuration and slope of the water table are similar to the configuration and slope of the land surface. Water in the aquifer generally moves from west to east, or perpendicular to the contours and in the direction of the arrows shown in **figure 54**. Water moves in response to the slope of the water table, which typically averages between 10 and 15 feet per mile. On the basis of this average slope and aquifer hydraulic properties, the velocity of water that moves through the aquifer is estimated to average about 1 foot per day.

Where the water-table contours cross streams, the configuration of the contours indicates the relation of water in the aquifer to the water in the stream. For example, where the contours from 3,200 to 4,000 feet in **figure 54** cross the North Platte River in western Nebraska, the contours bend upstream. This upstream flexture indicates that water moves from the aquifer to the stream, and the North Platte River is a gaining stream in this area. By contrast, where the 2,000-foot contour crosses the Platte River in west-central Nebraska, a slight downstream bend in the contour indicates that water is moving from the stream to the aquifer; the Platte River is a losing stream in this area, and the water from the river recharges the aquifer.

In southwestern Kansas, the Bear Creek and the Crooked Creek Fault Zones (**fig. 52**) have displaced the High Plains aquifer and little or no saturated thickness of the aquifer exists on the upthrown side of the faults. In these areas, the water-table contours shown in **figure 54** end abruptly at the faults.

EXPLANATION

Depth to water in 1980, in feet

- 0 to 50
- 50 to 100
- 100 to 200
- 200 to 300
- 300 to 400

Little saturated thickness

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

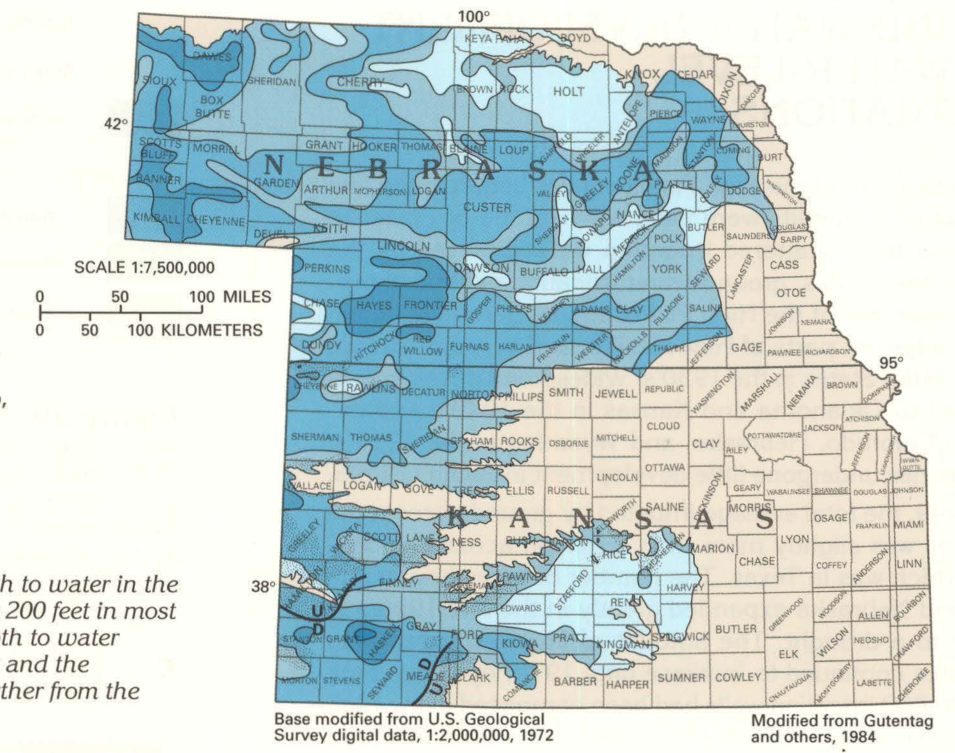


Figure 53. *In 1980, the depth to water in the High Plains aquifer was less than 200 feet in most of Kansas and Nebraska. The depth to water generally was less near the Platte and the Arkansas Rivers than in areas farther from the rivers.*

The spacing of the water-table contours is affected by different hydrologic conditions. For example, where contours are widely separated, such as in western Nebraska, the slope of the water table is gentler than where the contours are more closely spaced. Widespread recharge to the aquifer by infiltration of precipitation through dune sands occurs in western Nebraska, and, thus, the slope of the water table is relatively gentle.

Recharge and Discharge

In an undisturbed ground-water flow system, the amount of water that moves into an aquifer (recharge) and the amount of water that moves out of the aquifer (discharge) are equal, and the flow system is in equilibrium. Before development in an unconfined aquifer, such as the High Plains aquifer, the water table of the aquifer and the quantity of water stored in the aquifer vary little in response to changes in precipitation, streamflow, and the amount and types of vegetation.

A ground-water flow system is no longer in equilibrium when the long-term discharge is not equal to the long-term recharge. The altitude of the water table rises when the recharge rate exceeds the discharge rate and declines when the discharge rate exceeds the recharge rate. Withdrawal of large quantities of ground water by wells and redistribution of surface water in ditches and canals, all for irrigation purposes, have changed the natural recharge and discharge of the High Plains aquifer.

Recharge to the High Plains aquifer is primarily by infiltration of precipitation and locally is by infiltration from streams and canals. Some surface water that is applied to crops for irrigation also percolates downward and recharges the aquifer. A small quantity of water from the underlying bedrock moves upward and mixes with water in the High Plains aquifer; this water is also considered to be recharge. The aquifer is recharged at total rates of between 0.05 and 6 inches per year in Nebraska and Kansas. The rates of recharge are highly variable and range from about 0.3 to 20 percent of the average annual precipitation in the dry and wet parts of these States. The greatest rates of recharge by precipitation are in areas where dune sand or other highly permeable material is at the land surface. Recharge by infiltration of streamflow usually is greatest when streamflow is high and, thus, provides a large difference between stream and aquifer water levels.

Natural discharge from the High Plains aquifer is to springs, seeps, and streams and by evapotranspiration. Where the water table is near the land surface, ground water can evaporate directly. Transpiration rates are greatest along stream valleys where deep-rooted salt cedar, willows, cottonwoods, and sedges grow. Where the High Plains aquifer locally is underlain by permeable bedrock and the water table in the aquifer is higher than that in the bedrock, small amounts of water move downward from the aquifer into the bedrock.

Large quantities of water are withdrawn from the aquifer by wells, and in some areas large amounts of water discharge from the aquifer to streams. For example, a study was done during 1975 to determine how much of the flow of the Platte River in Nebraska was derived from ground water. The gain in streamflow within Nebraska was about 3 million acre-feet, most of which was ground-water discharge from the High Plains aquifer to the river. Large quantities of surface water are diverted from the Platte River and used for irrigation; thus, the amount of ground-water discharge to the river probably was significantly greater than the measured gain in streamflow.

Most of the discharge from the High Plains aquifer is by withdrawals from wells, and practically all of the water withdrawn is used for irrigation purposes. Total withdrawals of water from the entire aquifer for irrigation increased from about 4 million acre-feet during 1949 to about 23 million acre-feet during 1978 (**fig. 55**) then decreased to about 16 million acre-feet during 1990. During 1978, more than 4 million acre-feet of irrigation water was withdrawn in Kansas and about 8 million acre-feet was withdrawn in Nebraska. During 1990, irrigation withdrawals in Kansas were about the same as those during 1978, whereas withdrawals in Nebraska were only about 5 million acre-feet per day.

Saturated Thickness and Well Yield

The saturated thickness of an aquifer is the vertical distance between the water table and the base of the aquifer and is one of the factors that determines the quantity of water that can be pumped from a well. Other factors that affect well yield include well construction and the hydraulic properties of the aquifer. The saturated thickness of the High Plains aquifer in 1980 (**fig. 56**) ranged from 0 (where the sediments that compose the aquifer were unsaturated) to about 1,000 feet. The greatest saturated thickness is in north-central Nebraska where the aquifer consists of the Ogallala Formation and overlying dune sands. Locally in southwestern Kansas, dissolution of salt in the Permian bedrock that underlies the High Plains aquifer has resulted in collapse features that were filled with younger sediments. These anomalously thick accumulations of sediments coincide with thick sequences of saturated aquifer materials. The average saturated thickness of the entire aquifer in 1992 was about 190 feet. In Nebraska, the average saturated thickness was 340 feet, but in Kansas, it was only about 90 feet.

Changes in the saturated thickness of the High Plains aquifer have resulted from ground-water development. Saturated thickness has decreased in most places (**fig. 57**), but in two areas in south-central Nebraska, recharge to the aquifer from surface-water irrigation combined with downward leakage of water from canals and reservoirs has increased saturated thickness. In large areas in southwestern Kansas, large-scale irrigation development has decreased the saturated thickness of the aquifer more than 25 percent. Decreases of more than 10 percent in saturated thickness result in a decrease in well yields and an increase in pumping costs because of the increased depth at which the pump must be set in order to lift the water.

The entire High Plains aquifer contained about 21.7 billion acre-feet of saturated material in 1992. The quantity of drainable water in storage in the aquifer can be estimated by multiplying the volume of saturated material by the average specific yield (15 percent). The specific yield of an aquifer is the volume of water that will drain from a unit volume of rock under the influence of gravity alone. Therefore, about 3.25 billion acre-feet of drainable water was in storage in the High Plains aquifer in 1992. About 65 percent of the drainable water in storage in the entire aquifer is in Nebraska, and about 10 percent is in Kansas. The remaining drainable water is in storage in Colorado, New Mexico, Texas, South Dakota, Oklahoma, and Wyoming. Not all drainable water in storage within the aquifer can be recovered for use. The quantity of water that can be recovered varies with location and depends on the lithology, saturated thickness, hydraulic conductivity, and specific yield of the aquifer at that location and on well construction. Water has been almost completely removed from about 8 percent of the formerly saturated aquifer material in Kansas, whereas the quantity of material dewatered in Nebraska is negligible.

The greatest yields of water generally are obtained from wells that are completed in coarse-grained aquifer material in places where the saturated thickness of the High Plains aquifer is great. A generalized map of the potential yield of properly constructed wells completed in the High Plains aquifer is shown in **figure 58**. The potential yield of wells is greater than 750 gallons per minute in most of Nebraska and large parts of Kansas. A well capable of producing 750 gallons per minute can irrigate 125 acres and effectively supply one center-pivot irrigation system.

Well yields from different formations that compose the aquifer vary. Yields from the Brule Formation typically are less than 300 gallons per minute. Wells completed in the Arikaree Group generally do not yield large quantities of water but might yield as much as 350 gallons per minute in western Nebraska where the saturated thickness is about 200 feet. Well yields from the Brule Formation and the Arikaree Group are greatest where secondary porosity, such as fractures or solution openings, has been developed in the rocks. Well yields from the Ogallala Formation are 1,000 gallons per minute from 100 feet of saturated sand and gravel in many parts of Kansas and Nebraska but are only 100 gallons per minute from 20 feet of saturated sand and gravel in western Kansas.

EXPLANATION

5000 — Water-table contour—Shows altitude of water table in 1978. Contour interval is 400 and 1000 feet. Datum is sea level

Little saturated thickness

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

→ Direction of ground-water flow

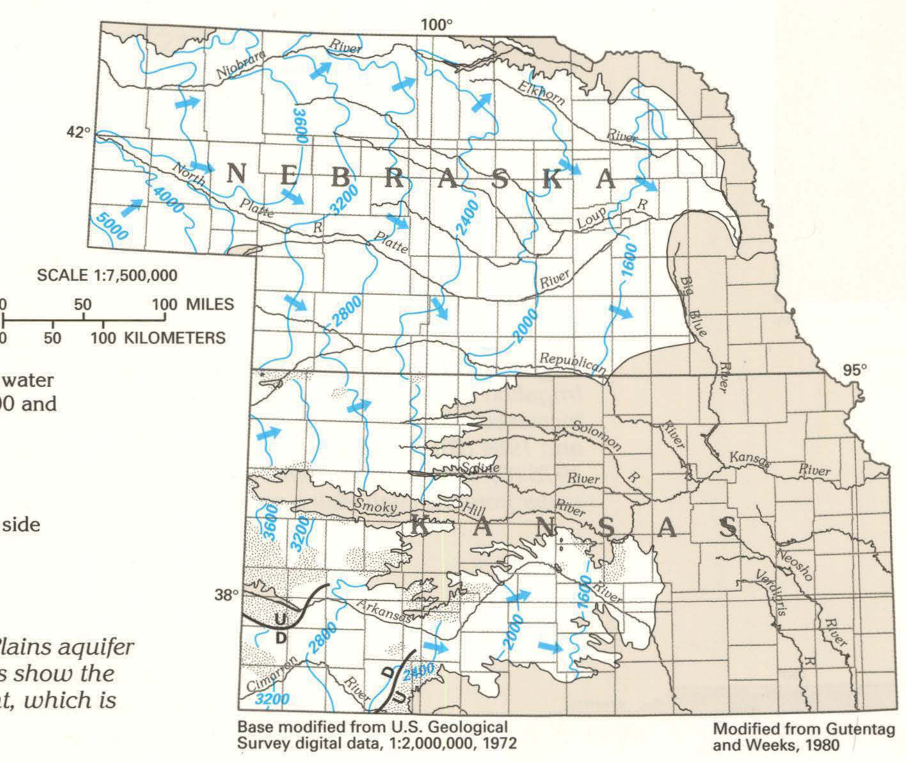


Figure 54. *The water table of the High Plains aquifer generally slopes from west to east. The arrows show the general eastward direction of water movement, which is locally diverted by major streams.*

EXPLANATION

Withdrawals in:

- Colorado, New Mexico, Oklahoma, South Dakota, and Wyoming combined
- Kansas
- Nebraska
- Texas

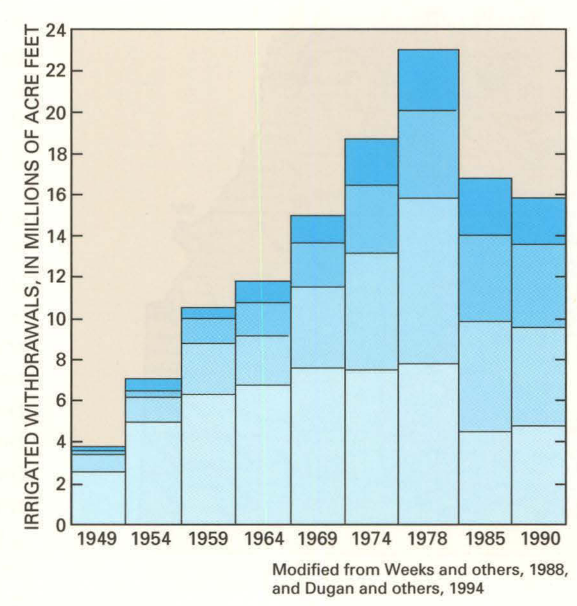


Figure 55. *Ground-water withdrawals from the entire High Plains aquifer for irrigation account for most of the discharge from the aquifer. About 9 million acre-feet of water was withdrawn from the aquifer for irrigation in Kansas and Nebraska during 1990.*

EXPLANATION

Saturated thickness in 1980, in feet

- 0 to 100
- 100 to 200
- 200 to 400
- 400 to 600
- 600 to1000

Little saturated thickness

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

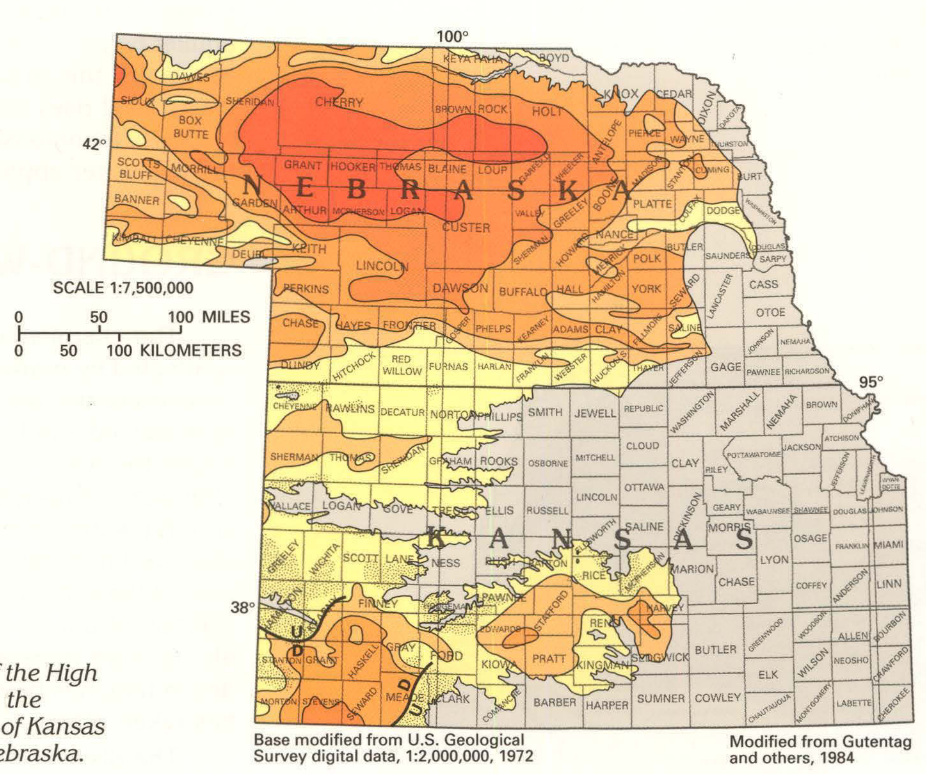


Figure 56. *The saturated thickness of the High Plains aquifer varies with location. In 1980, the saturated thickness ranged from 0 in parts of Kansas to as much as 1,000 feet in north-central Nebraska.*

EXPLANATION

Saturated thickness changes, in percent, predevelopment to 1980

- Increase of more than 10
- 10 to -10
- -10 to -25
- Decrease of more than 25

Little saturated thickness

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

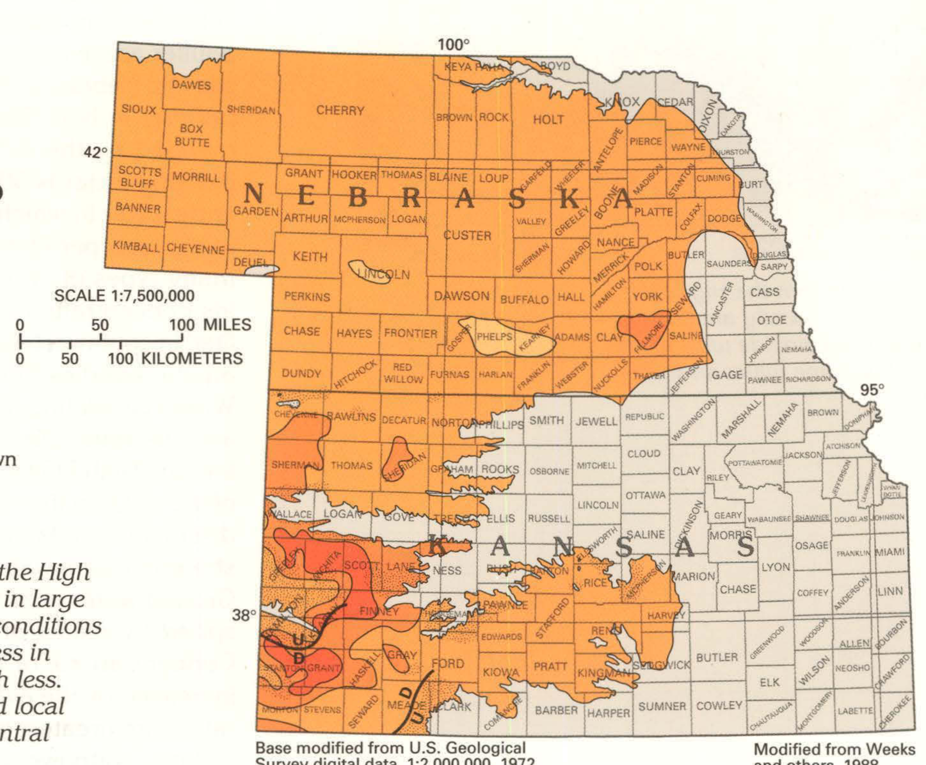


Figure 57. *The saturated thickness of the High Plains aquifer decreased 10 percent or more in large areas in Kansas between pre-development conditions and 1980; the decrease in saturated thickness in Nebraska during the same period was much less. Recharge by surface-water irrigation caused local increases in saturated thickness in south-central Nebraska.*

EXPLANATION

Potential yield of wells, in gallons per minute

- Less than 250
- 250 to 275
- More than 750

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

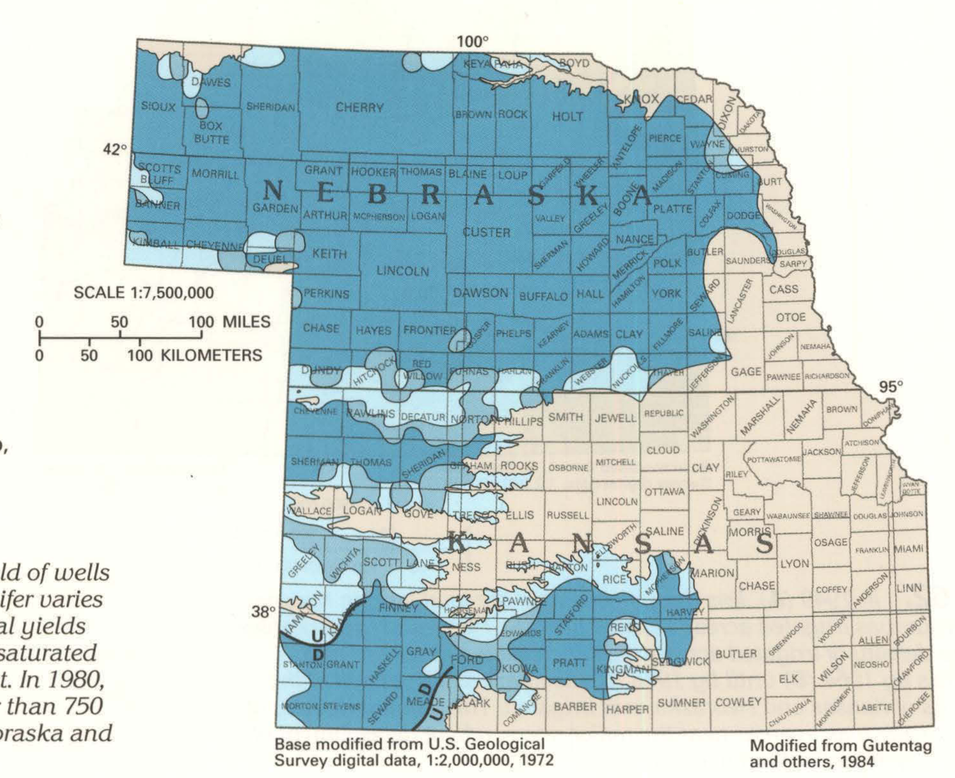


Figure 58. *The potential yield of wells completed in the High Plains aquifer varies with location. The largest potential yields generally are in areas where the saturated thickness of the aquifer is greatest. In 1980, potential well yields were greater than 750 gallons per minute in most of Nebraska and a large part of Kansas.*

GROUND-WATER DEVELOPMENT AND WATER-LEVEL FLUCTUATIONS

Development of the High Plains aquifer began in the late 1800's, when windmills were used as a source of power to pump water from scattered irrigation wells. Spurred by the drought of the 1930's, ground-water irrigation expanded rapidly. Development of the High Plains aquifer generally began in Texas, adjacent parts of New Mexico, and in major stream valleys in other States in the 1930's. Widespread development progressed to Oklahoma and Kansas in the 1940's and extended to Colorado, Nebraska, and Wyoming in the 1950's; the aquifer has undergone little development in South Dakota.

In 1949, the total acreage irrigated by ground water in the High Plains was slightly more than 2 million acres (**fig. 59**), most of which was in Texas. The number of acres irrigated in Kansas and Nebraska expanded greatly in the late 1950's in response to a drought. The amount of irrigated acreage in those States continued to increase until 1978, by which time nearly 170,000 irrigation wells had been completed in the High Plains aquifer; about 23,000 of these wells were in Kansas, and about 59,300 were in Nebraska. Collectively, irrigation wells in eight States pumped about 23 million acre-feet of water from the High Plains aquifer in 1978 to irrigate about 13 million acres. In 1978, water from the High Plains aquifer was used to irrigate about 4.5 million acres in Nebraska and more than 2 million acres in Kansas. The large increase in the number of wells drilled for irrigation between 1952 and 1978 was partially a result of the development of center-pivot irrigation systems during the 1960's. Center-pivot systems, such as those shown from an aerial view in **figure 60**, are supplied by irrigation wells and have the water-distribution pipes mounted on a wheeled boom that rotates in a circle around the center of the irrigated area. Such systems make it possible to irrigate the rolling terrain of the High Plains. In Nebraska alone, the number of center-pivot irrigation systems increased from about 2,800 in 1972 to more than 27,000 by the end of 1984 (**fig. 61**).

As the number of irrigation wells increased, the percentage of land that was irrigated also increased. In 1949, the 5 percent or less of land that was irrigated in most of Nebraska and Kansas (**fig. 62*A***), was mostly along river valleys. By 1964, the percentage of irrigated land had increased, and much of the irrigated acreage was away from the rivers (**fig. 62*B***). By 1978, the percentage of irrigated acreage had greatly increased (**fig. 62*C***) as more upland areas were irrigated.

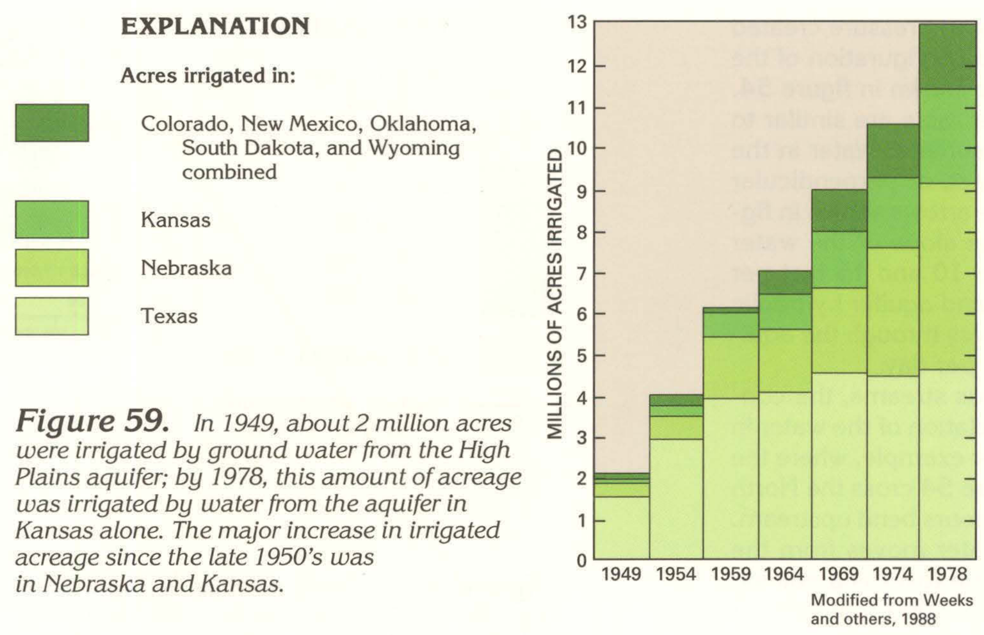


Figure 59. *In 1949, about 2 million acres were irrigated by ground water from the High Plains aquifer; by 1978, this amount of acreage was irrigated by water from the aquifer in Kansas alone. The major increase in irrigated acreage since the late 1950's was in Nebraska and Kansas.*

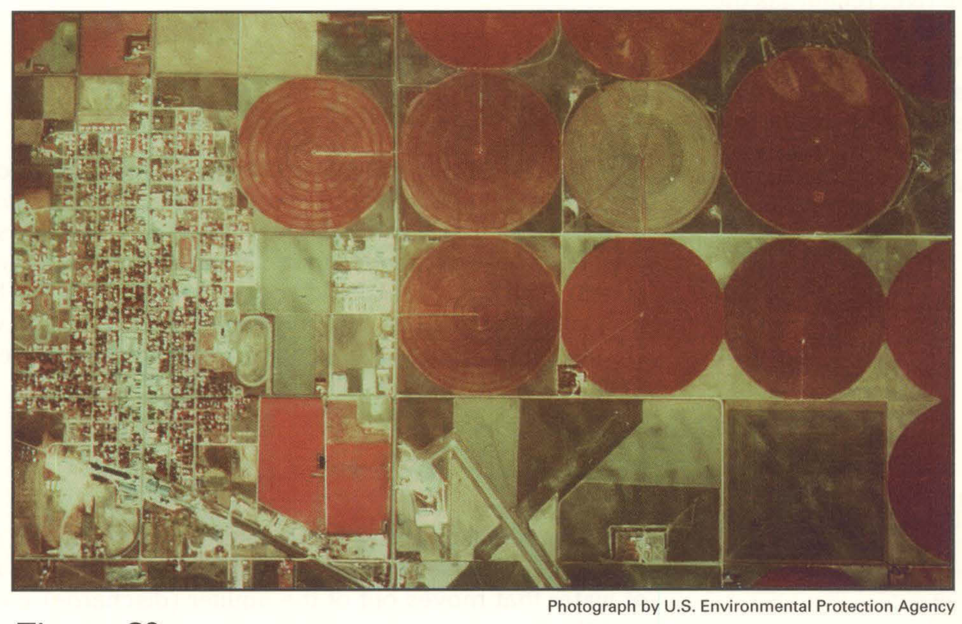


Figure 60. *Center-pivot irrigation systems are supplied by wells and have a wheeled boom that rotates in a circle around the center of the irrigated area. In this false-color aerial image that shows part of Chase County, Nebraska, irrigated crops appear in red, and fallow fields are tan. Each of the square areas that contain circles in the right part of the photograph encompasses about 160 acres; the circles themselves encompass about 125 acres.*

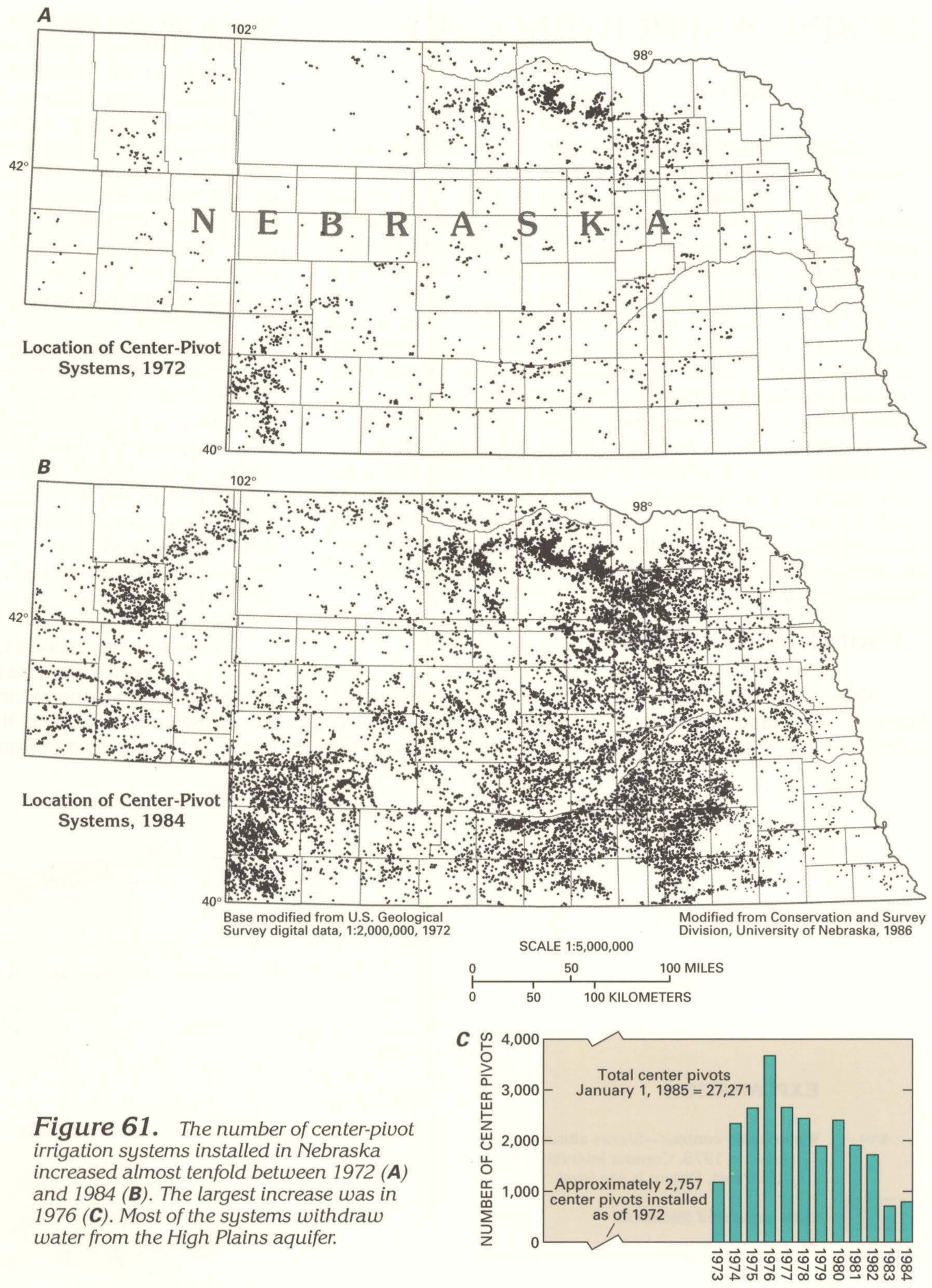


Figure 61. *The number of center-pivot irrigation systems installed in Nebraska increased almost tenfold between 1972 (**A**) and 1984 (**B**). The largest increase was in 1976 (**C**). Most of the systems withdraw water from the High Plains aquifer.*

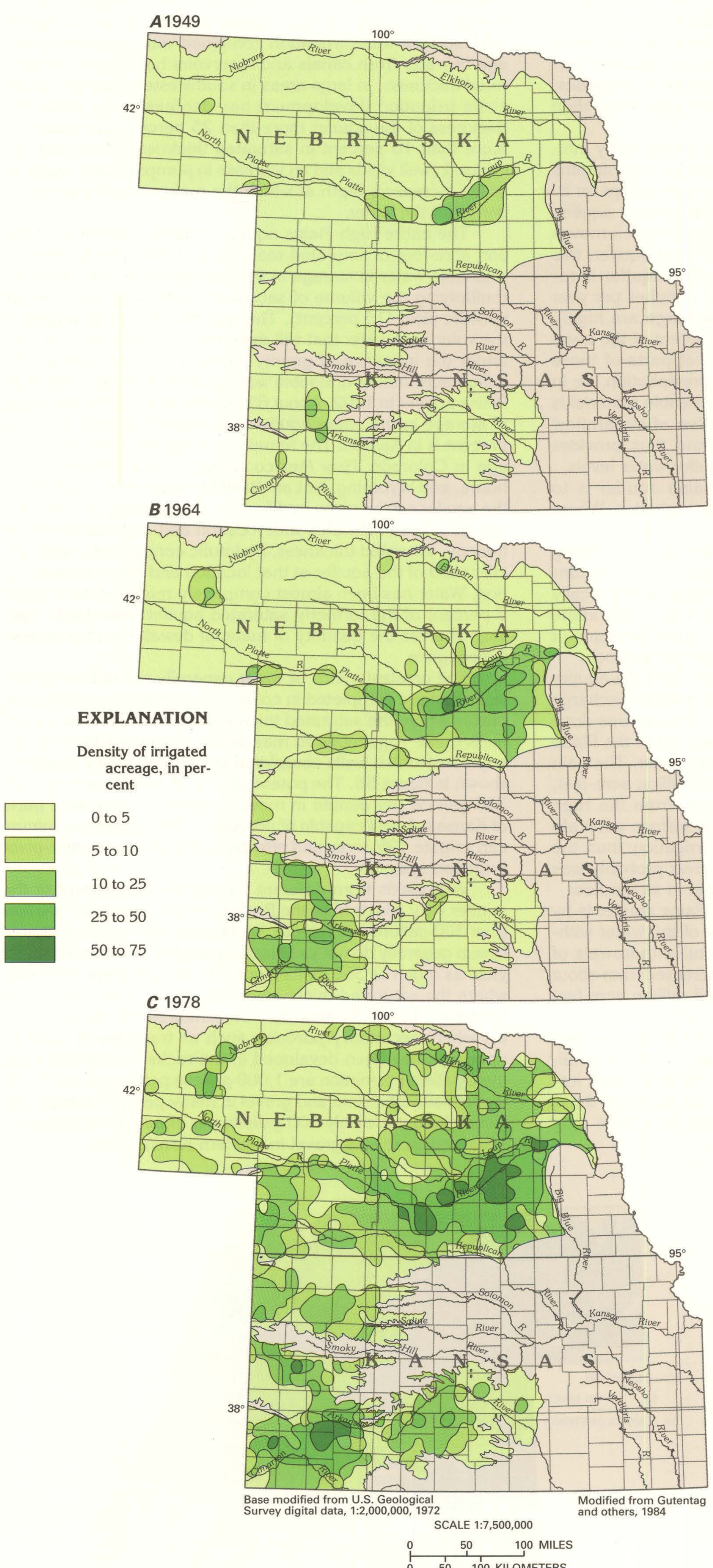


Figure 62. *In 1949 (**A**), less than 5 percent of the total land in Kansas and Nebraska was irrigated acreage except near the Platte and the Arkansas Rivers. The density of irrigated acreage had increased and spread into upland areas by 1964 (**B**) until by 1978 (**C**), as much as 75 percent of the land in parts of Kansas and Nebraska was irrigated. The greatest density of irrigated acreage was in areas near the major rivers, where development of the aquifer began earlier than in other areas.*

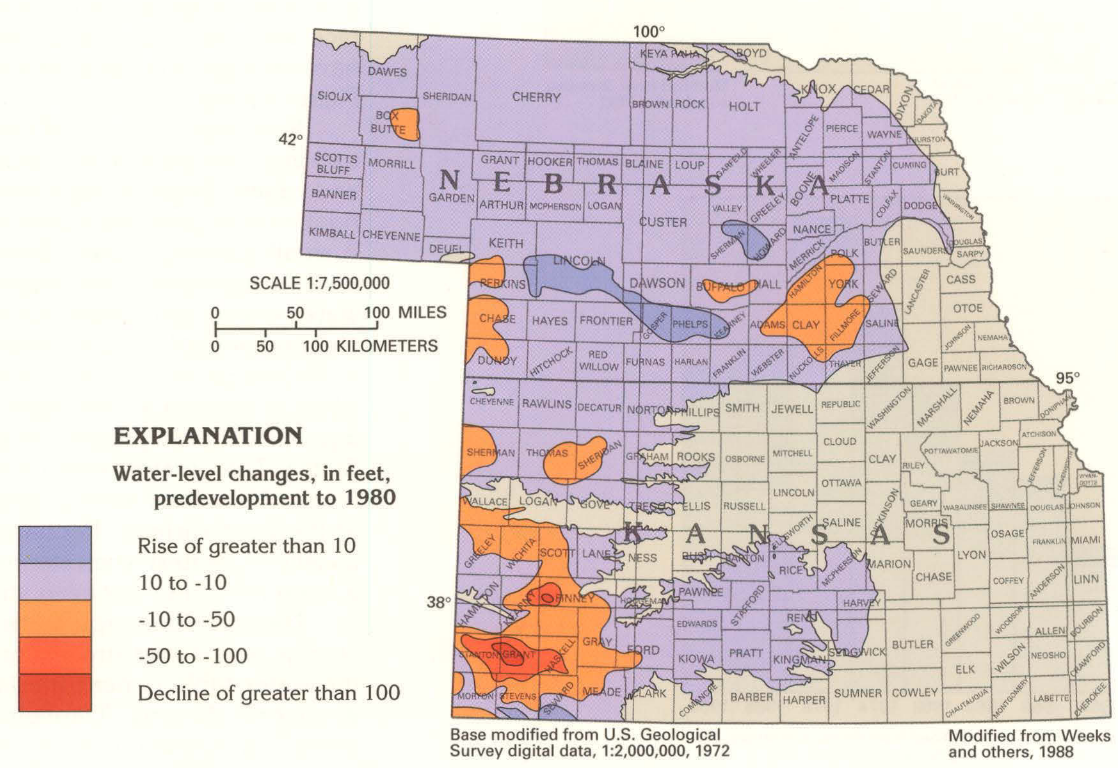


Figure 63. *From predevelopment conditions to 1980, water levels in the High Plains aquifer have remained stable in most of Nebraska and Kansas but have declined more than 100 feet in parts of southwestern Kansas. In southern Nebraska, water levels have risen as a result of infiltration of surface-water irrigation.*

As development of the High Plains aquifer became more extensive, water levels in the aquifer began to decline in some locations. Well yields decreased in some places as a result of the water-level declines. The cost of pumping increased as water levels declined because pumps were set deeper and more energy was required to lift the water an increased distance. The cost of the energy used to pump the water also increased. This increased cost for obtaining irrigation water decreased the profit in growing crops that require irrigation in parts of the High Plains area.

Average annual withdrawals of water from the High Plains aquifer generally are much larger than recharge to the aquifer from precipitation. In places where recharge rates are high, the demand for irrigation water could be as low as twice the average annual recharge; where recharge rates are low, the demand could be more than 100 times the recharge. The quantity of water removed from storage from the entire aquifer between predevelopment conditions and 1980 is estimated to be about 166 million acre-feet, of which about 27 million acre-feet was withdrawn in Kansas. No significant quantity of water has been removed from storage in Nebraska. By 1980, withdrawals of water from the High Plains aquifer had resulted in water-level declines of more than 100 feet in parts of southwestern Kansas (**fig. 63**). Development of the aquifer in this area began in the 1940's, which is earlier than in most other places in Kansas. Generally, the later development of the aquifer began in an area and the less intense the development has been, the smaller the water-level decline in that area. Water-level rises shown in parts of southern Nebraska are in response to increased recharge of the aquifer by infiltration of surface water applied for irrigation.

GROUND-WATER QUALITY

The chemical quality of water in the High Plains aquifer is affected by many factors. These factors include the chemical composition and solubility of aquifer materials, the increase in dissolved-solids concentrations in ground water in areas where the water discharges by evapotranspiration, and the chemical composition of the water that recharges the aquifer. Ground water generally contains smaller concentrations of dissolved minerals near recharge areas where the residence time of the water in the aquifer has been short, and, thus, dissolution of aquifer minerals has been less. The water generally is more mineralized near discharge areas because residence time has been longer and more dissolution of minerals has taken place.

The dissolved-solids concentration in ground water is a general indicator of the chemical quality of the water. Dissolved-solids concentrations in water from the High Plains aquifer are less than 500 milligrams per liter in most of Kansas and Nebraska (**fig. 64**) but locally exceed 1,000 milligrams per liter in both States. The limit of dissolved solids recommended by the U.S. Environmental Protection Agency for drinking water is 500 milligrams per liter. Most crops can tolerate water in which the dissolved-solids concentration is 500 milligrams per liter or less. In places with well-drained soils, many types of crops can tolerate water with a dissolved-solids concentration of between 500 and 1,500 milligrams per liter. In southwestern and south-central Kansas, the High Plains aquifer overlies Permian bedrock that contains bedded salt. Where circulating ground water has dissolved some of this salt and the mineralized water has subsequently moved upward into the High Plains aquifer, the dissolved-solids concentration of the water in the High Plains aquifer is greatly increased. Also, dissolved-solids concentrations generally are greater near streams where water from the High Plains aquifer discharges. Ground water near the streams is shallow enough to be transpired by plants or to be evaporated directly from the soil. Concentrations of dissolved solids in the ground water are increased by the evapotranspiration process. Rates of transpiration are greatest where deep-rooted phreatophytes, such as sedges, cottonwood, willows, and salt cedar, grow.

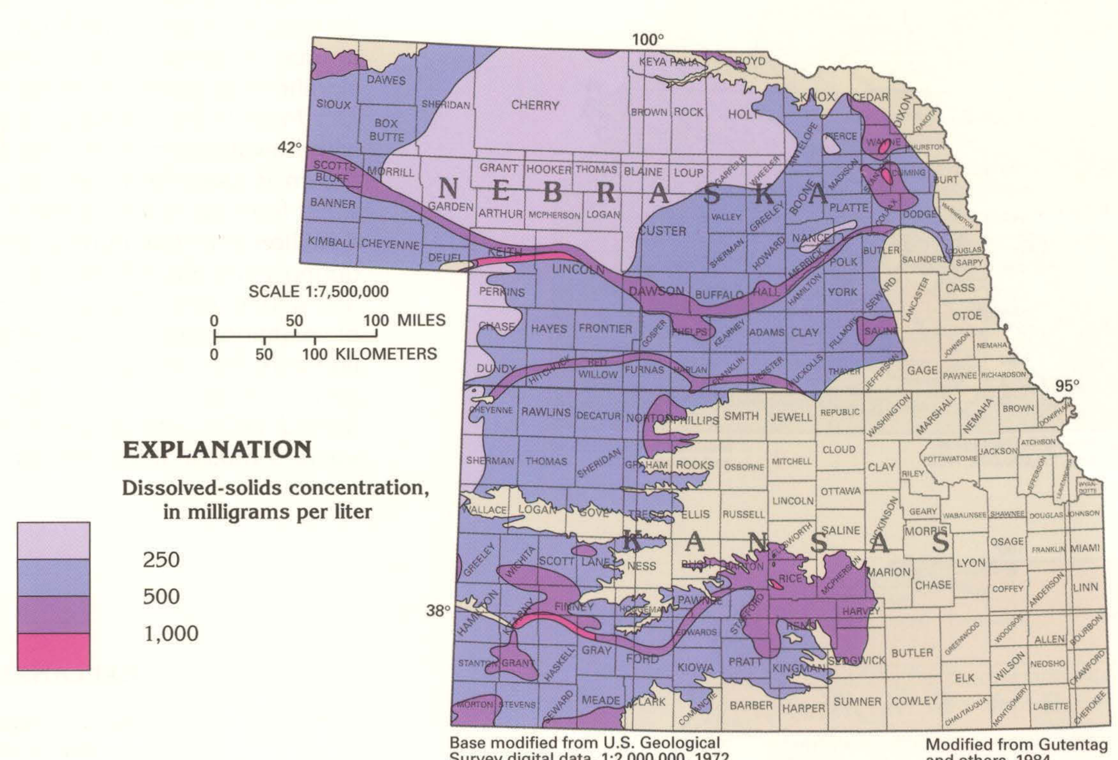


Figure 64. *Dissolved-solids concentrations in water from the High Plains aquifer generally are less than 500 milligrams per liter but locally are greater than 1,000 milligrams per liter. The larger concentrations coincide with places where the bedrock that underlies the aquifer contains saline water and near streams where evapotranspiration rates are high.*

Excessive concentrations of sodium in water adversely affect plant growth and soil properties, and constitute salinity and sodium hazards that may limit irrigation development. Sodium that has been concentrated in the soil by evapotranspiration and ion exchange decreases soil tillability and permeability. Areas of high or very high sodium hazard occur in parts of Kansas. Sodium hazard is evaluated by the sodium adsorption ratio, which relates the concentration of sodium to calcium plus magnesium; if this ratio is high, then the sodium can destroy any clay in the soil and thus affect soil structure. Sodium concentrations in water from the High Plains aquifer in Kansas and Nebraska are shown in **figure 65**. Concentrations are less than 25 milligrams per liter in most of Nebraska and northern Kansas. Concentrations are greatest in southwestern Kansas where evapotranspiration rates are high and in south-central Kansas where the High Plains aquifer overlies Permian bedrock that contains saline water derived from partial dissolution of salt beds. Sodium concentrations are increased along the Platte and the Republican Rivers where evapotranspiration rates also are high. Salinity and sodium hazards generally are low in Nebraska where the High Plains aquifer primarily consists of sand and gravel, which contain few sodium-bearing minerals.

Excessive fluoride concentrations are a widespread problem in water from the High Plains aquifer. Some of the fluoride is derived from dissolution of fluoride-bearing minerals in parts of the aquifer that contain sand and gravel, such as the Ogallala Formation. Extremely large concentrations (2–8 milligrams per liter) of fluoride are reported where the aquifer contains volcanic ash deposits or where it is underlain by rocks of Cretaceous age. Large concentrations of fluoride in drinking water cause staining of teeth, but fluoride is not a concern in irrigation water.

The generally shallow depth of the water table in the High Plains aquifer makes water in the aquifer susceptible to contamination. Application of fertilizers and organic pesticides to cropland has greatly increased since the 1960's, thus increasing the availability and the amount of potential contaminants available. Increased concentrations of sodium, alkalinity, nitrate, and triazine (a herbicide) have been found in water that underlies small areas of irrigated cropland in Nebraska and Kansas. Of 132 wells sampled during 1984–85 in Nebraska, 43 had measurable concentrations (greater than 0.04 microgram per liter) of the herbicide atrazine. Increased concentrations of 2,4-Dichlorophen-oxyacetic acid (2,4-D, a pesticide) were found in water that underlies rangeland in a small part of the Great Bend area of the Arkansas River in Kansas.

FRESH GROUND-WATER WITHDRAWALS

Withdrawals of fresh ground water from the High Plains aquifer in Segment 3 during 1990 totaled 8,181 million gallons per day (**fig. 66**). Of this amount, 4,556 million gallons per day was withdrawn in Nebraska. About 97 percent of the total withdrawals, or about 7,900 million gallons per day, was used for agricultural, primarily irrigation, purposes. About 200 million gallons per day was pumped for public supply. Domestic and commercial withdrawals were about 40 million gallons per day, and industrial, mining, and thermoelectric power withdrawals also were about 40 million gallons per day.

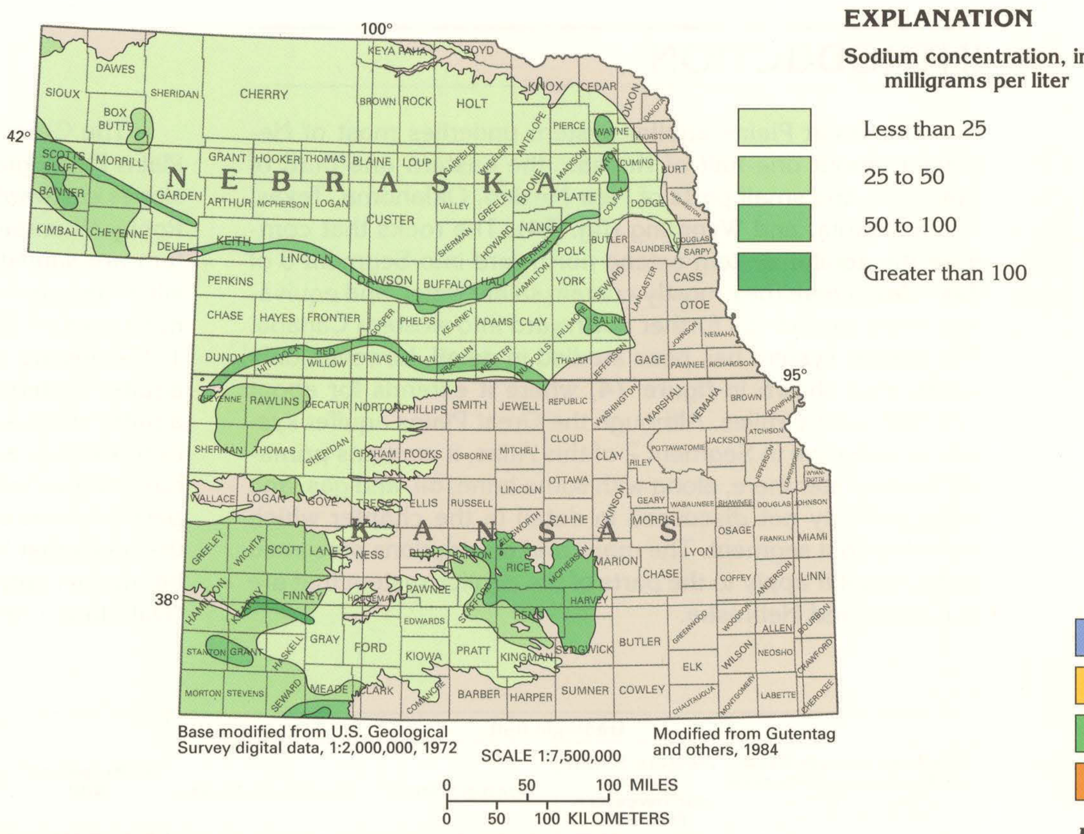


Figure 65. *Sodium concentrations in water from the High Plains aquifer generally are less than 50 milligrams per liter but locally exceed 100 milligrams per liter. Concentrations are largest near streams, where evapotranspiration rates are high, and in places where the underlying bedrock contains saline water.*

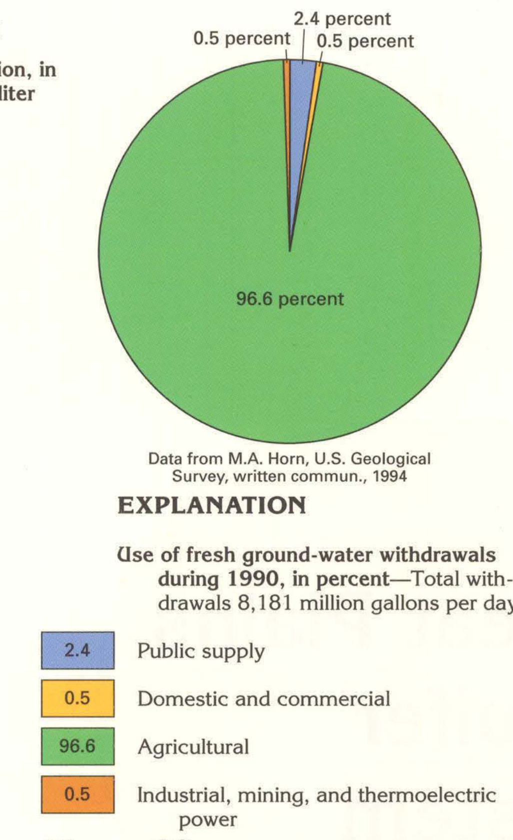


Figure 66. *Most of the water withdrawn from the High Plains aquifer during 1990 was used for irrigation. Less than 4 percent of the water pumped from the aquifer was used for nonagricultural purposes.*

Mississippi embayment aquifer system

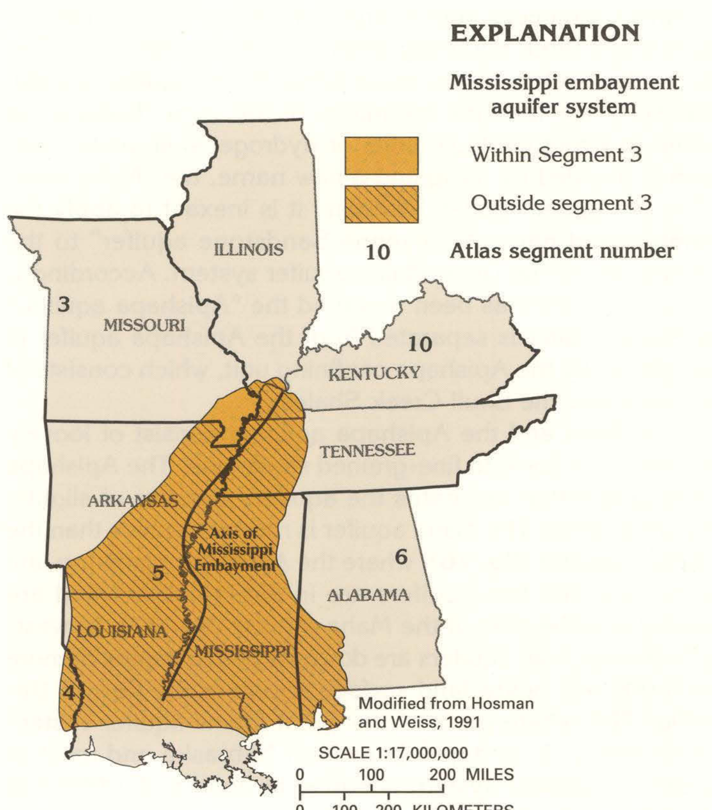


Figure 67. *Sediments of the Mississippi embayment aquifer system underlie all or parts of eight counties in the bootheel of Missouri and adjacent areas.*

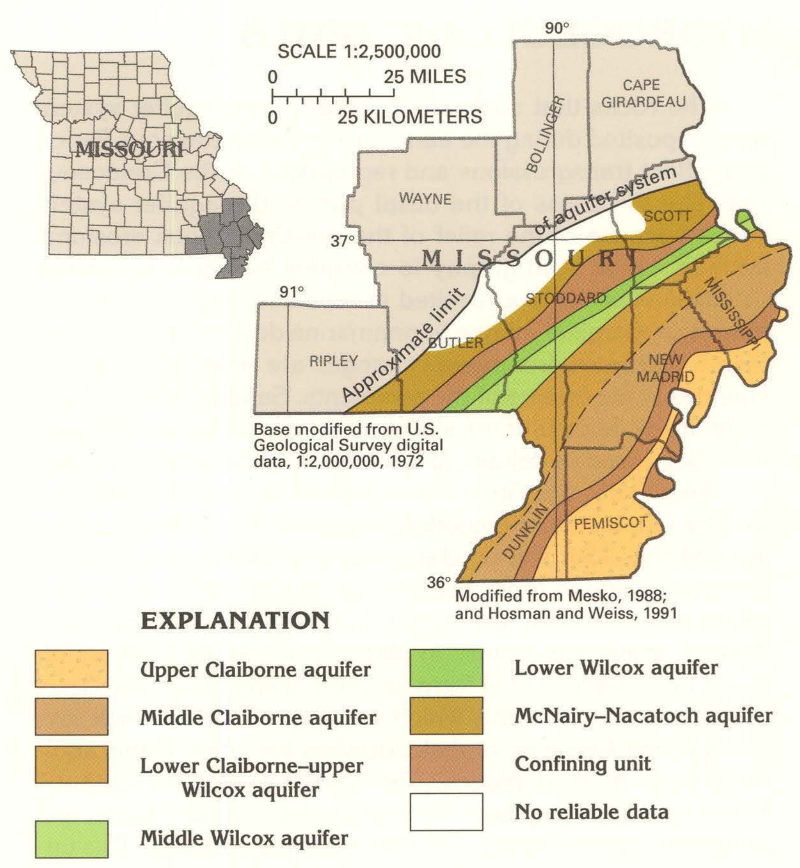


Figure 68. *The aquifers and confining units of the Mississippi embayment aquifer system subcrop in a sequence of arcuate bands beneath the Mississippi River Valley alluvial aquifer. The aquifers are on the northwestern flank of the Mississippi Embayment, which is a large reentrant of Coastal Plain sediments in a downwarp of the Earth's crust.*

System	Series	Geologic unit		Lithology	Hydrogeologic unit[1]	
Tertiary	Eocene		Jackson Formation	Silty sand and clayey silt	Vicksburg–Jackson confining unit	
		Claiborne Group	Cockfield Formation	Sand and silt	Upper Claiborne aquifer	Mississippi embayment aquifer system
			Cook Mountain Formation	Clay and silt	Middle Claiborne confining unit	
			Memphis Sand	Sand and minor clay, some lignite	Middle Claiborne aquifer	
		Wilcox Group	Flour Island Formation		Lower Claiborne-upper Wilcox aquifer	
	Paleocene		Fort Pillow Sand		Middle Wilcox aquifer	
			Old Breastworks Formation		Lower Wilcox aquifer	
		Midway Group	Porters Creek Clay	Clay and marl, glauconite	Midway confining unit	
			Clayton Formation			
Cretacous	Upper		Owl Creek Clay[2]	Clay	McNairy–Nacatoch aquifer	
			McNairy Sand	Sand		

[1]Hydrogeologic unit names apply to the entire Mississippi embayment aquifer system. Local names may differ.
[2]Local confining unit

Modified from Mesko, 1988; and Hosman and Weiss, 1991

Figure 69. *Six sand aquifers and two clayey confining units compose the Mississippi embayment aquifer system. The aquifers are in sediments that range in age from Eocene to Cretaceous.*

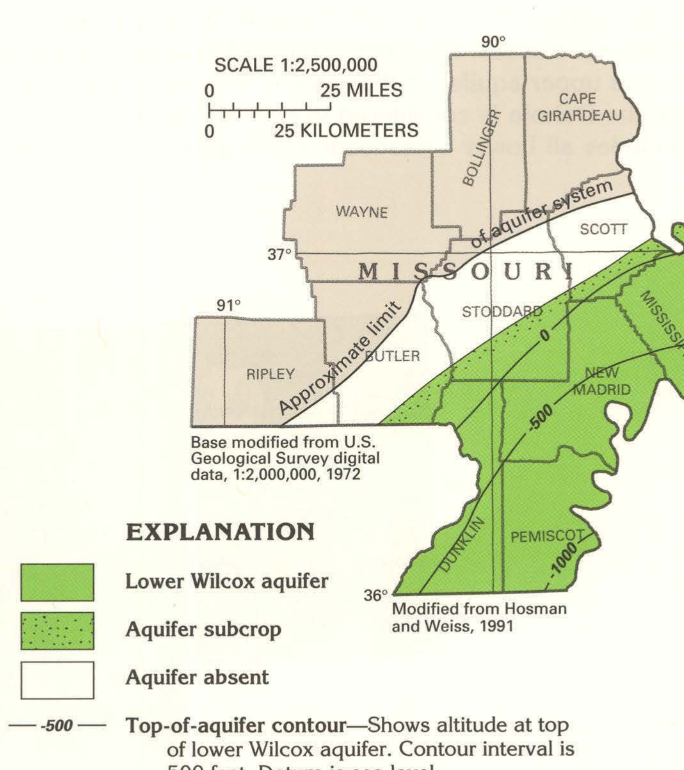


Figure 70. *The altitude of the top of the lower Wilcox aquifer is about 200 feet above sea level where the aquifer subcrops in southeastern Missouri. The top of the aquifer slopes to more than 1,000 feet below sea level in part of Pemiscot County.*

INTRODUCTION

The Mississippi embayment aquifer system in Segment 3 is in southeastern Missouri (**fig. 67**) on the western side of the Mississippi Embayment section of the Coastal Plain Physiographic Province. The aquifers that comprise the aquifer system are unconsolidated to semiconsolidated sands that range in age from Eocene to Late Cretaceous. The Mississippi embayment aquifer system extends over large areas in Arkansas, Louisiana, and Mississippi and smaller areas in Alabama, Florida, Illinois, Kentucky, Missouri, and Tennessee (**fig. 67**). The aquifer system is areally extensive in Segment 5 of this Atlas and is discussed in greater detail in chapter F which describes that segment. Little freshwater is withdrawn from the Mississippi embayment aquifer system in Missouri because it is overlain in most places by the productive Mississippi River Valley alluvial aquifer.

HYDROGEOLOGIC UNITS

The six aquifers and two confining units that compose the Mississippi embayment aquifer system in Missouri subcrop as narrow bands (**fig. 68**) beneath the Mississippi River Valley alluvial aquifer. Five of the aquifers of the Mississippi embayment aquifer system are in Tertiary rocks (**fig. 69**). In descending order, these are the upper Claiborne aquifer, the middle Claiborne aquifer, the lower Claiborne-upper Wilcox aquifer, the middle Wilcox aquifer, and the lower Wilcox aquifer. The clayey middle Claiborne confining unit separates the upper Claiborne and middle Claiborne aquifers. The McNairy–Nacatoch aquifer, deepest aquifer in the system, is in sands of Cretaceous age and underlies thick clay of the Midway confining unit. Clayey silt of the Vicksburg–Jackson confining unit overlies the aquifer system locally in an area adjacent to Tennessee.

Although some of the aquifers in the Mississippi embayment aquifer system are not separated by regional confining units, they can be defined on the basis of changes in lithology and hydraulic head (water level) between aquifers. The vertical movement of water between the middle Claiborne through lower Wilcox aquifers is restricted somewhat by interbedded fine-grained sediments within the aquifers. In contrast, the middle Claiborne and Midway confining units more effectively retard the vertical movement of water between aquifers.

The extensive, massive water-yielding sands of the aquifer system slope and thicken in Missouri toward the axis of the Mississippi Embayment. The lower Wilcox aquifer has been chosen to illustrate the aquifer system because it extends over a wide area and has been penetrated by numerous wells. The top of the lower Wilcox aquifer is about 200 feet above sea level at its updip limit but slopes to more than 1,000 feet below sea level in southeastern Pemiscot County (**fig. 70**). On the opposite (Tennessee) side of the Embayment, the top of the aquifer is shallower. The aquifer, thus, has a troughlike shape, as do the aquifers that overlie and underlie it.

The lower Wilcox aquifer thickens from a featheredge at its northwestern limit to more than 300 feet in southeastern Pemiscot County (**fig. 71**). The troughlike shape of the aquifer is shown by the curvature of the lines of equal thickness near the Mississippi River. East of the river, the aquifer thins toward its outcrop area in Tennessee. Shallower and deeper aquifers in the Mississippi embayment aquifer system show the same thickening and thinning trends as those of the lower Wilcox aquifer.

GROUND-WATER FLOW

Because the Mississippi embayment aquifer system in Missouri is covered by the Mississippi River Valley alluvial aquifer in most places, the aquifer system is recharged mostly by downward leakage of water from the alluvial aquifer. Water enters the lower Wilcox aquifer in a band where sands of the aquifer are in hydraulic contact with those of the overlying Mississippi River Valley alluvial aquifer (**fig. 72**). The water then moves southeastward down the dip of the sand beds in the lower Wilcox aquifer. Water in the aquifer also moves westward and southwestward from aquifer outcrop areas in Tennessee and Kentucky. Because the lower Wilcox aquifer is deeply buried, this water moves under the Mississippi River without discharging to the river. Water discharges from the aquifer by upward leakage to shallower aquifers in Arkansas.

GROUND-WATER QUALITY

The chemical quality of freshwater in the aquifers of the Mississippi embayment aquifer system in Missouri is suitable for most uses. The water is fresh except locally in the McNairy–Nacatoch aquifer, which is the deepest aquifer of the system (**fig. 73**). Dissolved-solids concentrations in water from this aquifer locally exceed 2,000 milligrams per liter in New Madrid and Stoddard Counties and exceed 1,000 milligrams per liter in an area of about 450 square miles. Water in this area is a sodium chloride type and probably has entered the McNairy–Nacatoch aquifer by upward leakage from underlying Paleozoic rocks that locally contain saline water. Water in shallower aquifers of the Mississippi embayment aquifer system is fresher than that in the McNairy–Nacatoch aquifer.

Water in the aquifers of the Mississippi embayment aquifer system is a calcium magnesium bicarbonate type in aquifer recharge areas. As the water moves down the hydraulic gradient, it changes to a sodium bicarbonate type and locally changes to a sodium chloride type in deeply buried, downgradient parts of the aquifers.

FRESH GROUND-WATER WITHDRAWALS

About 95 million gallons per day of freshwater was pumped from all the aquifers of the Mississippi embayment aquifer system in Missouri during 1990. Most of the water was withdrawn for agricultural, primarily irrigation, use. Because the overlying Mississippi River Valley alluvial aquifer is a thick, productive aquifer, larger amounts of water are withdrawn from it than from the deeper Mississippi embayment aquifer system.

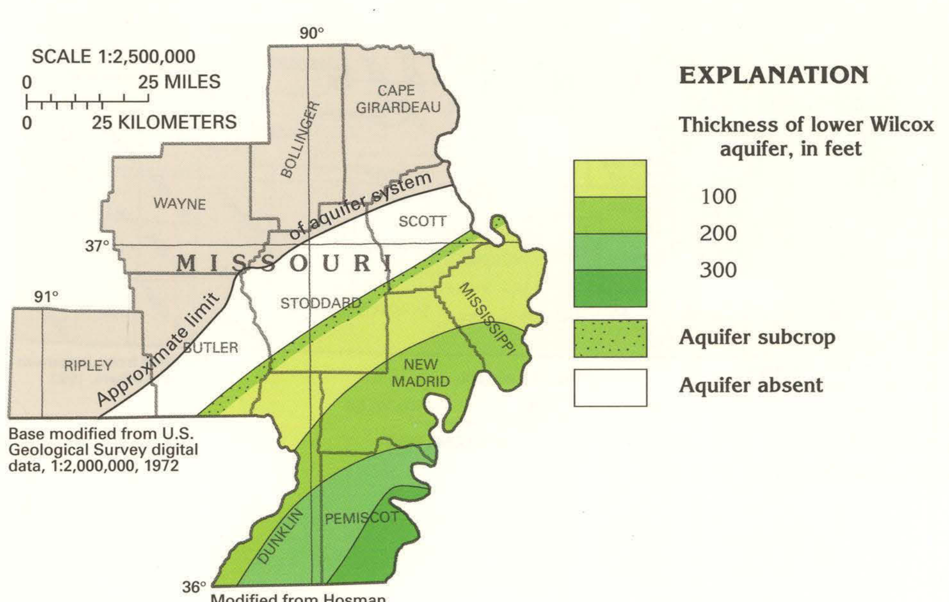


Figure 71. *From a featheredge near its northwestern limit, the lower Wilcox aquifer thickens southeastward to more than 300 feet in Pemiscot County, Missouri.*

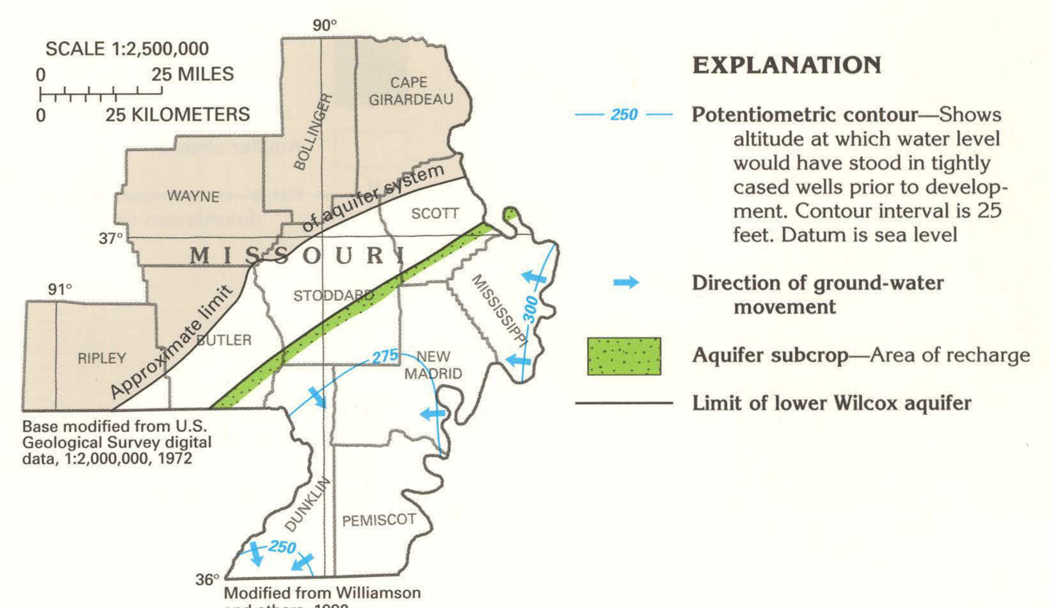


Figure 72. *Water in the lower Wilcox aquifer moves southeastward from recharge areas in Missouri and westward and southwestward from recharge areas in Tennessee and Kentucky.*

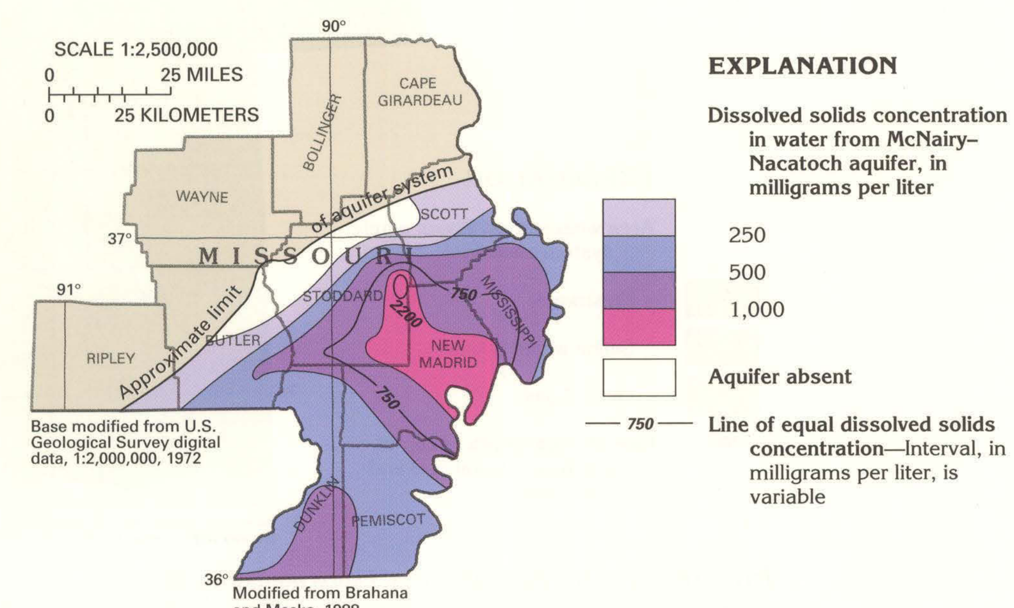


Figure 73. *Water in the McNairy–Nacatoch aquifer contains less than 1,000 milligrams per liter dissolved-solids concentrations except for an area in New Madrid and Stoddard Counties. Dissolved-solids concentrations in the shallower aquifers of the Mississippi embayment aquifer system are smaller than those shown here.*

Great Plains aquifer system

INTRODUCTION

The Great Plains aquifer system underlies most of Nebraska, about one-half of Kansas, the eastern one-third of Colorado, and small parts of New Mexico, Oklahoma, Texas, South Dakota, and Wyoming (**fig. 74**). The rocks that compose the aquifer system extend northward into Segment 8 of this Atlas, where they mostly contain saline water, and equivalent rocks extend still further northward into western Canada. The aquifer system has been studied in detail, however, only in the area shown in **figure 74**, where it extends for about 170,000 square miles. Although the Great Plains aquifer system is extensive in Segment 2 of this Atlas, it contains primarily saline water there, along with some brine, oil, and gas, and is accordingly not discussed in detail in the chapter which describes that segment. The maps and descriptions presented in this chapter apply to the parts of the aquifer system that are in Kansas and Nebraska.

The Great Plains aquifer system is named for the Great Plains Physiographic Province, which is a vast, rolling plain that slopes eastward for several hundred miles from the front of the Rocky Mountains. The water-yielding rocks of the aquifer system are sandstone; confining units in the system consist of siltstone and shale. Water has been produced from the uppermost part of the aquifer system for many years; more than 1,000 flowing wells were reported to produce water from the aquifer system in 1905. In the early 1900's, the uppermost aquifer of the system was named the Dakota aquifer and was described as a classic artesian system. More recent studies have shown that the flow system of this aquifer is more complex than was originally thought. Likewise, the stratigraphy of the rocks that form the aquifer is complex. It is now known to be an oversimplification to refer to the aquifer simply as the "Dakota aquifer," and it has accordingly been renamed.

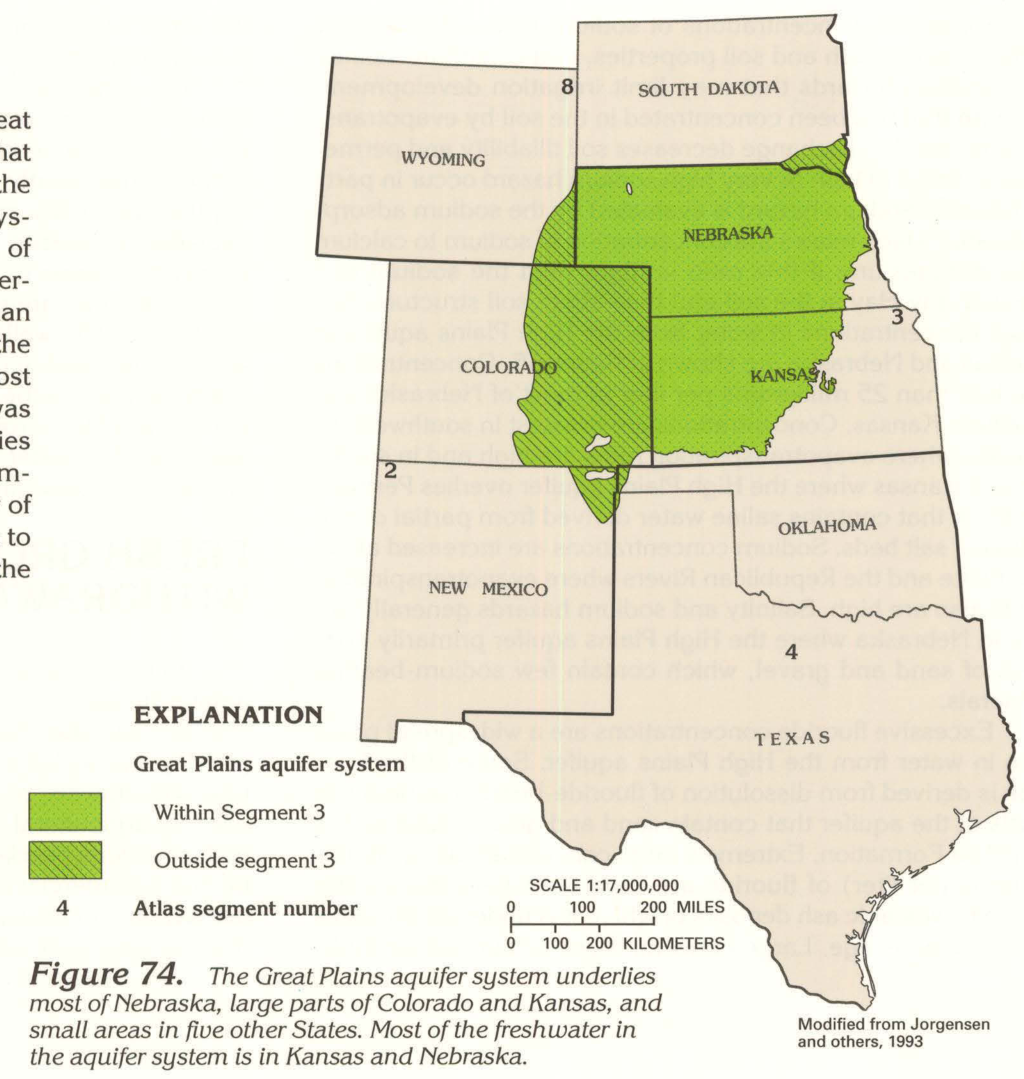


Figure 74. *The Great Plains aquifer system underlies most of Nebraska, large parts of Colorado and Kansas, and small areas in five other States. Most of the freshwater in the aquifer system is in Kansas and Nebraska.*

Geologic unit								Hydrogeologic unit
Northern Denver Basin, southwestern Nebraska (Usage of Nebraska Geological Survey)			Western South Dakota, northwestern Nebraska		Central Kansas		Eastern Nebraska	
Dakota Group	Omadi Sandstone	Gurley ("D") sandstone[1]	Newcastle Sandstone		Dakota Formation	Janssen Clay Member	Dakota Sandstone	Great Plains aquifer system
		Huntsman shale[1]						
		Cruise ("J") sandstone[1]				Terra Cotta Clay Member		
	Skull Creek Shale		Skull Creek Shale		Kiowa Shale		Missing rocks	
	Fall River Sandstone		Inyan Kara Group	Fall River Sandstone	Cheyenne Sandstone			
	Fuson Shale			Fuson Shale				
	Lakota Formation			Lakota Formation				

[1]Informal subsurface usage

Modified from Helgesen and others, 1993

EXPLANATION
- Maha aquifer
- Apishapa confining unit
- Apishapa aquifer
- Missing rocks

Figure 75. *The Great Plains aquifer system consists of the Maha and the Apishapa aquifers and the intervening Apishapa confining unit. Several geologic formations compose each aquifer in the western part of Segment 3, but the aquifer system contains fewer formations in the eastern part of the segment.*

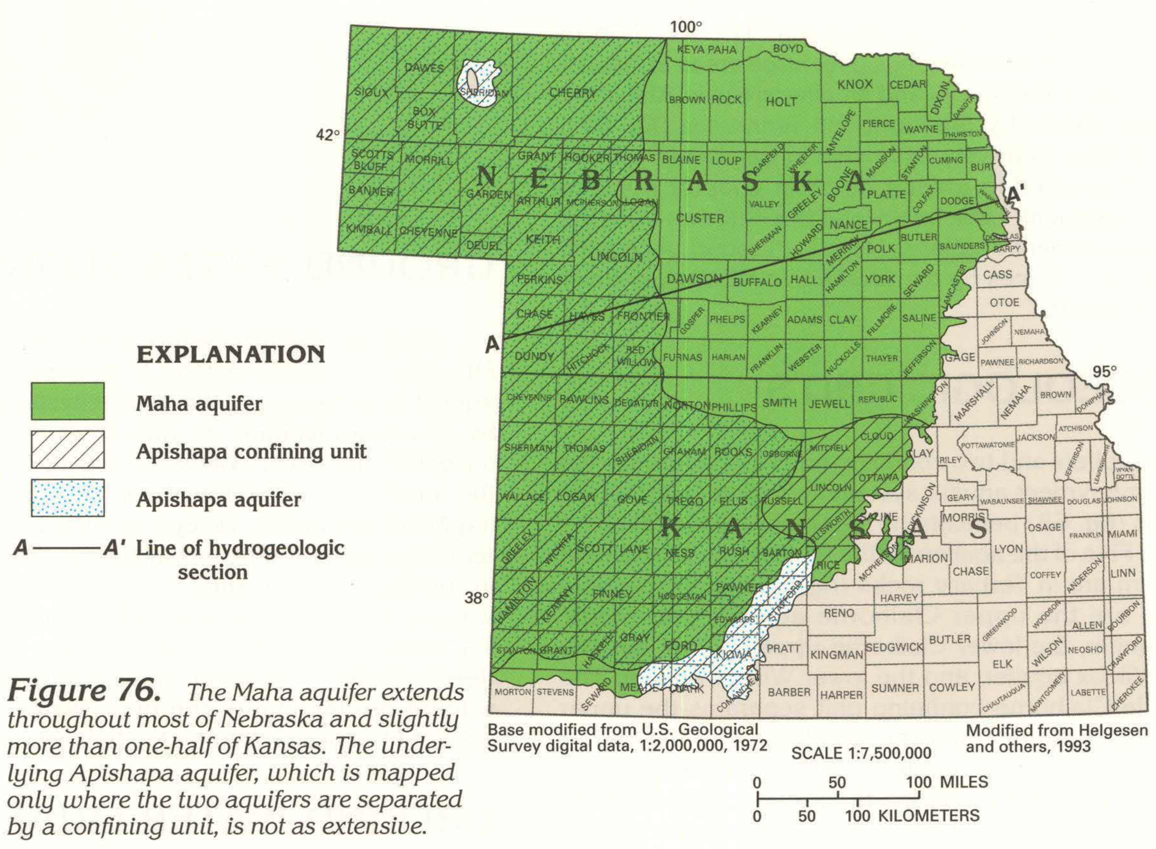


Figure 76. *The Maha aquifer extends throughout most of Nebraska and slightly more than one-half of Kansas. The underlying Apishapa aquifer, which is mapped only where the two aquifers are separated by a confining unit, is not as extensive.*

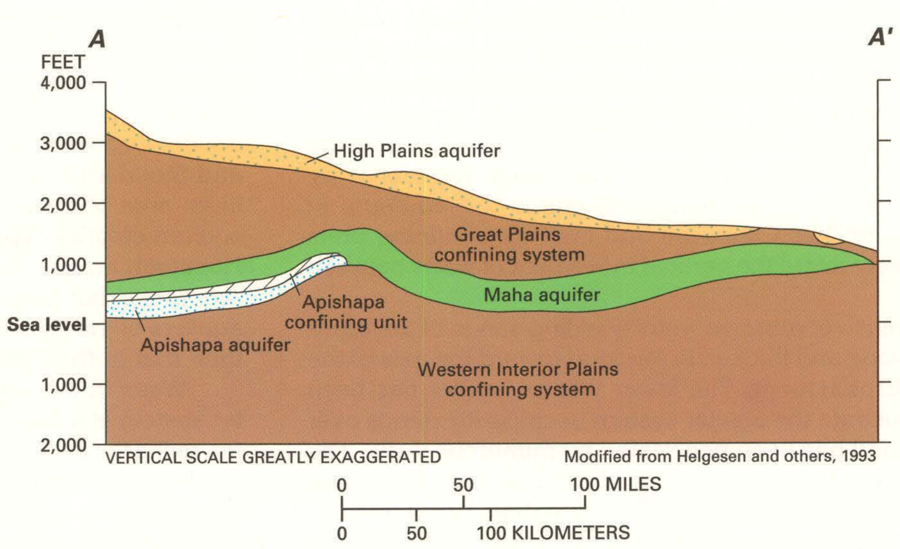


Figure 77. *The Great Plains aquifer system is overlain and underlain by thick shale confining units. The two aquifers that compose the aquifer system merge into a single aquifer in central Nebraska. The line of the hydrogeologic section is shown in figure 76.*

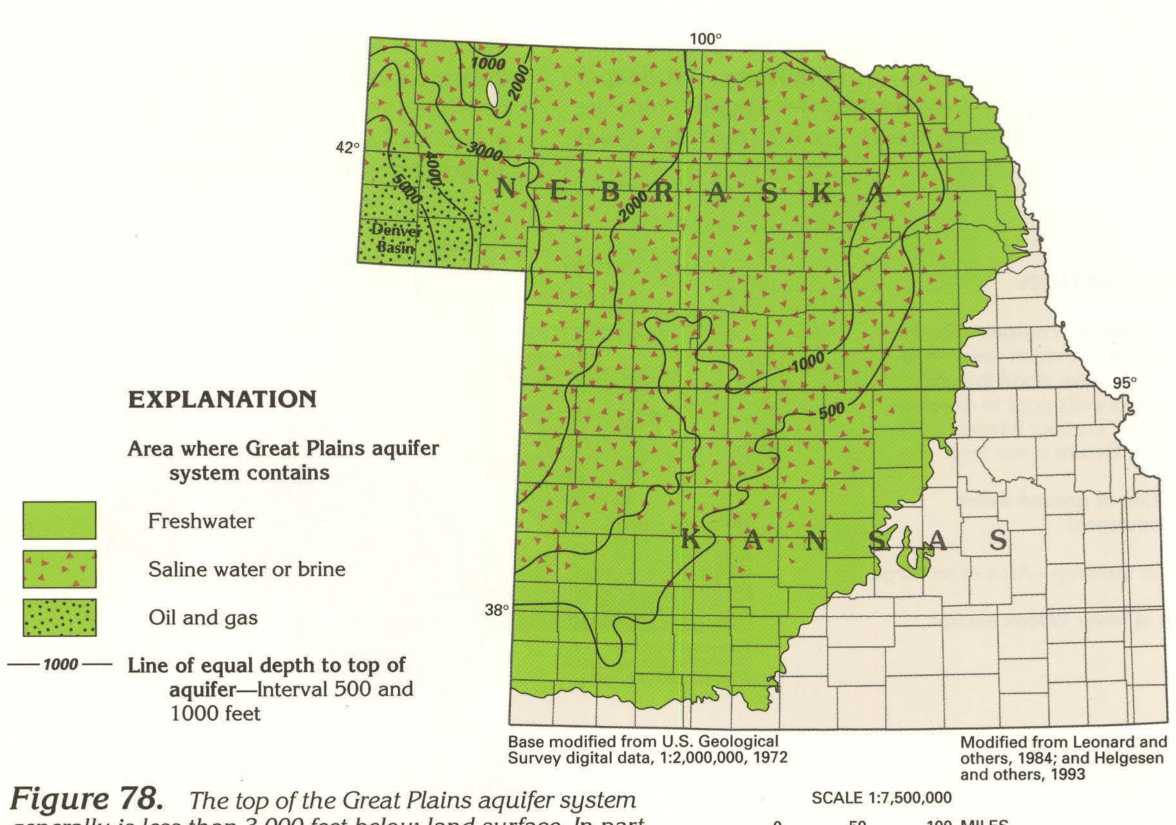


Figure 78. *The top of the Great Plains aquifer system generally is less than 3,000 feet below land surface. In part of the Denver Basin, however, the aquifer system is deeper than 5,000 feet below land surface and locally contains oil and gas. Most of the freshwater is withdrawn from the aquifer system where the overlying rocks are thin.*

HYDROGEOLOGIC UNITS

The rocks that contain the Great Plains aquifer system were deposited during the early part of the Cretaceous Period and reflect transgressions and regressions of the Cretaceous sea. The thickness of the basal part of the aquifer system varies because of the relief of the pre-Cretaceous erosional surface. Local stratigraphy is complex because numerous oscillations of the sea resulted in repeated, rapid shifts from marine to marginal marine to nonmarine depositional environments. These environmental changes are reflected in abrupt changes in the texture of the sediments. Sand bodies are typically linear, lenticular, or sinuous, which indicates that they were deposited in deltaic, shoreline, or fluvial environments.

Regionally, the Great Plains aquifer system is characterized by two sandstone aquifers separated by a shale confining unit (**fig. 75**). The aquifer system contains more geologic formations and is more complex in southwestern Nebraska, where it is extremely thick, than to the east in Nebraska and Kansas, where it is thinner. In places, both aquifers are subdivided by shale beds that form local confining units. The Great Plains confining system, which consists mostly of thick layers of Upper Cretaceous shale, overlies the Great Plains aquifer system in most places. The aquifer system is confined below by a thick sequence of shale, limestone, sandstone, and anhydrite beds of Jurassic to Late Mississippian age. This underlying sequence of confining beds is called the Western Interior Plains confining system.

The upper aquifer of the Great Plains aquifer system is called the Maha aquifer. This aquifer was formerly called the Dakota aquifer from the Dakota Sandstone, which is a prominent part of the aquifer. The Maha is the best known and most used part of the aquifer system. The correlation chart (**fig. 75**) shows the different usage of the term "Dakota" in different places throughout the extent of the aquifer system. In eastern Nebraska and Kansas, the name "Dakota Formation" applies only to the upper aquifer of the system. In southwestern Nebraska, the Dakota is considered to be a stratigraphic group that includes all Lower Cretaceous rocks and the lower part of Upper Cretaceous rocks, and consists of four sandstone aquifers and three confining units. In Kansas, the term "Dakota aquifer" refers to the entire Great Plains aquifer system. Because of the multiple meanings of the term "Dakota" as applied to either geologic units or hydrogeologic units, confusion is avoided by assigning a new name, the "Maha aquifer," to the upper aquifer. Likewise, it is inexact to apply the formerly used name "Cheyenne Sandstone aquifer" to the lower aquifer of the Great Plains aquifer system. Accordingly, this lower aquifer has been renamed the "Apishapa aquifer." The Maha aquifer is separated from the Apishapa aquifer in most places by the Apishapa confining unit, which consists of the Kiowa and the Skull Creek Shales.

The Maha and the Apishapa aquifers consist of loosely cemented, medium- to fine-grained sandstone. The Apishapa confining unit that separates the aquifers consists of slightly permeable shale. The Maha aquifer is more extensive than the Apishapa aquifer (**fig. 76**); where the Apishapa confining unit pinches out, the two aquifers are in direct contact and are considered to be part of the Maha aquifer (**fig. 77**). In western Nebraska, both aquifers are downwarped to depths of more than 5,000 feet below land surface in part of the Denver Basin (**fig. 78**), where parts of the Great Plains aquifer system contain brine, oil, and gas. In eastern Nebraska and most of Kansas, the aquifer system is buried to depths of 1,000 feet or less below land surface.

The Maha aquifer is much thicker than the Apishapa aquifer in most places. The thickness of the Maha aquifer generally is about 200 to 300 feet in western Nebraska and most of Kansas, but locally the aquifer is more than 800 feet thick in north-central Nebraska (**fig. 79**). The greatest thicknesses of the Maha aquifer are just east of where the Apishapa confining unit pinches out and the sandstones of the underlying Apishapa aquifer merge with those of the Maha aquifer. The Apishapa aquifer typically is between 100 and 200 feet thick (**fig. 80**) but locally is more than 400 feet thick in west-central Nebraska. The thickness of the Apishapa aquifer varies because the sedimentary rocks that compose the aquifer were deposited on an irregular erosional surface.

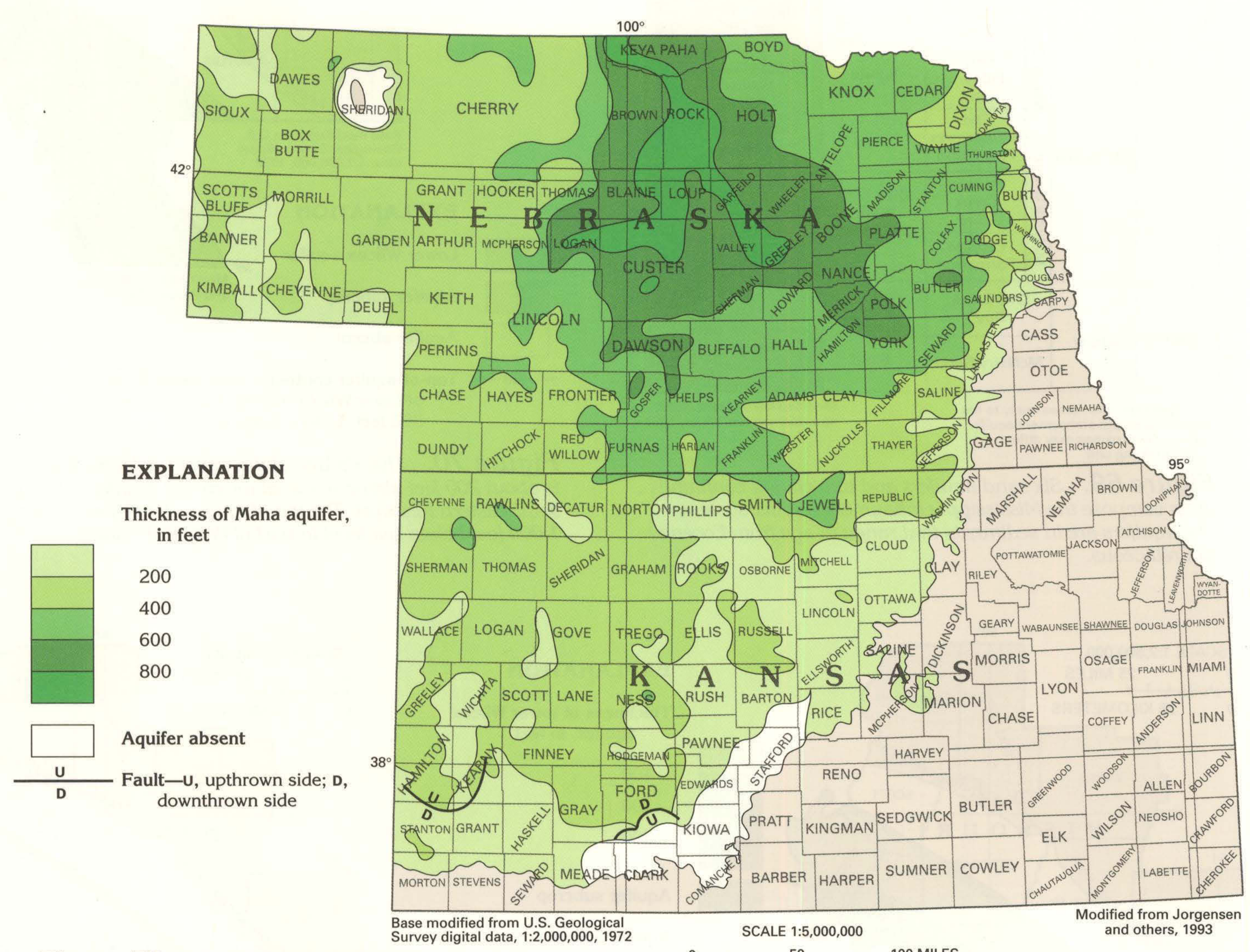


Figure 79. *The Maha aquifer is thickest in north-central Nebraska and thins toward the east, west, and south. The aquifer is less than 400 feet thick in most places, but locally is more than 800 feet thick in Nebraska.*

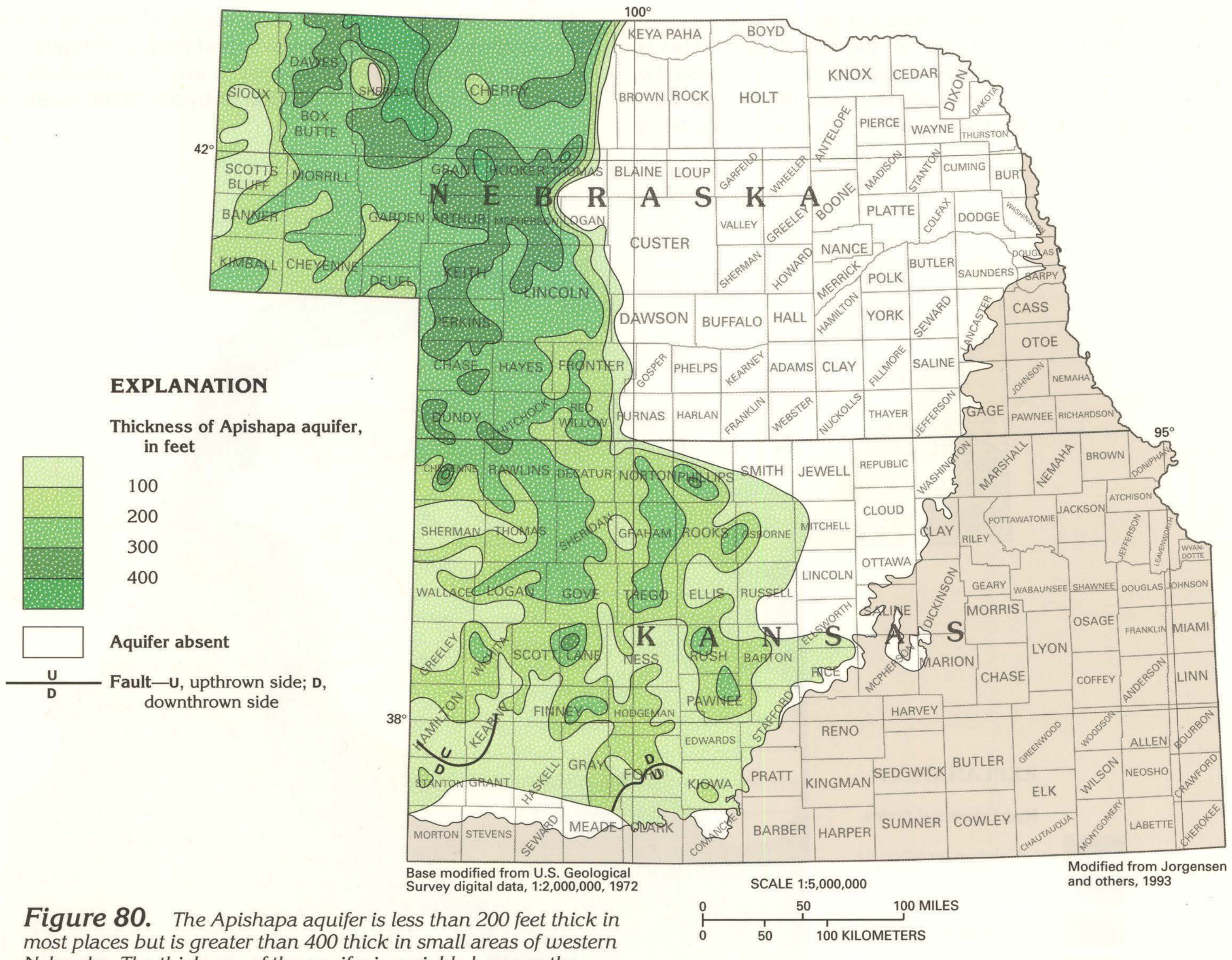


Figure 80. *The Apishapa aquifer is less than 200 feet thick in most places but is greater than 400 thick in small areas of western Nebraska. The thickness of the aquifer is variable because the sandstone that composes it was deposited on an erosional surface.*

GROUND-WATER FLOW

The regional movement of water in the Great Plains aquifer system in Segment 3 can be inferred from a map of the potentiometric surface of the aquifer system (**fig. 81**). Water levels in the aquifer system are highest in southwestern Kansas and northwestern Nebraska. Water moves generally eastward and northeastward from recharge areas in southeastern Colorado toward discharge areas in central Kansas, eastern Nebraska, and along the Missouri River in northeastern Nebraska. In its central parts, the aquifer system typically is overlain by a thick confining system, and the hydraulic gradient is flat. Water in the aquifer system in these places moves sluggishly. Near the eastern limit of the aquifer system, the hydraulic gradient becomes steeper, which indicates a more dynamic ground-water flow system.

Much of the recharge to the aquifer system is from precipitation that falls directly on aquifer outcrop areas in southern and southeastern Colorado and east-central Kansas. Some recharge, however, enters the aquifer system as downward leakage through the overlying Great Plains confining system. The High Plains aquifer overlies this confining system, and the hydraulic gradient is downward from the High Plains aquifer to the Great Plains aquifer system in most places (**fig. 82**). For example, in the southwestern part of the Nebraska panhandle, the water table in the High Plains aquifer is more than 2,500 feet higher than the hydraulic head in the Great Plains aquifer system. In many places near the eastern limit of the Great Plains aquifer system, however, water levels in the High Plains aquifer and the Great Plains aquifer system are about equal. Locally, the hydraulic gradient is reversed, and discharge takes place by upward leakage from the Great Plains aquifer system to the High Plains aquifer. Most discharge from the Great Plains aquifer system is by upward leakage, but some discharge is as base flow to streams in aquifer outcrop areas.

The Great Plains aquifer system is mostly confined above by the Great Plains confining system and below by the Western Interior Plains confining system. Movement of water through the confined parts of the aquifer system is very slow and is estimated to be 10 feet per year or less. Flow is more rapid in places where the aquifer system crops out or the overlying confining system is thin. The presence of oil, gas, and brine in deeply buried parts of the aquifer system, such as the Denver Basin, indicates that the water in such places is virtually stagnant.

Most of the data available for the water-yielding capability of the Great Plains aquifer system are from the Maha aquifer. Sparse data from the deeper Apishapa aquifer indicate that the two aquifers have similar hydraulic properties, which show similar trends. Most of the porosity in the aquifer system is intergranular; that is, it consists of pore spaces between individual sand grains. Joints, fractures, and bedding planes exist locally in the sandstones, but most of the water moves through the intergranular pore spaces. Sandstone porosity in the Great Plains aquifer system generally decreases as the depth of burial of the aquifer system increases because the sandstone has compacted where it is buried beneath thousands of feet of overlying rocks. The compaction has reduced the percentage of pore space in the sandstone from more than 30 percent where overlying rocks are thin to less than 10 percent where the aquifer system is deeply buried. This reduction in pore space not only reduces the capacity of the aquifer to store water, but also its capability to transmit water.

Transmissivity, or the capacity of an aquifer or aquifer system to transmit water, is one way to measure the ease with which ground water moves. The greater the transmissivity of an aquifer, the more readily water moves through it, and the greater the chances of obtaining large well yields from the aquifer. The distribution of the estimated transmissivity of the Maha aquifer is shown in **figure 83**. The transmissivity of the aquifer is greater in its eastern parts, and the larger transmissivity values (1,000 to more than 10,000 feet squared per day) coincide with places where the aquifer is thickest. The transmissivity values in western Nebraska locally are less than 100 feet squared per day where the aquifer is deeply buried and compacted in part of the Denver Basin. Reported yields of wells completed in the Maha aquifer in eastern Nebraska and central Kansas commonly exceed 50 gallons per minute and locally are as much as 1,000 gallons per minute. These large-yield areas coincide with places where the transmissivity of the aquifer is high.

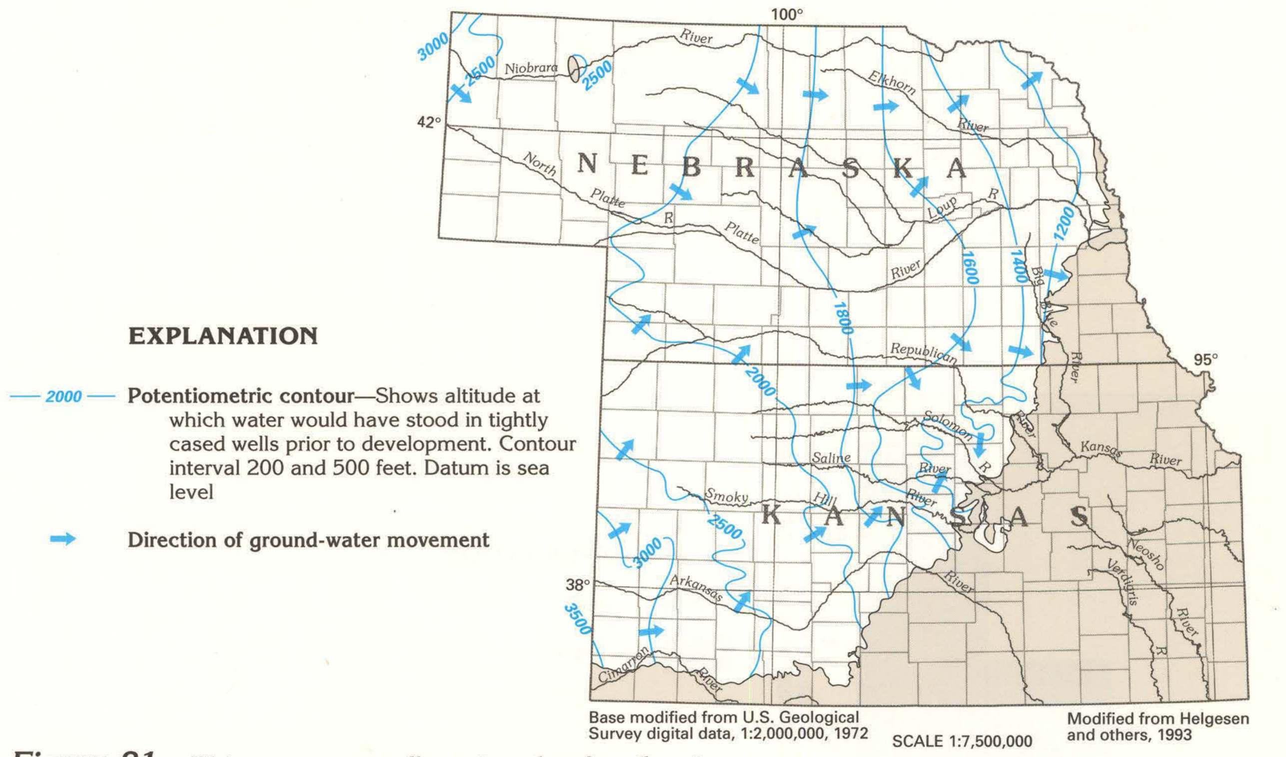


Figure 81. *Water moves generally eastward and northeastward in the Great Plains aquifer system. Regional movement is from areas of high water levels in southeastern Colorado to areas of low water levels in eastern Nebraska and central Kansas.*

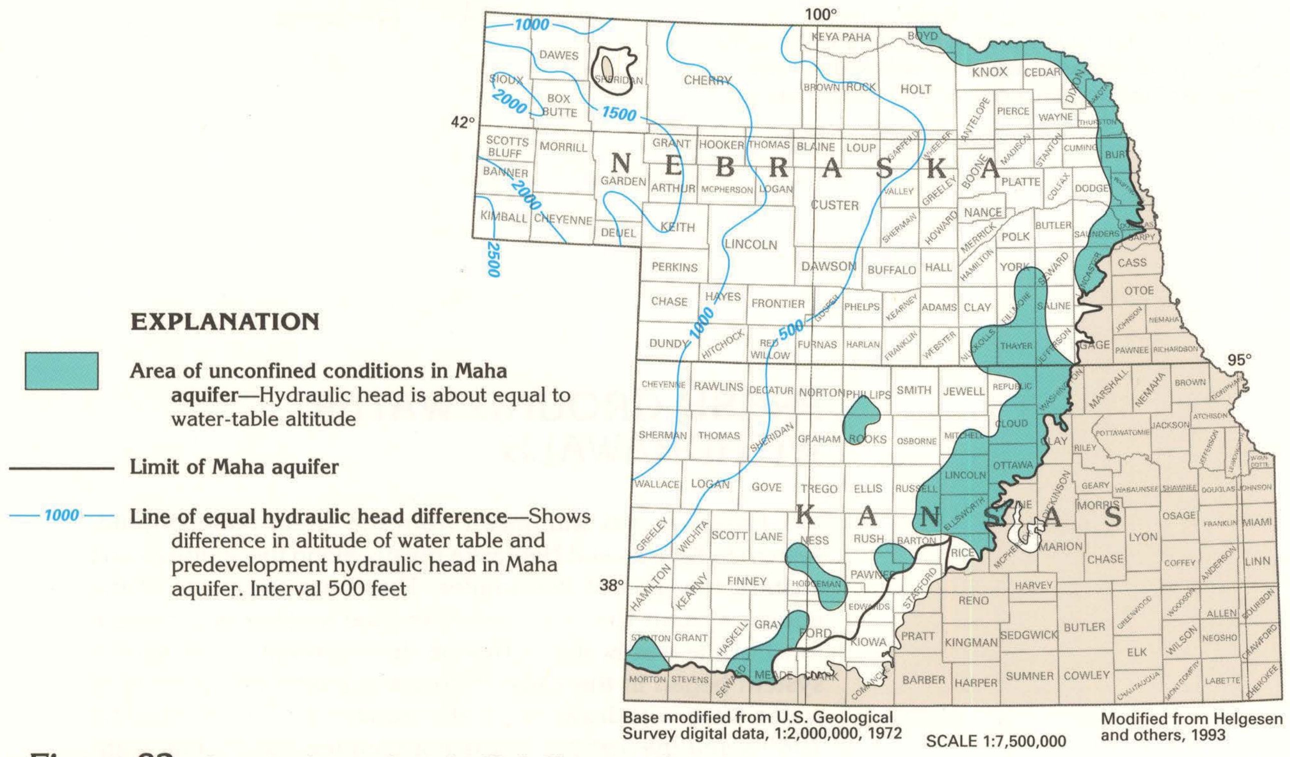


Figure 82. *In most places where the High Plains aquifer overlies the Great Plains aquifer system, water levels in the High Plains aquifer are much higher than those in the Great Plains aquifer system. Regionally, water leaks downward through a confining system to recharge the Great Plains aquifer system.*

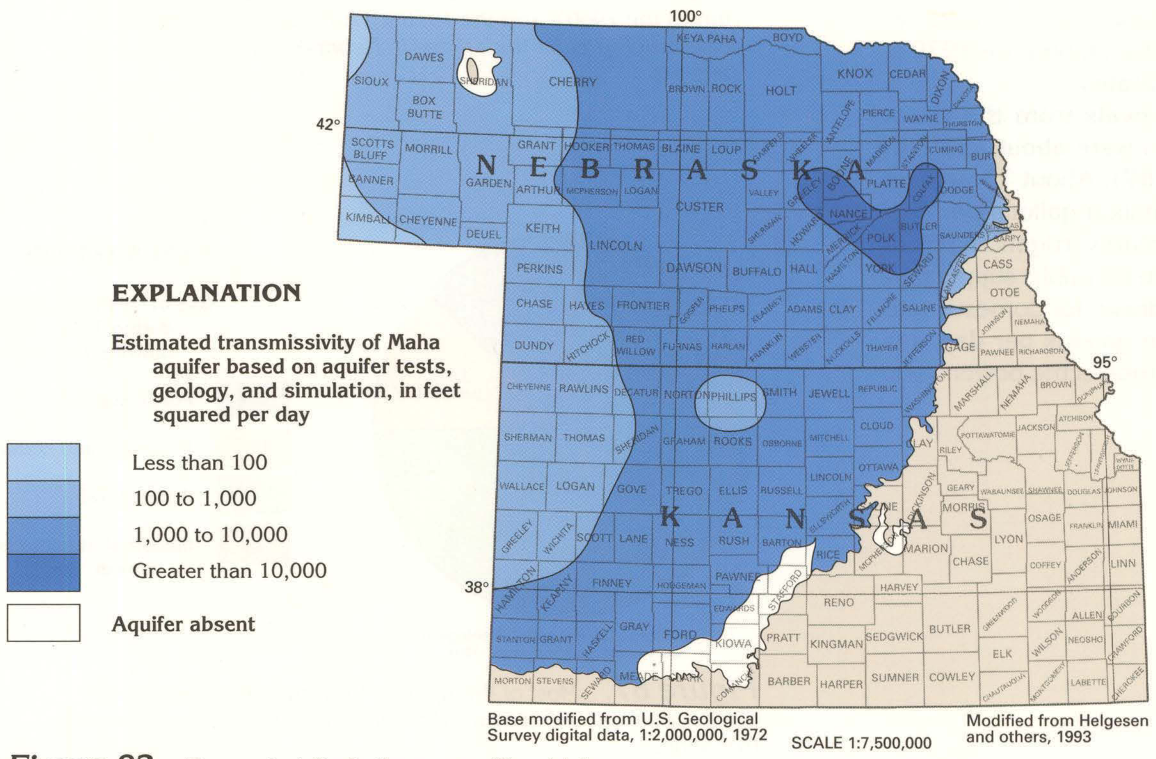


Figure 83. *Transmissivity is the ease with which an aquifer will transmit water. The transmissivity of the Maha aquifer is greatest in eastern Nebraska. Low transmissivity values in the western part of the aquifer indicate that it will yield little water there.*

GROUND-WATER QUALITY

The chemical character of water in the Great Plains aquifer system is determined by many factors. Some of or all the following factors determine the ground-water chemistry: the mineral content of the soil or aquifer material through which the water has passed; the rate of movement of the water; the length of time the water remains in the aquifer; the chemistry of water trapped during sediment deposition; diagenesis, or the chemical and physical changes that take place in aquifer sediments after they are deposited; and mixing of the water with water in adjacent hydrogeologic units or from the land surface.

Concentrations of dissolved solids in water from the Maha aquifer are mapped in **figure 84**. The aquifer contains freshwater only near its southern and eastern margins and in a small area in northwestern Nebraska. These are places where the overlying confining unit is thick and represent areas of aquifer recharge or discharge; the flow system is accordingly dynamic, and mineralized water can be readily flushed from the aquifer. Also, the quartz sand that composes most of the aquifer is not readily dissolved; this condition leads to small dissolved-solids concentrations in the ground water.

Water that contains dissolved-solids concentrations of between 1,000 and 10,000 milligrams per liter is considered to be slightly to moderately saline. Such water is characteristic of much of the Great Plains aquifer system and results from incomplete flushing of highly mineralized water by a sluggish flow system. Some of the mineralized water has leaked upward from underlying Permian rocks that contain halite and evaporite minerals.

In places where the Maha aquifer is deeply buried, it locally contains water with dissolved-solids concentrations of greater than 125,000 milligrams per liter (**fig. 84**). Such excessively large concentrations result from increased mineralization of saline water, which was trapped when the sandstones were deposited, by mixing with brine. The brine might have formed in barred basins into which seawater periodically spilled and became concentrated by evaporation, or it might have migrated into the aquifer in water that moved through and partially dissolved nearby salt or evaporite deposits. Concentrations of dissolved solids that range from 10,000 to about 20,000 milligrams per liter are common in water from the central and east-central parts of the aquifer. Concentrations of this magnitude can result from the combination of incomplete flushing and the upward migration of highly mineralized water from underlying Permian rocks.

Ground water can be classified into hydrochemical facies on the basis of the dominant cations and anions in the water. To demonstrate the classification used, a sodium chloride water is one in which sodium ions account for more than 50 percent of the total cations in the water, and chloride ions account for more than 50 percent of the total anions. The distribution of hydrochemical facies in water from the Great Plains aquifer system is shown in **figure 85**. In many artesian flow systems, the water changes progressively from a calcium bicarbonate type in upgradient recharge areas to a sodium chloride type in deep, confined parts of the flow system. This is not the case with the Great Plains aquifer system because the distribution of hydrochemical facies is more complex (**fig. 85**). Calcium bicarbonate type water mostly is in a narrow band along the eastern and southern limits of the aquifer system. Where the aquifer system is confined, it mostly contains sodium bicarbonate or sodium chloride type waters. These hydrochemical facies are in places where mineralized water in the aquifer system has not been completely flushed by circulating freshwater and where underlying saline water leaks upward faster than it can be flushed. Some of the sodium bicarbonate water may be the result of ion exchange of calcium for sodium on the surface of clay or other sodium-rich minerals in the rocks of the aquifer system. The calcium sulfate type water in northeastern Nebraska results from the upward leakage of mineralized water from underlying rocks that contain anhydrite and gypsum. The leakage is thought to take place along fractures and faults. In summary, incomplete flushing, slow circulation through most of the aquifer system, rock-water interactions in the aquifer system, and mixing of highly mineralized waters from adjacent rocks are the processes that produce the observed distribution of hydrochemical facies.

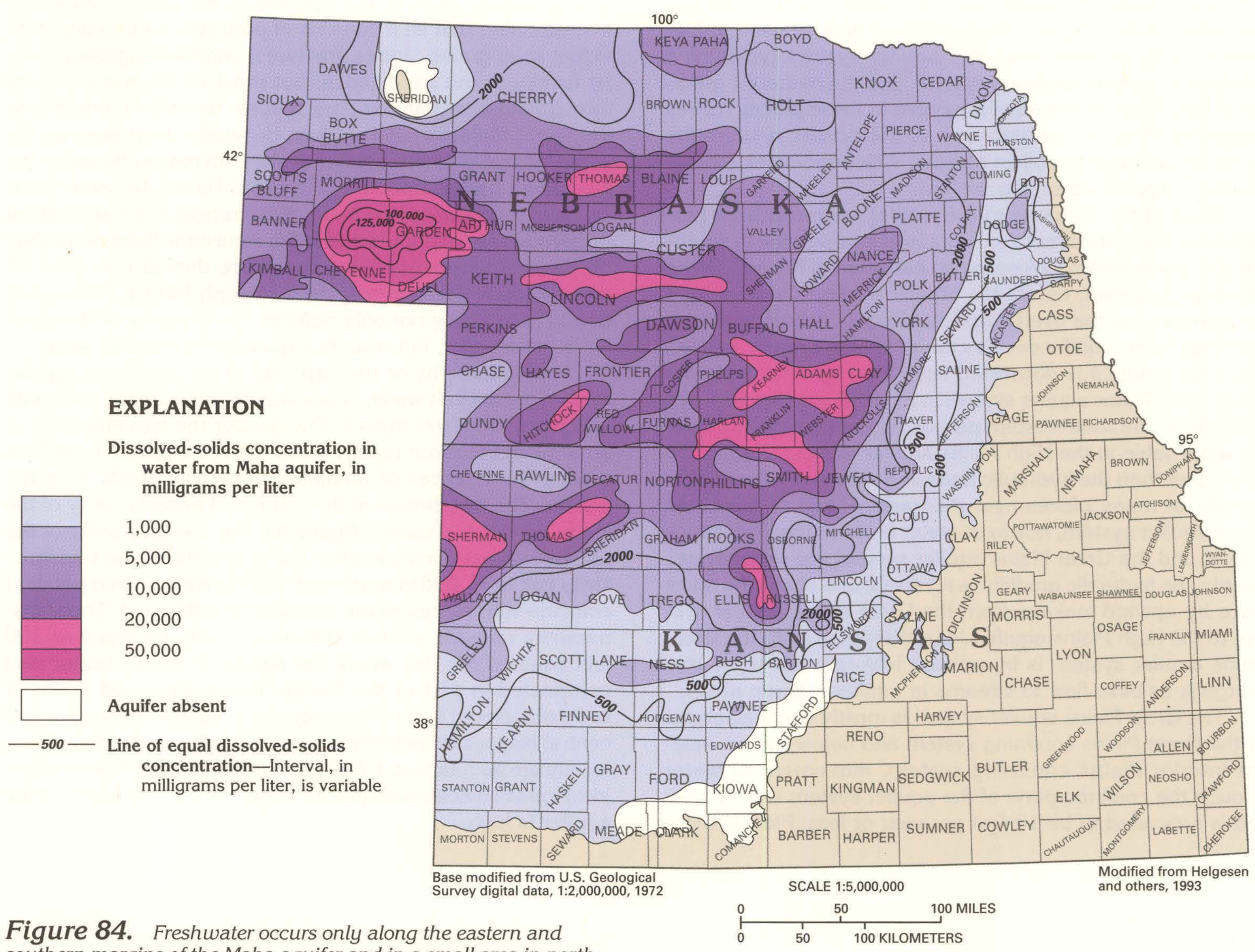


Figure 84. *Freshwater occurs only along the eastern and southern margins of the Maha aquifer and in a small area in northwestern Nebraska. Concentrations of dissolved solids are greater where the aquifer is confined and are very large in deeply buried parts of the aquifer.*

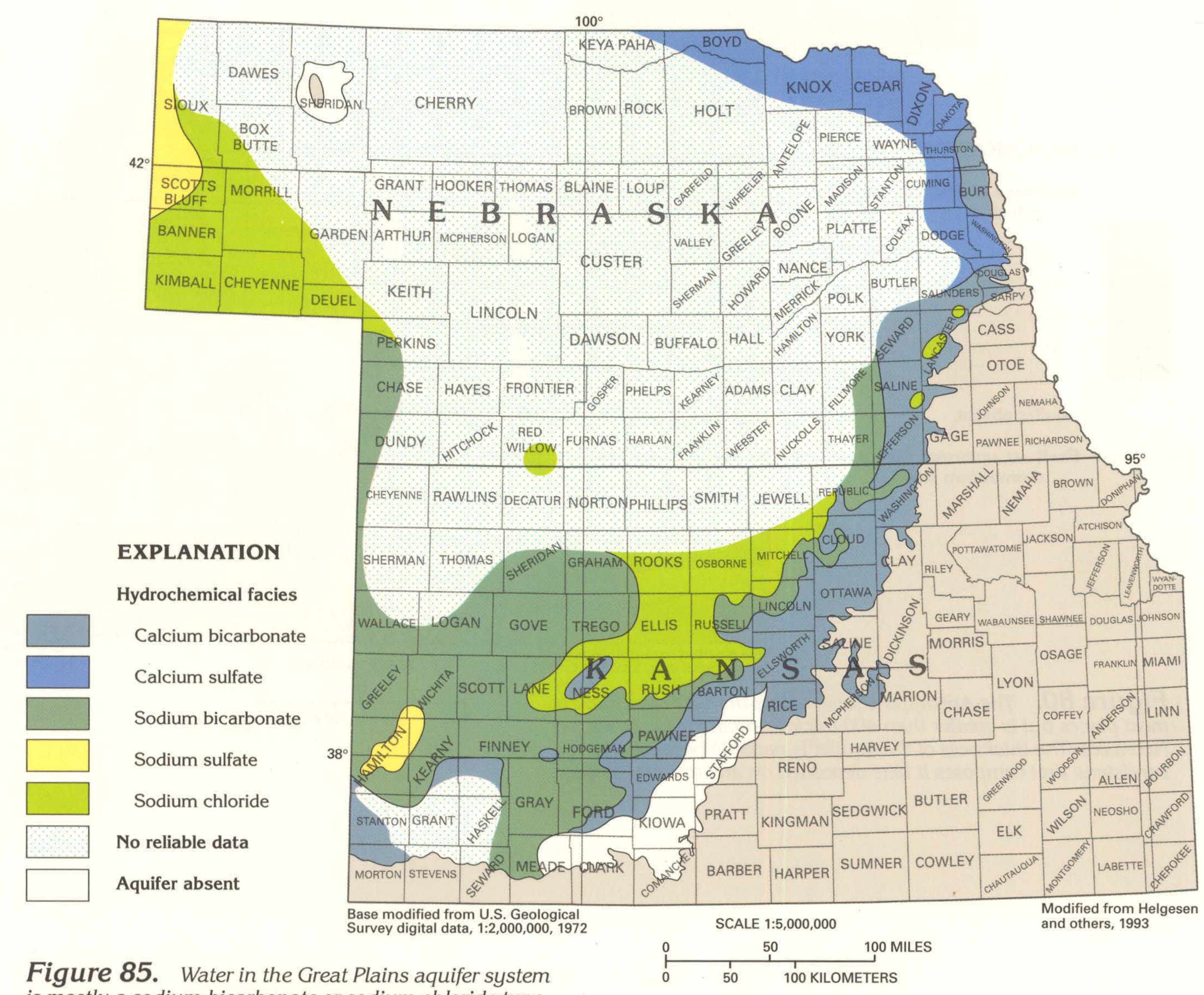


Figure 85. *Water in the Great Plains aquifer system is mostly a sodium bicarbonate or sodium chloride type where the system is confined and a calcium bicarbonate type where it is unconfined. The water types mapped mostly reflect slow circulation of water in the aquifer system, incomplete flushing of the system by freshwater, rock-water interaction within the aquifer system, and upward leakage of highly mineralized water from underlying rocks.*

FRESH GROUND-WATER WITHDRAWALS

Freshwater is withdrawn from the Great Plains aquifer system in Kansas and Nebraska mostly along the southern and eastern margins of the aquifer. These are the parts of the aquifer system that are nearest to land surface and contain most of the freshwater. Although development of the aquifer system began in the early 1900's and moderate amounts of water were withdrawn from the aquifer system during the 1940's and the 1950's, it was not until the 1960's that withdrawals were significant (**fig. 86**). Estimated withdrawals from the aquifer system in Kansas and Nebraska during the 1970's were at a rate of about 390,000 acre-feet per year, which is almost eight times the rate of withdrawal during the 1950's. The distribution of withdrawals has changed with time. During the 1950's, withdrawals in Kansas and Nebraska were about equal; during the 1960's, however, withdrawals increased greatly in Kansas, while withdrawals in Nebraska remained about the same as in the 1950's. During the 1970's, withdrawals increased greatly in both States.

Total fresh ground-water withdrawals from the Great Plains aquifer in Kansas and Nebraska were about 133 million gallons per day during 1990 (**fig. 87**). About 73 percent of the water withdrawn, or about 97 million gallons per day, was used for agricultural purposes, primarily irrigation. About 17 million gallons per day was withdrawn for public supply purposes, and the same amount was withdrawn for domestic and commercial purposes. About 2 million gallons per day was pumped for industrial, mining, and thermoelectric power uses.

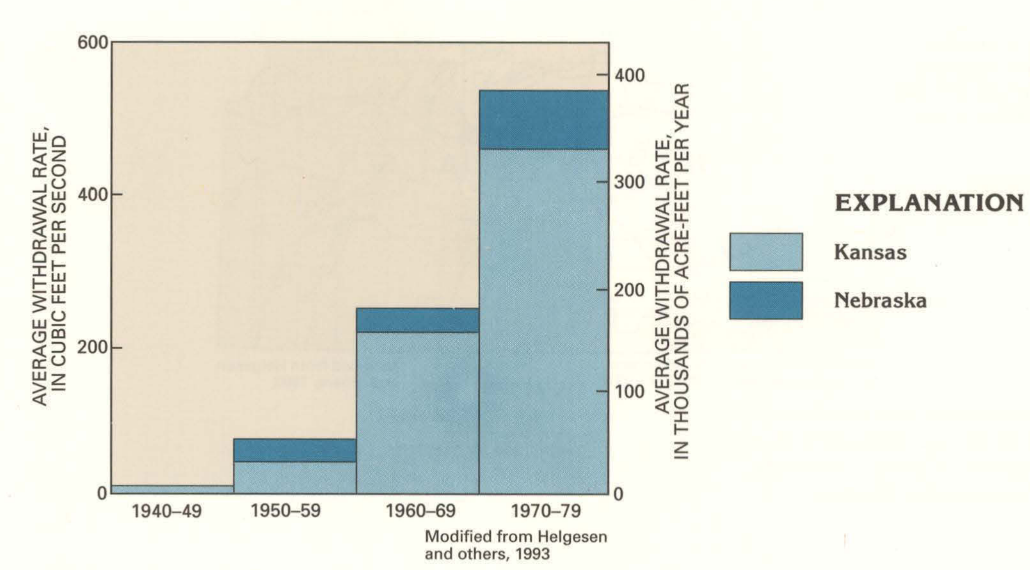


Figure 86. *Rates of withdrawal of freshwater from the aquifer system in Kansas and Nebraska increased greatly during the 1960's and the 1970's. Withdrawals in Kansas were much greater than those in Nebraska during these two decades.*

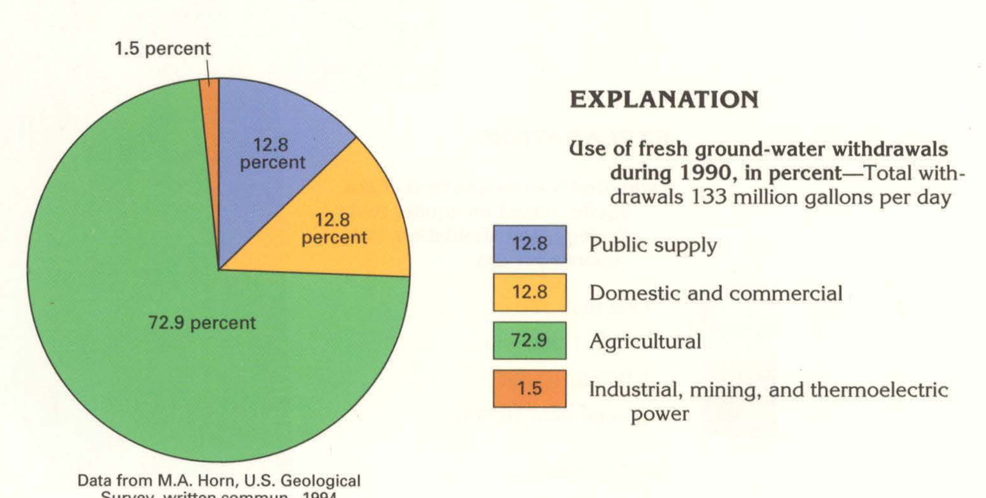


Figure 87. *Most of the water withdrawn from the aquifer system during 1990 was used for agricultural purposes, primarily irrigation.*

INTRODUCTION

The Ozark Plateaus aquifer system contains most of the freshwater in the aquifers that consist of Mississippian and older rocks in Segment 3. The aquifer system underlies most of southern Missouri and a small part of extreme southeastern Kansas in this segment; it also underlies a large area in northwestern Arkansas and a small part of northeastern Oklahoma (**fig. 88**). The Arkansas part of the aquifer system is discussed in detail in the chapter of this Atlas that describes Segment 5, and the Oklahoma part is discussed briefly in the chapter that describes Segment 4.

Rocks equivalent to parts of the Ozark Plateaus aquifer system locally contain freshwater in parts of northeastern Missouri and are called the Mississippian and the Cambrian-Ordovician aquifers. Equivalent carbonate rocks to the west and northwest that contain saline water or brine have been named the "Western Interior Plains aquifer system" (**fig. 89**). The water-yielding rocks in the Ozark Plateaus aquifer system and equivalent beds are mostly limestones and dolomites, but some sandstones are productive aquifers. Confining units within the aquifer system and its equivalents are shale or dolomite. The lithology of the individual aquifers and confining units and their hydraulic character are consistent over large areas.

Ground water in the aquifer system locally moves from topographically high recharge areas to surface streams. Regional movement is northwestward, eastward, and southward from the St. Francois Mountains and other topographically high areas in southern Missouri. The water moves upward at the transition zone between the Ozark Plateaus and the Western Interior Plains aquifer systems and discharges either to streams as base flow or to shallow stream valley alluvial aquifers.

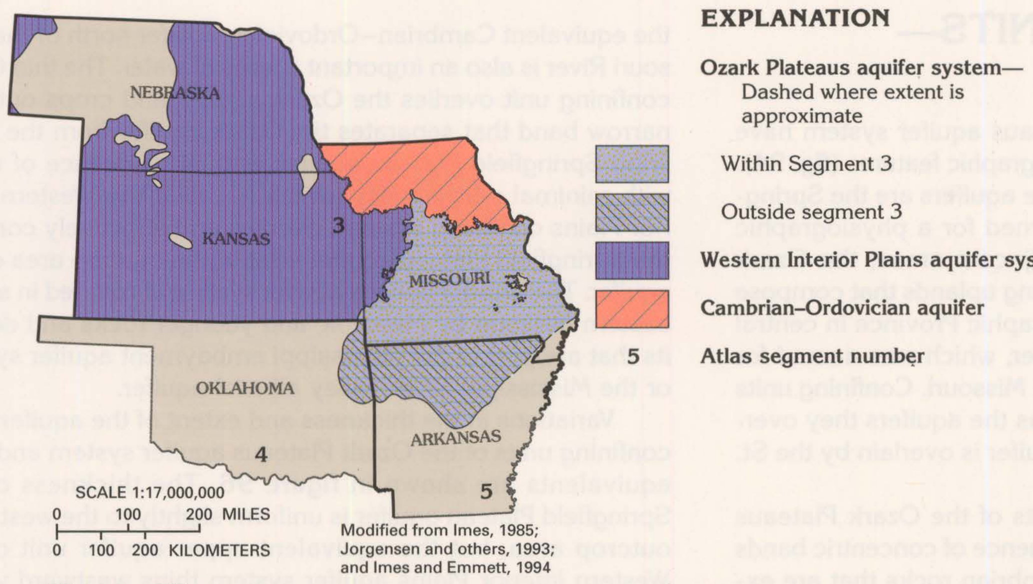


Figure 88. The Ozark Plateaus aquifer system extends over most of southern Missouri and smaller parts of adjacent States. An equivalent aquifer system to the west, the Western Interior Plains aquifer system, contains saline water or brine. The Cambrian–Ordovician aquifer in northern Missouri partly contains freshwater and is equivalent to part of the Ozark Plateaus aquifer system.

System	Southern Missouri (Modified from Imes and Emmett, 1994)		Western Missouri, Kansas and Nebraska (Modified from Jorgensen and others, 1993)		Northern Missouri (Modified from Imes, 1985)
Mississippian	Ozark Plateaus aquifer system	Springfield Plateau aquifer	Western Interior Plains aquifer system[2]	Upper aquifer unit	Mississippian aquifer[1]
		Ozark confining unit		Confining unit	
Devonian		Ozark aquifer		Lower aquifer units	Upper confining bed
Silurian					
Ordovician					Cambrian–Ordovician aquifer
Cambrian		St. Francois confining unit			Confining unit
		St. Francois aquifer			Minor aquifer[3]

[1]Contains freshwater
[2]Contains saline water or brine
[3]Poorly known

Figure 89. The major aquifers and confining units of the Ozark Plateaus aquifer system grade westward into equivalent hydrogeologic units of the Western Interior Plains aquifer system and have stratigraphic equivalents in northern Missouri. The Mississippian aquifer in northern Missouri has little hydraulic connection with the Springfield Plateau aquifer. By contrast, the Ozark aquifer and the Cambrian-Ordovician aquifer appear to be hydraulically connected, at least in part.

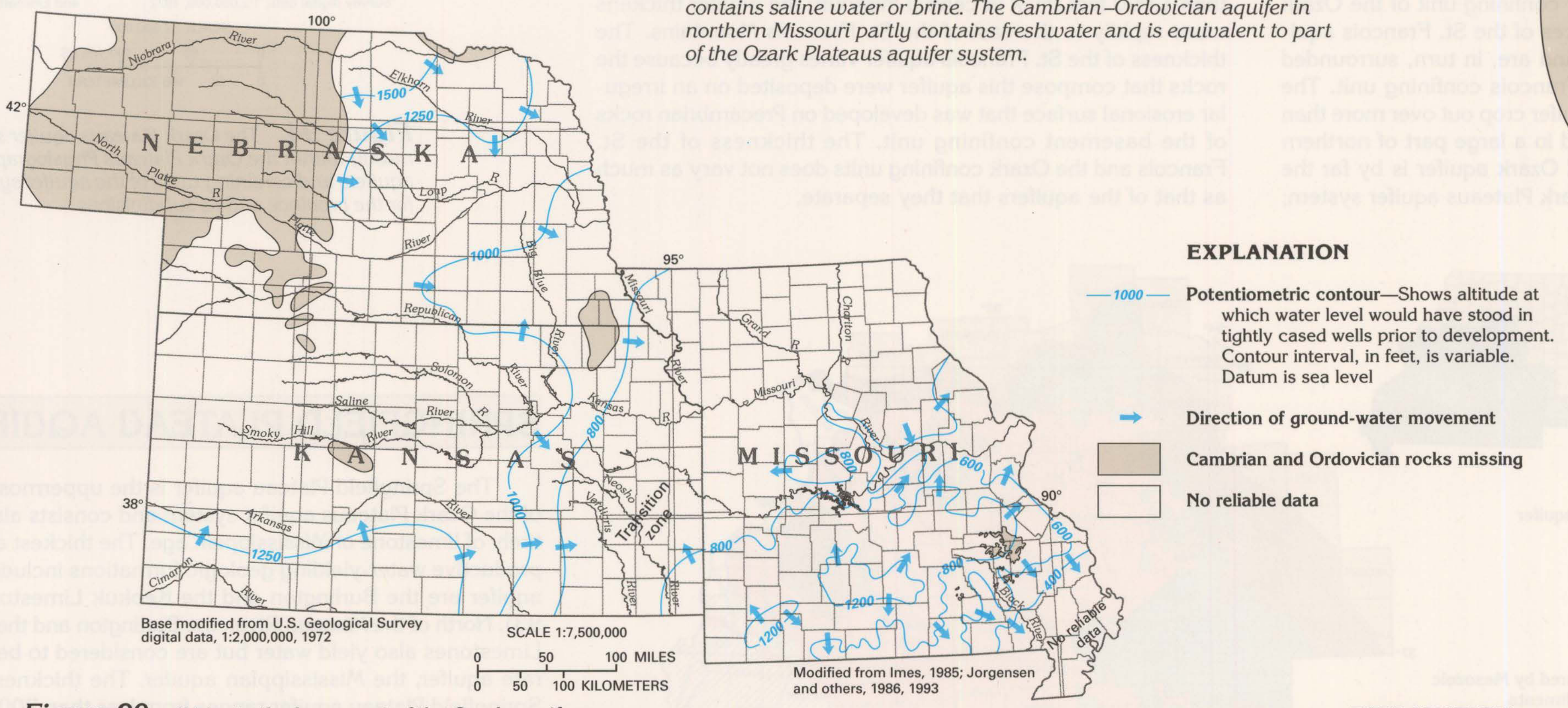


Figure 90. Water in the lower part of the Ozark aquifer moves northward, southward, and northwestward from a high area on the potentiometric surface in south-central Missouri. Some of the water that moves northwestward merges with eastward-moving water in equivalent aquifers in Nebraska and Kansas. The flow systems merge in a transition zone in eastern Kansas and west-central Missouri.

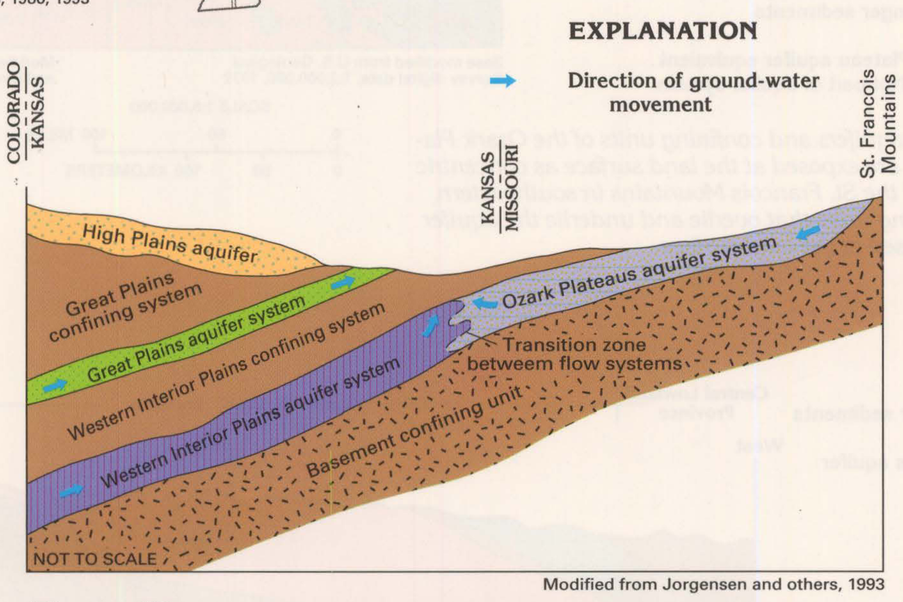


Figure 91. This idealized hydrogeologic section in central Kansas and southern Missouri shows that the predominantly lateral movement of water in the Ozark Plateaus and the Western Interior Plains aquifer systems changes to vertical upward movement in the transition zone between the two aquifer systems. The water eventually discharges to shallower aquifers or to surface streams.

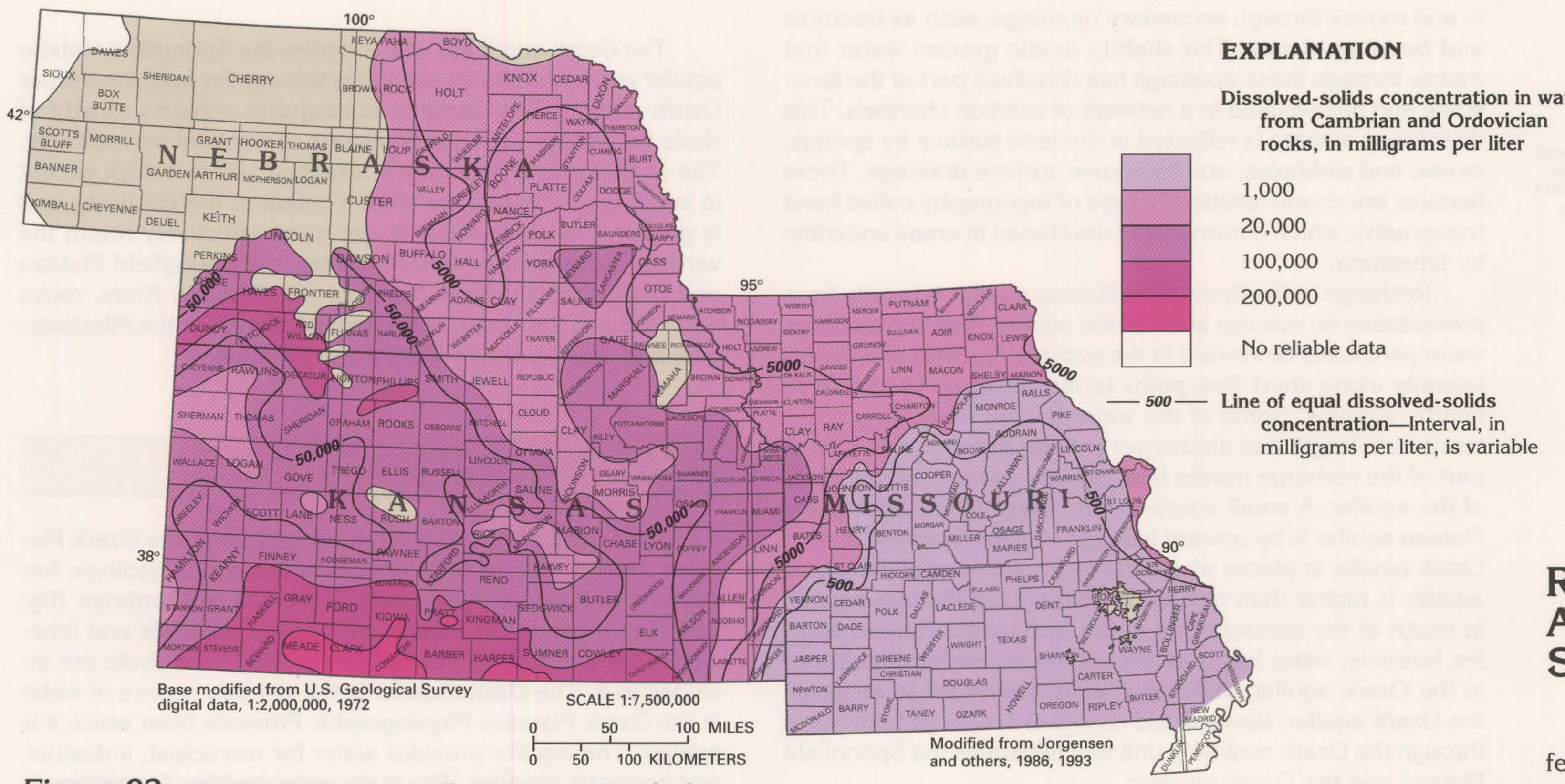


Figure 92. The Ozark Plateaus aquifer system contains freshwater, whereas the water in the Western Interior Plains aquifer system is slightly saline to briny. Water in the Cambrian–Ordovician aquifer is fresh to slightly saline. The freshwater is in areas of vigorous ground-water circulation, and the more highly mineralized water is found where ground-water movement is slow.

System	Missouri		Kansas	Hydrogeologic unit	
Mississippian	St. Louis Limestone Salem Limestone Warsaw Limestone Keokuk Limestone Burlington Limestone Elsey Formation Reeds Spring Limestone Pierson Formation		St. Louis Limestone Salem Limestone Warsaw Limestone Keokuk Limestone Burlington Limestone Reeds Spring Limestone Fern Glen Limestone	Springfield Plateau aquifer	Ozark Plateaus aquifer system
	Northview Shale Sedalia Formation Compton Limestone		Chouteau Limestone Sedalia Formation Compton Limestone	Ozark confining unit	
Devonian	Chattanooga Shale		Chattanooga Shale		
	Callaway Formation Fortune Formation			Ozark aquifer	
Ordovician	Kimmswick Limestone Plattin Limestone Joachim Dolomite St. Peter Sandstone Everton Formation Smithville Formation Powell Dolomite Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Van Buren Formation		Kimmswick Limestone Plattin Limestone St. Peter Sandstone Smithville Formation Powell Dolomite Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Van Buren Formation		
Cambrian	Eminence Dolomite Potosi Dolomite		Eminence Dolomite Potosi Dolomite		
	Derby–Doe Run Dolomite Davis Formation		Doe Run Dolomite Derby Dolomite Davis Formation	St. Francois confining unit	
	Bonneterre Dolomite		Bonneterre equivalent	St. Francois aquifer	
	Reagan Sandstone	Lamotte Sandstone	Reagan Sandstone Lamotte Sandstone		

Modified from Imes, 1990a

Figure 93. Several geologic formations, mostly of limestone, dolomite, and sandstone, compose the aquifers of the Ozark Plateaus aquifer system. Confining units between the aquifers are mostly shale but locally include other rock types. The gray area represents missing rocks.

RELATION TO ADJACENT AQUIFERS AND AQUIFER SYSTEMS

The Ozark Plateaus aquifer system consists of three aquifers separated by two confining units (**fig. 89**), all of which grade laterally westward into equivalent hydrogeologic units that are part of the Western Interior Plains aquifer system. Sparse information indicates that the rocks of the St. Francois confining unit, which is the lowermost confining unit within the Ozark Plateaus aquifer system, are thin or absent in the area of the Western Interior Plains aquifer system. The combined Ozark and St. Francois aquifers of the Ozark Plateaus aquifer system are thus considered to be equivalent to the unnamed lower aquifer units of the Western Interior Plains aquifer system. The Ozark confining unit and the Springfield Plateau aquifer of the Ozark Plateaus aquifer system are equivalent to the confining unit and upper aquifer unit (both unnamed) of the Western Interior Plains aquifer system, respectively.

Hydrogeologic units of the Ozark Plateaus aquifer system also are equivalent to aquifers and confining units north of the Missouri River in Missouri (**fig. 89**). The Springfield Plateau aquifer is stratigraphically equivalent to the Mississippian aquifer of northern Missouri, but limited information indicates that these aquifers have little or no hydraulic connection. Part of the Ozark aquifer is equivalent to the Cambrian–Ordovician aquifer of northern Missouri, and these two aquifers are considered to be hydraulically connected in places. Upper Devonian and Lower Mississippian rocks compose a confining unit in the Ozark Plateaus aquifer system in southern Missouri, and equivalent rocks are part of a thick confining unit in northern Missouri. The lowermost aquifer of the Ozark Plateaus aquifer system is equivalent to a poorly known, unnamed minor aquifer in northern Missouri.

The general direction of ground-water movement in the lower part of the Ozark aquifer and its equivalents can be inferred from a map of the potentiometric surface of these aquifers (**fig. 90**). Water in Cambrian and Ordovician rocks in southern Missouri moves northward, southward, and northwestward from a ground-water divide in south-central Missouri. Water in the Western Interior Plains aquifer system generally moves southeastward and eastward; locally, in southwestern Kansas, the water moves northward. Little or no water leaks upward across the thick, effective Western Interior Plains confining system that overlies most of the Western Interior Plains aquifer system. Lateral flow in the two aquifer systems merges in a northeast-trending transition zone in eastern Kansas and west-central Missouri. This transition zone, which separates the regional ground-water flow systems (**fig. 91**), coincides with a low area on the potentiometric surface and with a topographically low area at the land surface. Ground water in the transition zone moves mostly upward, and discharges either to streams as base flow or to shallow, unconfined, stream-valley alluvial aquifers. Water that moves northward in the lower part of the Ozark aquifer discharges mostly to the Missouri River along a low area of the potentiometric surface parallel to the river (**fig. 90**). The Missouri River is likewise a discharge area for water that moves southward in the Cambrian–Ordovician aquifer, which is located north of the river. Locally, water in the Ozark and Cambrian–Ordovician aquifer system moves eastward toward the Mississippi River, which is the largest and most deeply incised regional drain in the area.

Water in the lower part of the Ozark aquifer is fresh in most of the southern one-half of Missouri and adjacent areas (**fig. 92**). Water in the equivalent Cambrian–Ordovician aquifer is fresh in a large area in east-central Missouri but is slightly to moderately saline in northern and northwestern Missouri where the aquifer is overlain by a thick confining unit and ground-water flow in the aquifer is sluggish. Water in the Western Interior Plains aquifer system is slightly saline or a brine (**fig. 92**) and locally contains dissolved-solids concentrations of more than 200,000 milligrams per liter in deeply buried parts of the aquifer system, such as those along the Kansas-Oklahoma State line. Compaction due to deep burial reduces the porosity and permeability of the aquifer system, and the hydraulic gradient of the system is small. Movement of water in the deep parts of the aquifer system is, therefore, very slow, and highly mineralized water has not been flushed from these parts of the system. The transition zone between the freshwater of the Ozark Plateaus aquifer system and the more mineralized water of the Western Interior Plains aquifer system is narrow and is reflected by an abrupt westward increase in dissolved solids in the ground water. Some of the mineralized water discharges upward to saline springs, such as those in Saline County, Missouri, and some locally discharges to the Osage River in Henry County, Missouri. This discharge of saline water indicates that water moves eastward in the Western Interior Plains aquifer system.

HYDROGEOLOGIC UNITS

Several geologic formations compose each of the three aquifers and two intervening confining units of the Ozark Plateaus aquifer system. These formations are grouped into the hydrogeologic units that make up the aquifer system in Missouri and Kansas (**fig. 93**). The top and bottom of each hydrogeologic unit coincide with the top or bottom of a sequence of geologic units, although the number of geologic units in each aquifer and confining unit varies from place to place. The water-yielding formations are mostly limestone and dolomite but locally include sandstone and chert. The confining units that separate the aquifers primarily are shale but also consist of limestone, dolomite, and sandstone, all of which have minimal permeability. For example, the St. Francois confining unit consists mostly of dolomite. Locally, shale beds within the aquifers form confining units of limited extent.

HYDROGEOLOGIC UNITS—Continued

The aquifers in the Ozark Plateaus aquifer system have been named for geographic or physiographic features (**fig. 94**). From shallowest to deepest, the three aquifers are the Springfield Plateau aquifer, which was named for a physiographic feature in western Missouri and adjacent areas; the Ozark aquifer, which was named for the rolling uplands that compose most of the Ozark Plateaus Physiographic Province in central Missouri; and the St. Francois aquifer, which was named for the St. Francois Mountains in eastern Missouri. Confining units in the system are named the same as the aquifers they overlie; for example, the St. Francois aquifer is overlain by the St. Francois confining unit.

The aquifers and confining units of the Ozark Plateaus aquifer system are exposed as a sequence of concentric bands that are centered around the Precambrian rocks that are exposed in the St. Francois Mountains (**fig. 95**). These Precambrian igneous and metamorphic rocks form the basement confining unit, which is the lower confining unit of the Ozark Plateaus aquifer system. Exposures of the St. Francois aquifer surround this confining unit and are, in turn, surrounded by a band of the overlying St. Francois confining unit. The rocks that compose the Ozark aquifer crop out over more than one-half of southern Missouri and in a large part of northern Arkansas. The thick, widespread Ozark aquifer is by far the most important aquifer of the Ozark Plateaus aquifer system; the equivalent Cambrian–Ordovician aquifer north of the Missouri River is also an important source of water. The thin Ozark confining unit overlies the Ozark aquifer and crops out as a narrow band that separates the Ozark aquifer from the overlying Springfield Plateau aquifer. A thick sequence of rocks with minimal permeability, which is called the Western Interior Plains confining system, overlies and effectively confines the Springfield Plateau aquifer west of the outcrop area of the aquifer. The Ozark Plateaus aquifer system is covered in southeastern Missouri by Mesozoic and younger rocks and deposits that are part of the Mississippi embayment aquifer system or the Mississippi River Valley alluvial aquifer.

Variations in the thickness and extent of the aquifers and confining units of the Ozark Plateaus aquifer system and their equivalents are shown in **figure 96**. The thickness of the Springfield Plateau aquifer is uniform slightly to the west of its outcrop area, but the equivalent upper aquifer unit of the Western Interior Plains aquifer system thins westward where it is covered by the Western Interior Plains confining system. The Ozark aquifer thickens gradually westward and is more than 1,000 feet thick in central Missouri; the aquifer thickens more rapidly to the east of the St. Francois Mountains. The thickness of the St. Francois aquifer varies greatly because the rocks that compose this aquifer were deposited on an irregular erosional surface that was developed on Precambrian rocks of the basement confining unit. The thickness of the St. Francois and the Ozark confining units does not vary as much as that of the aquifers that they separate.

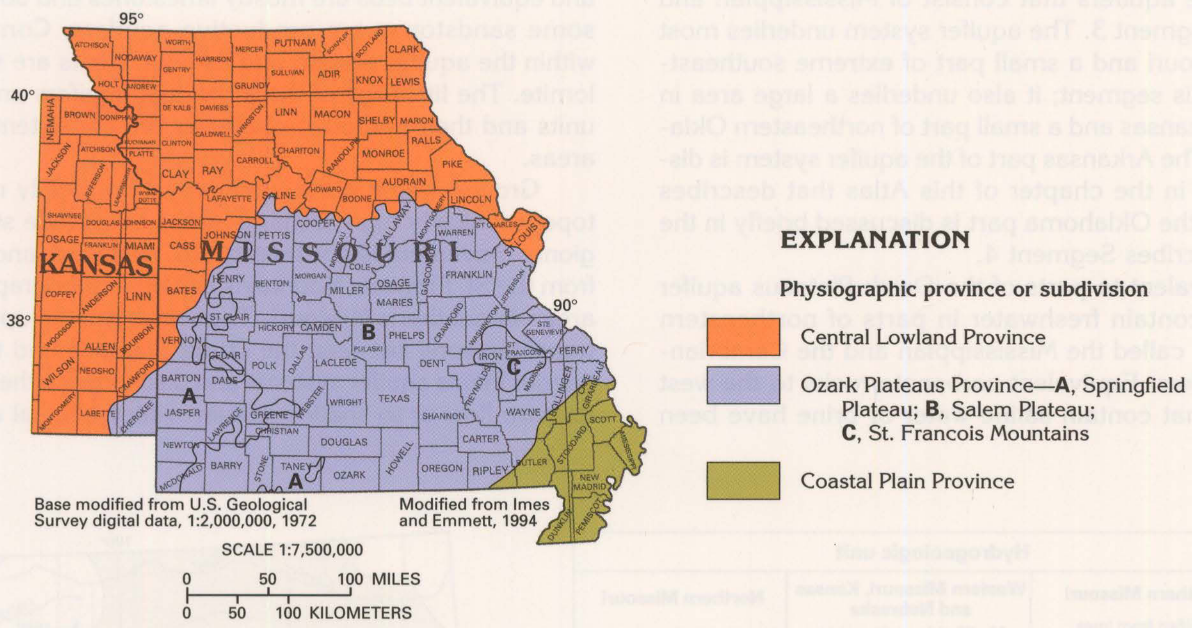


Figure 94. The Ozark Plateaus aquifer system is located mostly within the Ozark Plateaus Physiographic Province. The aquifers and confining units of the aquifer system are named for the province and its subdivisions.

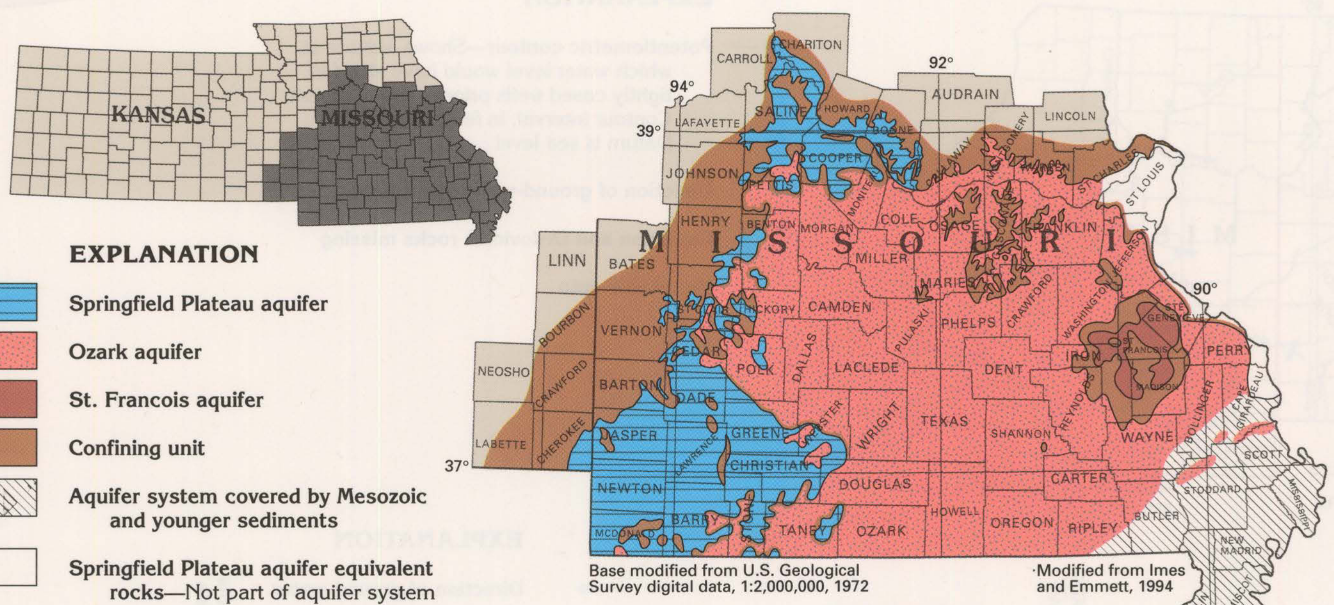


Figure 95. The aquifers and confining units of the Ozark Plateaus aquifer system are exposed at the land surface as concentric bands that surround the St. Francois Mountains in southeastern Missouri. The confining units that overlie and underlie the aquifer system also are exposed at the land surface.

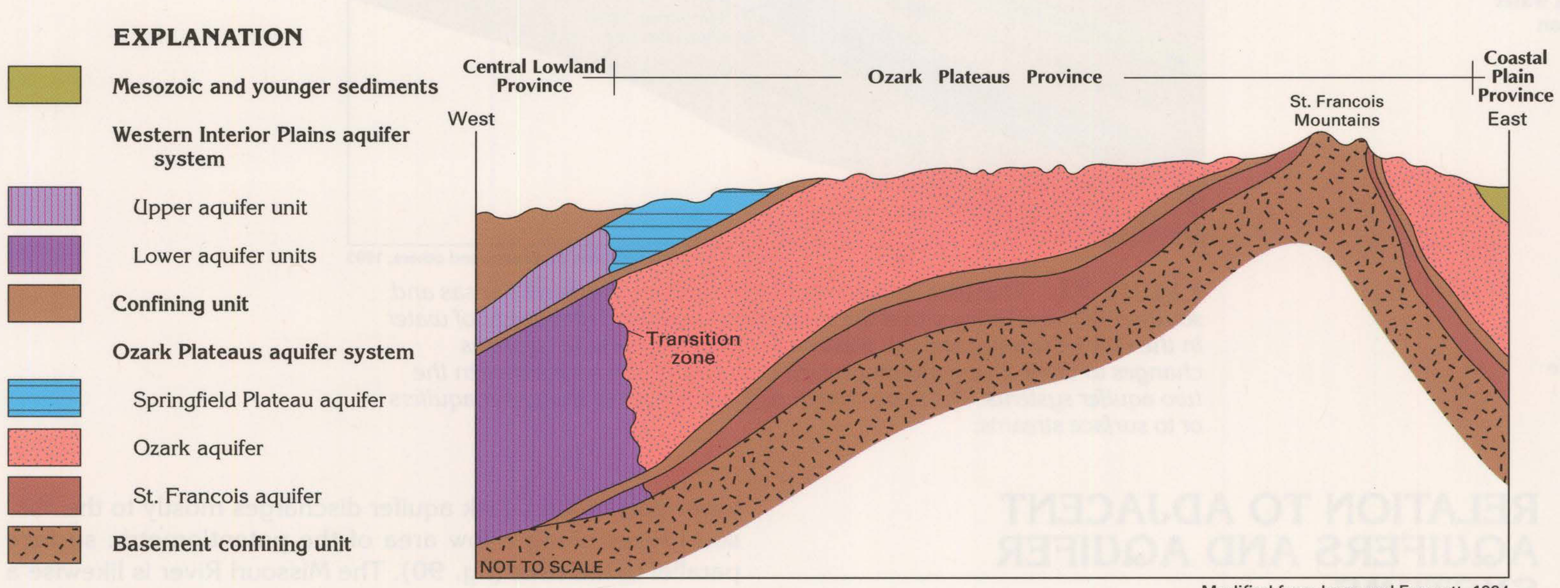


Figure 96. This idealized hydrogeologic section in south-central Missouri shows that the thickness of the lower two aquifers in the Ozark Plateaus aquifer system varies considerably. The thickness of the uppermost aquifer and the confining units in the aquifer system is more uniform.

SPRINGFIELD PLATEAU AQUIFER

The Springfield Plateau aquifer is the uppermost aquifer of the Ozark Plateaus aquifer system and consists almost entirely of limestone of Mississippian age. The thickest and most productive water-yielding geologic formations included in the aquifer are the Burlington and the Keokuk Limestones (**fig. 93**). North of the Missouri River, the Burlington and the Keokuk Limestones also yield water but are considered to be a separate aquifer, the Mississippian aquifer. The thickness of the Springfield Plateau aquifer ranges from less than 200 to more than 400 feet (**fig. 97**) and averages about 200 feet. Locally, the aquifer is absent in the subsurface. The aquifer thins abruptly at the eastern edge of the Salem Plateau. Equivalent rocks in two small areas in St. Louis and Ste. Genevieve Counties, Missouri, are not considered to be part of the aquifer.

Most of the water in the Springfield Plateau aquifer occurs in and moves through secondary openings, such as fractures and bedding planes. The slightly acidic ground water that moves through these openings has dissolved part of the limestone and has resulted in a network of solution channels. This dissolution activity is reflected at the land surface by springs, caves, and sinkholes, and by sparse surface drainage. These features are characteristic of a type of topography called karst topography, which commonly is developed in areas underlain by limestone.

Recharge to the Springfield Plateau aquifer is mostly from precipitation on outcrop areas of the aquifer. After the recharge water percolates downward to the water table, most of it moves laterally along short flow paths to discharge as base flow to nearby streams. Some of the water follows flow paths of intermediate length and discharges to large streams, and a small part of the recharge moves laterally into deep, confined parts of the aquifer. A small amount of recharge to the Springfield Plateau aquifer is by upward leakage of water from the deeper Ozark aquifer in places where the hydraulic head of the Ozark aquifer is higher than that of the Springfield Plateau aquifer. In much of the outcrop area of the Springfield Plateau aquifer, however, water levels in this aquifer are higher than those in the Ozark aquifer, and water leaks downward to recharge the Ozark aquifer. Upward and downward leakage take place through the Ozark confining unit that separates the Springfield Plateau and the Ozark aquifers.

A map of the estimated potentiometric surface of the Springfield Plateau aquifer before development (**fig. 98**) shows that water in the aquifer moved mostly from local recharge areas to nearby surface drains. The configuration of the potentiometric surface contours is irregular because of the influence of streams on the ground-water flow system. Where the aquifer is confined above by the Western Interior Plains confining system, the contours are smoother and only reflect the influence of large streams. The regional movement of water in the aquifer is westward.

The chemical quality of water in the Springfield Plateau aquifer generally is suitable for most uses where the aquifer is unconfined or where the confining unit that overlies the aquifer is thin. The water commonly is a calcium bicarbonate type and is moderately hard. Dissolved-solids concentrations in water from the aquifer generally are less than 1,000 milligrams per liter except where the aquifer is confined (**fig. 99**). Dissolved-solids concentrations increase rapidly downgradient where the aquifer becomes confined. Concentrations of sulfate generally are small in water from the aquifer except in the Tri-State lead-zinc mining district of southwestern Missouri, southeastern Kansas, and northeastern Oklahoma where concentrations of more than 500 milligrams per liter are reported near some mining areas. These large concentrations result from leaching of the sulfide minerals that contain the lead and zinc.

Most of the water withdrawn from the Springfield Plateau aquifer is used for domestic and stock-watering supplies. Yields of wells completed in the aquifer generally are less than 20 gallons per minute.

OZARK CONFINING UNIT

The Ozark confining unit underlies the Springfield Plateau aquifer and hydraulically separates this aquifer from the deeper Ozark aquifer. The Ozark confining unit consists mostly of shale but locally includes limestone of minimal permeability. The confining unit generally is less than 100 feet thick except in small areas. Where the shale content of the confining unit is greater, the confining unit can more effectively retard the vertical movement of water between the Springfield Plateau and the Ozark aquifers. North of the Missouri River, rocks equivalent to the Ozark confining unit separate the Mississippian and the Cambrian-Ordovician aquifers.

OZARK AQUIFER

The Ozark aquifer is the middle aquifer of the Ozark Plateaus aquifer system and consists of numerous geologic formations that range in age from Devonian to Cambrian (**fig. 93**). The rocks of the aquifer are mostly dolomite and limestone, but some beds of sandstone, chert, and shale are included in it. The Ozark aquifer is the primary source of water in the Ozark Plateaus Physiographic Province from which it is named. The aquifer provides water for municipal, industrial, and domestic supplies. The main water-yielding formations in the Ozark aquifer are the Upper Cambrian Potosi Dolomite, the Lower Ordovician Gasconade Dolomite, and the Roubidoux Formation. The Potosi Dolomite is the most permeable of these three formations. North of the Missouri River, rocks that are equivalent to the Ozark aquifer are called the Cambrian–Ordovician aquifer. Like the Ozark aquifer, the Cambrian–Ordovician aquifer consists mostly of dolomite and limestone; however, it also includes beds of sandstone and shale. The Upper Cambrian Potosi and the Eminence Dolomites are the main water-yielding formations in the Cambrian–Ordovician aquifer, but the Lower Ordovician Gasconade Dolomite and locally the Middle Ordovician St. Peter Sandstone are important sources of water. Most wells completed in the Cambrian–Ordovician aquifer are open to more than one water-yielding unit. The Ozark and the Cambrian–Ordovician aquifers are mapped together in this report.

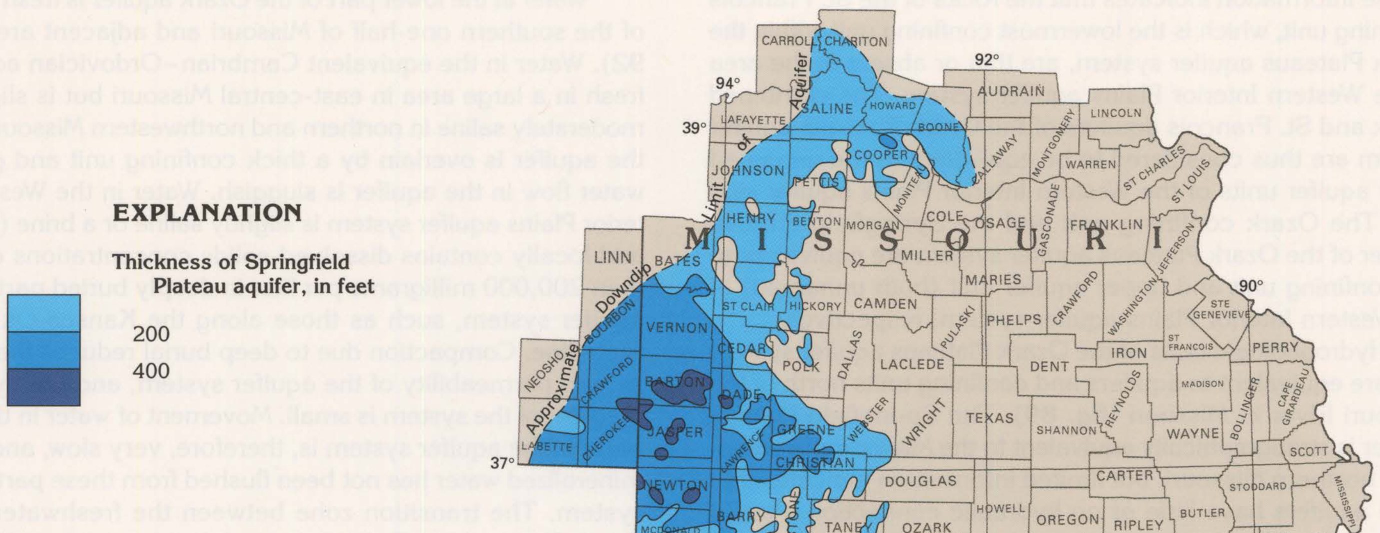


Figure 97. The thickness of the Springfield Plateau aquifer averages about 200 feet. Local variations in thickness are the result of erosion.

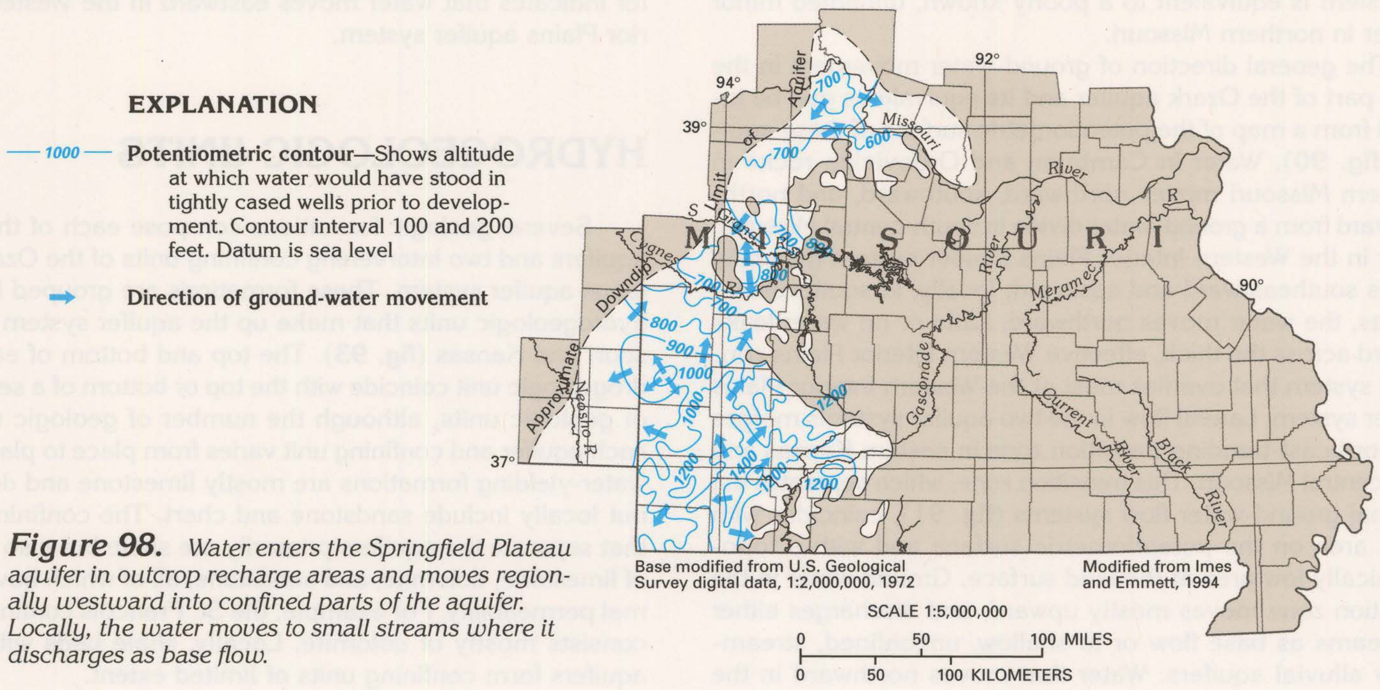


Figure 98. Water enters the Springfield Plateau aquifer in outcrop recharge areas and moves regionally westward into confined parts of the aquifer. Locally, the water moves to small streams where it discharges as base flow.

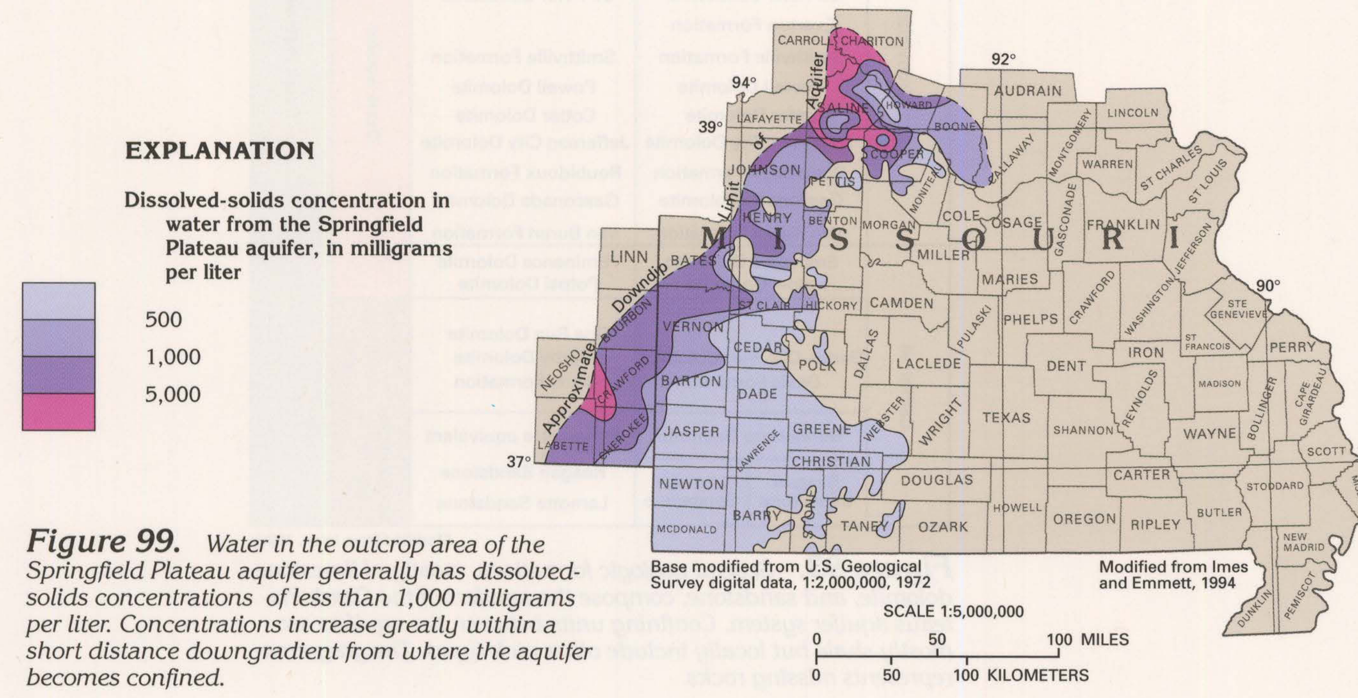


Figure 99. Water in the outcrop area of the Springfield Plateau aquifer generally has dissolved-solids concentrations of less than 1,000 milligrams per liter. Concentrations increase greatly within a short distance downgradient from where the aquifer becomes confined.

The Ozark aquifer underlies most of Missouri south of the Missouri River, and the Cambrian–Ordovician aquifer underlies the eastern one-half of Missouri north of that river (**fig. 100**). The Ozark aquifer is less than 1,000 feet thick throughout the Salem Plateau but thickens to more than 3,000 feet in southeastern Missouri just north and east of the bootheel. The Ozark aquifer pinches out against the flanks of the St. Francois Mountains, and its thickness is irregular where it has been eroded in outcrop areas. Caves, sinkholes, and other types of solution features characteristic of karst topography have developed on the carbonate-rock units that compose the aquifer. North of the Missouri River, the thickness of the Cambrian–Ordovician aquifer averages about 1,200 feet but is locally greater than 1,800 feet. Carbonate rocks equivalent to the Cambrian-Ordovician aquifer in northwestern Missouri are deeply buried and contain saline water.

Recharge to the Ozark aquifer is mostly from precipitation on aquifer outcrop areas. Small volumes of water recharge the aquifer by downward leakage from the shallower Springfield Plateau aquifer. Most ground-water flow in the shallow part of the Ozark aquifer moves from topographically high recharge areas along short flow paths to discharge as base flow to nearby streams. The shallow flow system is accordingly controlled mostly by topography. The ground water mostly occurs in and moves through fractures and bedding planes in carbonate rocks. These openings have been enlarged by dissolution of the carbonate rocks and have been reported at depths of as great as 1,500 feet below land surface. Where sinkholes have formed from dissolution of the carbonate rocks, water that runs over the land surface may enter the sinkholes and large volumes of recharge can enter the aquifer in this manner. Recharge to the equivalent Cambrian–Ordovician aquifer likewise is mostly from precipitation on aquifer outcrop areas, but small amounts of recharge enter this aquifer by downward leakage of water from the overlying Mississippian aquifer.

Discharge from the Ozark and the Cambrian–Ordovician aquifers is mostly to streams in aquifer outcrop areas. Some water follows flow paths of intermediate length and discharges to regional drains, such as the Missouri and the Mississippi Rivers. A small volume of water leaks upward from the Ozark aquifer and locally discharges to the overlying Springfield Plateau aquifer. In southeastern Missouri, a small volume of water discharges from the Ozark aquifer to the Mississippi River Valley alluvial aquifer by upward leakage.

A map of the potentiometric surface of the Ozark and the Cambrian–Ordovician aquifers before development of the aquifers began (**fig. 101**) can be used to show the regional direction of ground-water movement in the aquifers. Water in the Ozark aquifer generally moved northward, westward, and southwestward from high areas on the potentiometric surface in south-central Missouri; some of the water moved toward the Mississippi and the Missouri Rivers. In the Cambrian–Ordovician aquifer, water moved along a gentle gradient from a high area on the potentiometric surface in north-central Missouri toward these same rivers. Movement of water in both aquifers at present is similar to movement before development except locally near well fields where the direction of ground-water flow is toward the pumping wells.

Water mostly is under unconfined conditions in the Ozark aquifer but is mostly under confined conditions in the Cambrian–Ordovician aquifer. Where the water is unconfined, water levels in the aquifer respond rapidly to changes in precipitation. For example, **figure 102** shows changes in the water level in a well completed in the Potosi Dolomite (part of the Ozark aquifer) at West Plains in central Howell County, Missouri. Although this well is more than 1,300 feet deep, water-level rises of as much as 140 feet were recorded soon after several inches of precipitation fell. Solution openings in the carbonate rocks that compose the aquifer allow large volumes of water to enter the aquifer quickly, which accounts for the rapid rise in the water level. A sinkhole over one such solution opening in West Plains collapsed in 1978 (**fig. 103**). This sinkhole formed in a municipal sewage lagoon and allowed raw sewage to enter the aquifer quickly and directly. Within a few days after the sinkhole collapsed, raw sewage was detected in nearby streams, and eventually traces of sewage were detected in a large spring 36 miles southwest of West Plains.

In most places, water in the Ozark aquifer is not highly mineralized, and the chemical quality of the water is suitable for most uses. Dissolved-solids concentrations in water from the Ozark and the Cambrian–Ordovician aquifers are mapped in **figure 104**. Concentrations in the Ozark aquifer are less than 1,000 milligrams per liter except in the westernmost parts of the aquifer and locally near the Mississippi River. In contrast, the equivalent Cambrian–Ordovician aquifer contains freshwater only in a small area in the southern part of the aquifer. In both aquifers, the water is fresh where the aquifer is unconfined or where the overlying confining unit is thin, and the ground-water flow system is vigorous. Water in the Ozark and the Cambrian–Ordovician aquifers generally is a calcium bicarbonate type but locally is a sodium bicarbonate type. Chloride and sulfate concentrations are less than 10 milligrams per liter in most places and the water is hard to moderately hard.

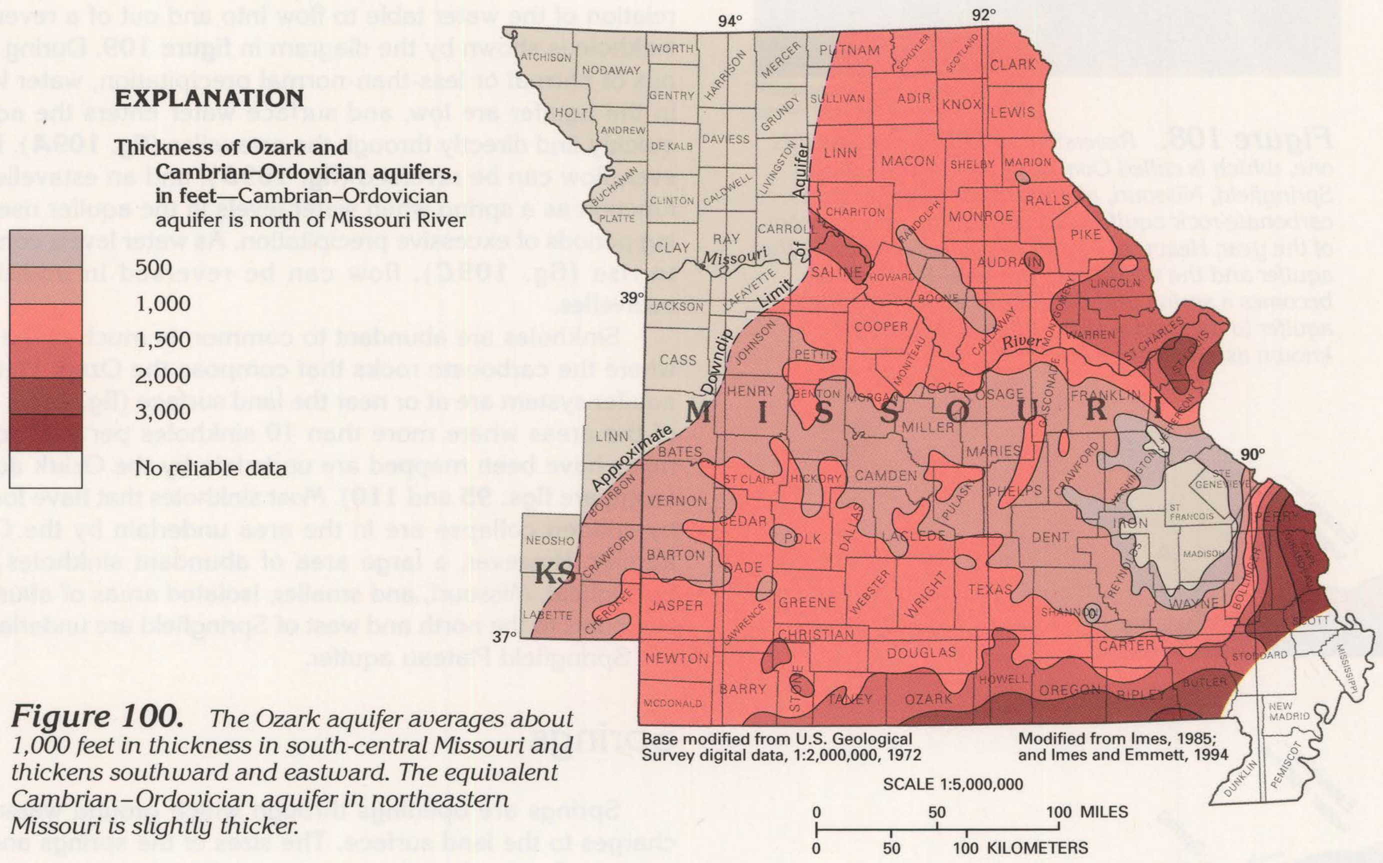


Figure 100. The Ozark aquifer averages about 1,000 feet in thickness in south-central Missouri and thickens southward and eastward. The equivalent Cambrian–Ordovician aquifer in northeastern Missouri is slightly thicker.

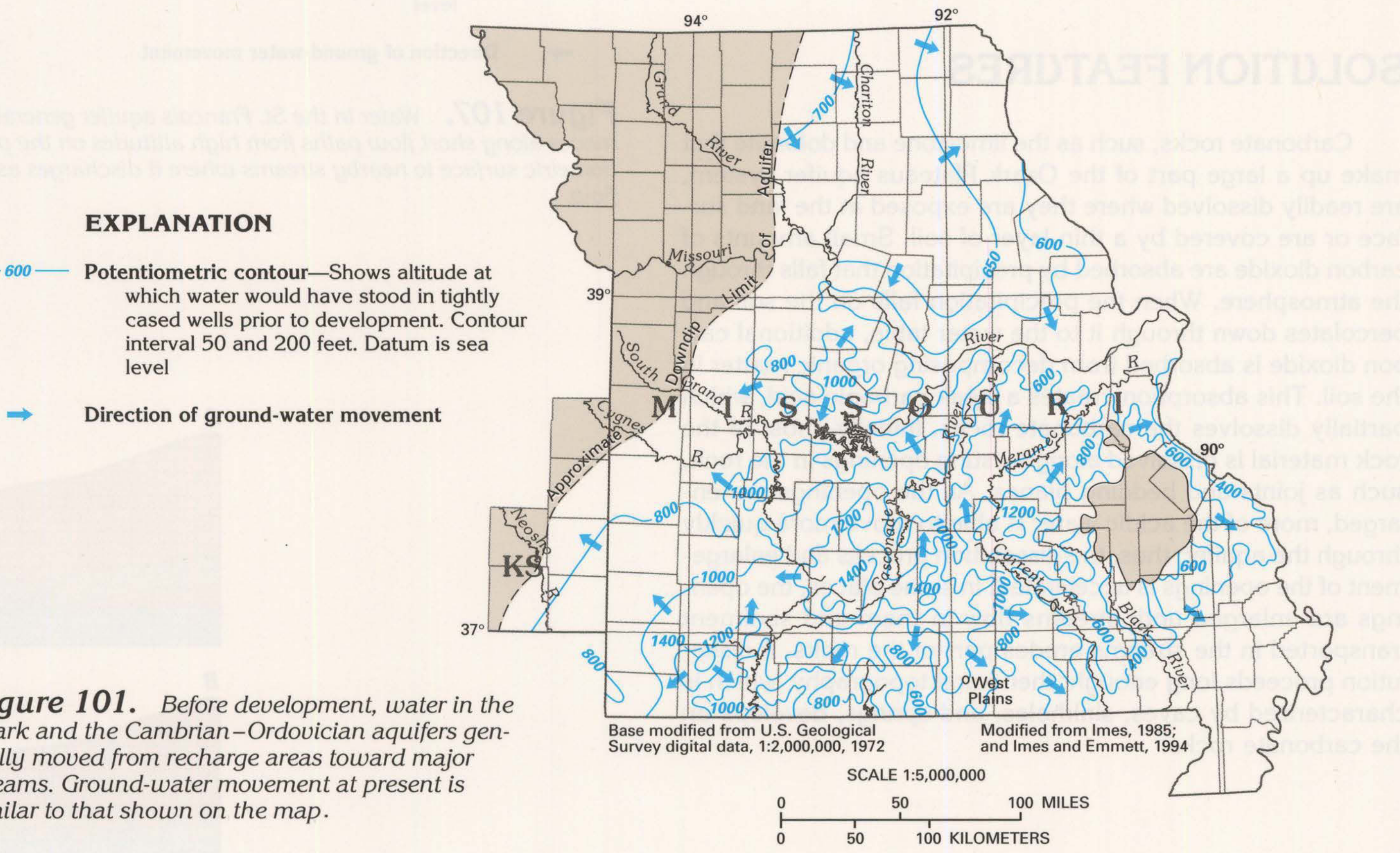


Figure 101. Before development, water in the Ozark and the Cambrian–Ordovician aquifers generally moved from recharge areas toward major streams. Ground-water movement at present is similar to that shown on the map.

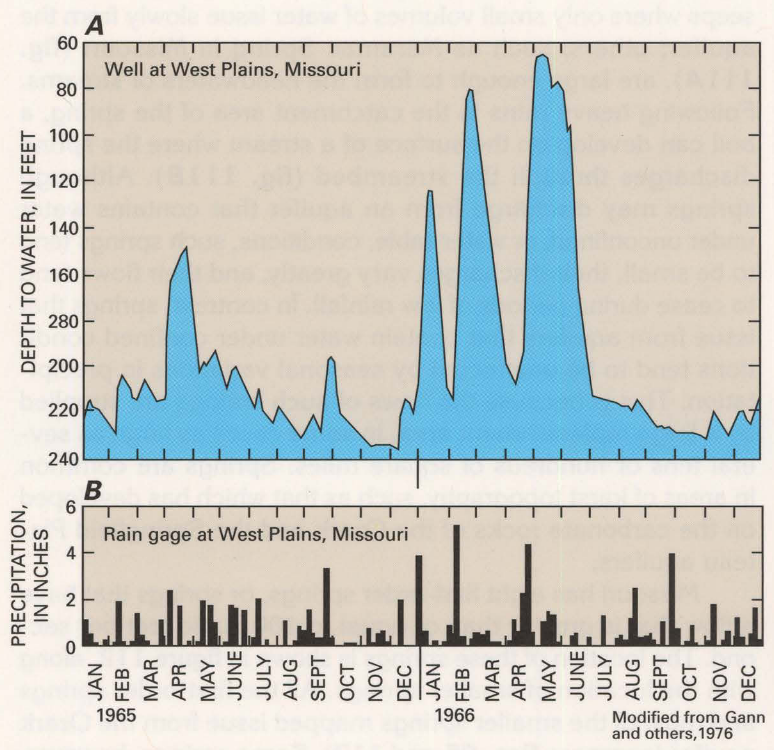


*Figure 102. Where the Ozark aquifer is unconfined, water levels in the aquifer can rise quickly following periods of heavy precipitation. Large solution openings in the carbonate rocks that compose the aquifer allow the precipita- tion to enter the aquifer rapidly. The locations of the well (**A**) and precipitation gage (**B**) at West Plains, Missouri, are shown in figure 101.*

Photo from files of U.S. Geological Survey, Rolla, Missouri

Figure 103. Sinkholes, such as this one that formed in a sewage lagoon at West Plains, Missouri, in 1978, allow contaminants to rapidly enter carbonate-rock aquifers.

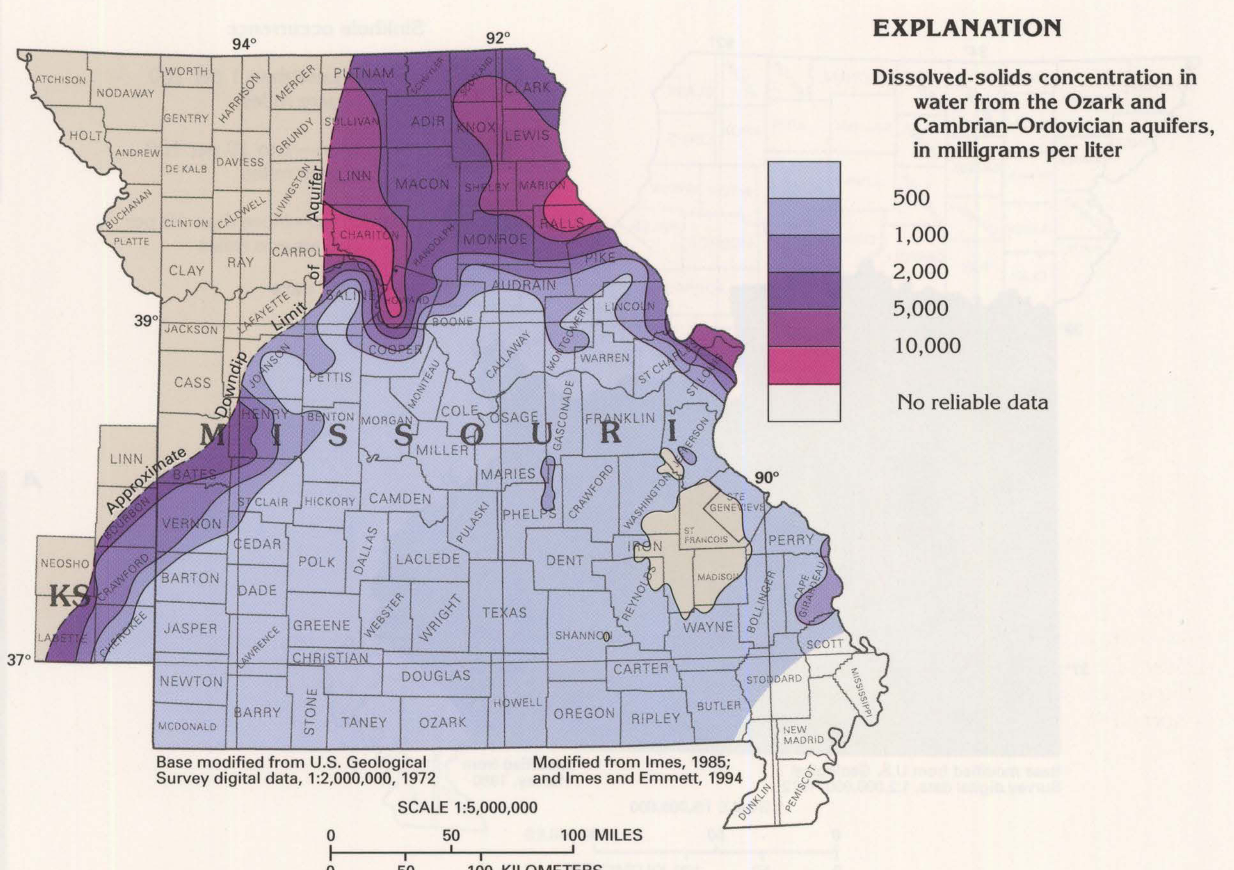


Figure 104. The Ozark and the Cambrian–Ordovician aquifers contain freshwater where the aquifers are either exposed at the land surface or thinly confined. In such places, a vigorous ground-water flow system has flushed highly mineralized water from the aquifers.

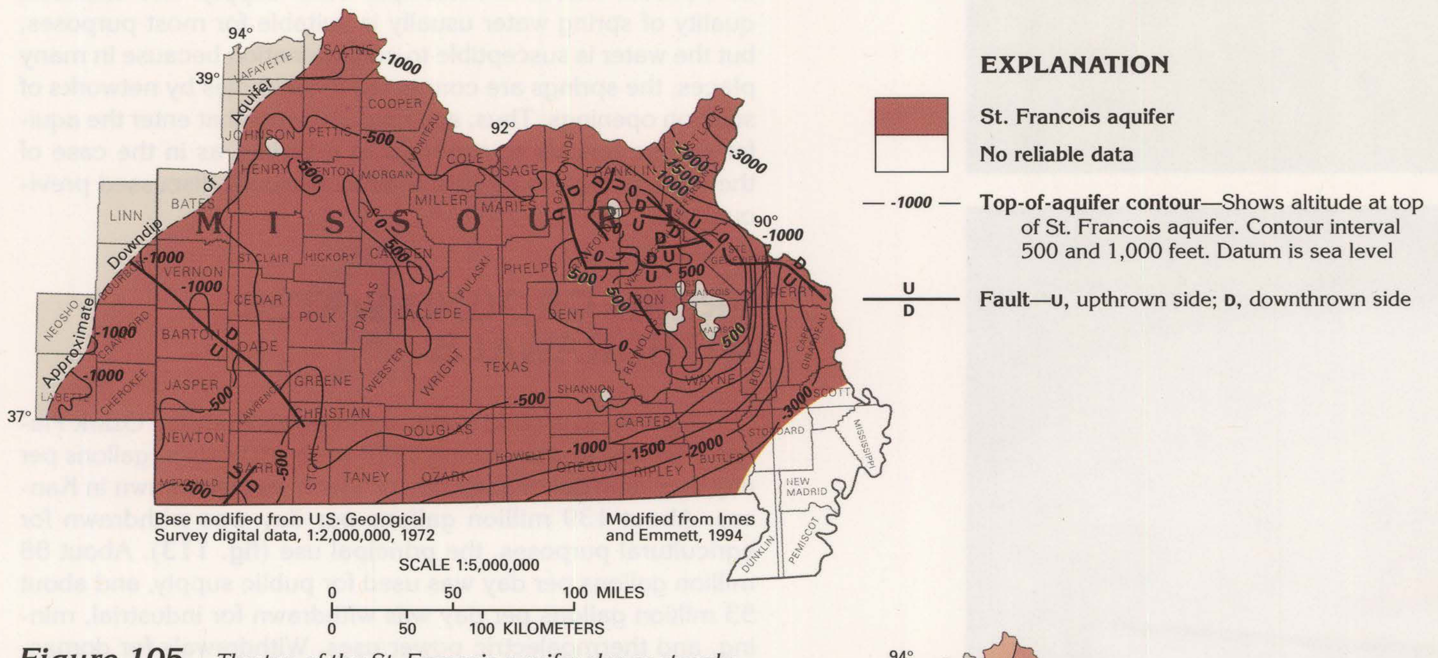


Figure 105. The top of the St. Francois aquifer slopes steeply to the east and more gently to the west from aquifer outcrop areas in the St. Francois Mountains. The tops of overlying aquifers in the Ozark Plateaus aquifer system would show a similar shape if the shallower aquifers had not been partly eroded.

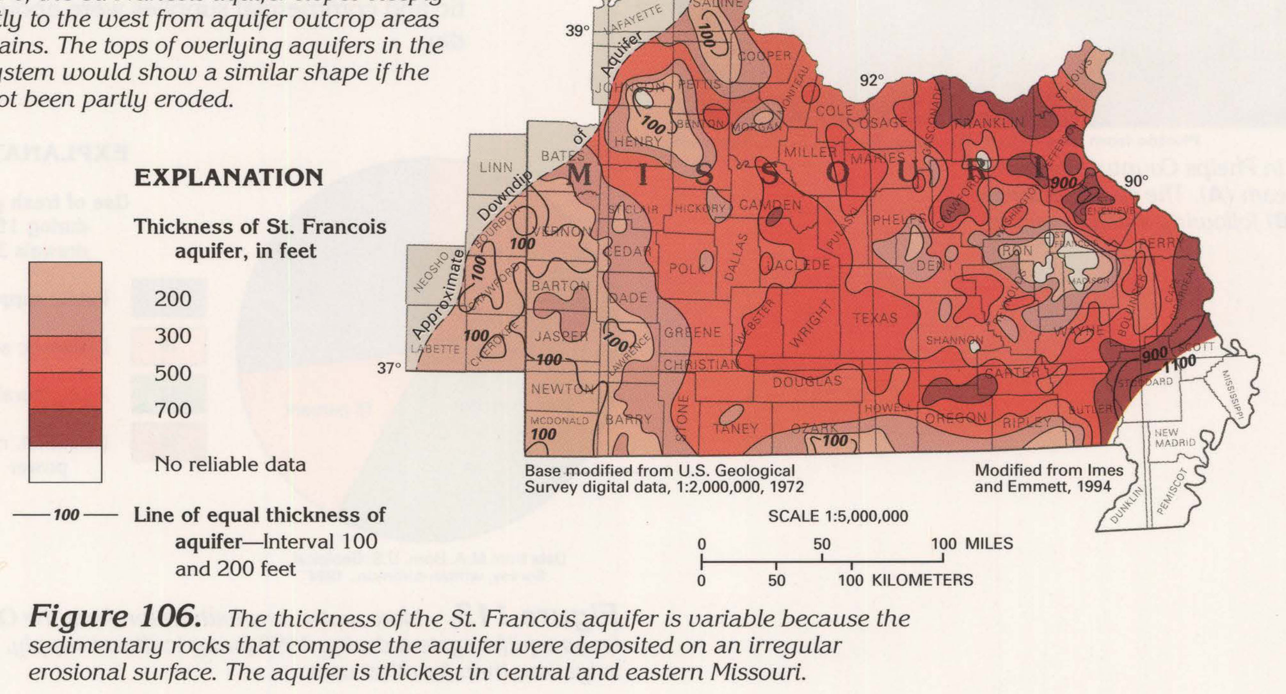


Figure 106. The thickness of the St. Francois aquifer is variable because the sedimentary rocks that compose the aquifer were deposited on an irregular erosional surface. The aquifer is thickest in central and eastern Missouri.

ST. FRANCOIS CONFINING UNIT

The St. Francois confining unit underlies the Ozark aquifer and separates it from the underlying St. Francois aquifer. The confining unit consists primarily of dolomite of minimal permeability but includes limestone, shale, and siltstone. Where the confining unit contains more shale and siltstone, it more effectively retards the movement of ground water between the two aquifers. The Davis Formation and the Derby and the Doe Run Dolomites are the geologic formations that compose the St. Francois confining unit. North of the Missouri River, the shaly Davis Formation is considered to be a confining unit, but the Derby and the Doe Run Dolomites yield small volumes of water.

The St. Francois confining unit crops out in a narrow band around the St. Francois Mountains. The confining unit is in the subsurface throughout the extent of the Ozark Plateaus aquifer system in Segment 3 except for local areas in western Missouri. The thickness of the eastern two-thirds of the confining unit generally is greater than 200 feet; in the western third, it is about 100 feet thick. However, the thickness of the unit is variable and locally is as great as 750 feet in northwestern Arkansas. Near the Mississippi River, the thickness of the confining unit is greater than 500 feet in several places.

ST. FRANCOIS AQUIFER

The St. Francois aquifer is the lowermost aquifer in the Ozark Plateaus aquifer system and is exposed at the land surface only in the St. Francois Mountains. Away from the mountains, the top of the aquifer slopes into the subsurface in all directions (**fig. 105**) and, within a short distance, it becomes buried beneath the more productive Ozark aquifer. The St. Francois aquifer is accordingly used as a source of supply only in and near the St. Francois Mountains. Several small faults cut the aquifer, especially in eastern Missouri, and locally displace its top. The top of the aquifer slopes steeply eastward from the St. Francois Mountains; westward, the slope is less steep, and the surface of the aquifer shows small hills and basins. The tops of the overlying aquifers and confining units in the Ozark Plateaus aquifer system would show the same overall shape as the top of the St. Francois aquifer if the overlying hydrogeologic units had not been partly eroded away.

The St. Francois aquifer consists of the Bonneterre Dolomite and the Lamotte Sandstone and its lateral equivalent, the Reagan Sandstone, all of which are of Cambrian age. The Lamotte Sandstone is the most productive of the geologic formations that compose the aquifer, and yields as high as 500 gallons per minute are reported from wells completed in this sandstone. Yields of wells completed in the Bonneterre Dolomite are reported to range between 10 and 50 gallons per minute. The water-yielding capability of the Reagan Sandstone is not well known. The Lamotte Sandstone and the Bonneterre Dolomite occur north of the Missouri River, but their water-yielding properties are not known; accordingly, no aquifer equivalent to the St. Francois aquifer is mapped there.

The thickness of the St. Francois aquifer generally is between 300 and 500 feet in south-central Missouri west of the St. Francois Mountains (**fig. 106**). The thickness of the aquifer is greater than 700 feet in several places to the north, east, and southeast of the mountains. The aquifer thins near its western and southern limits. The thickness of the St. Francois aquifer is irregular because the sedimentary rocks that compose the aquifer were deposited on a rugged erosional surface that was developed on Precambrian rocks of the basement confining unit. Places where the aquifer is missing in the subsurface may have been islands in the Cambrian sea where the aquifer sediments were deposited.

ST. FRANCOIS AQUIFER—Continued

Water is withdrawn from the St. Francois aquifer only where the aquifer crops out or is buried to shallow depths. Little is known, therefore, about the regional ground-water flow system or the chemical quality of the water in the aquifer. Sparse water-level data (**fig. 107**) indicate that flow in the aquifer in and near outcrop areas primarily is controlled by topography. Water enters the aquifer as recharge from precipitation that falls on topographically high outcrop areas. Most of the water moves along short flow paths and discharges as base flow to nearby streams. A small volume of water moves along slightly longer flow paths into confined parts of the aquifer and discharges to shallower aquifers by upward leakage.

The chemical quality of the water in the St. Francois aquifer in and near the aquifer outcrop areas generally is suitable for most uses. The water is a calcium magnesium bicarbonate type with dissolved-solids concentrations reported to range between 200 and 450 milligrams per liter. Chloride concentrations in the water generally are less than 60 milligrams per liter, and sulfate concentrations are 150 milligrams per liter or less. Freshwater has been reported from the St. Francois aquifer as far west as Jasper and Pettis Counties, Missouri, which indicates a regional ground-water flow system in the aquifer.

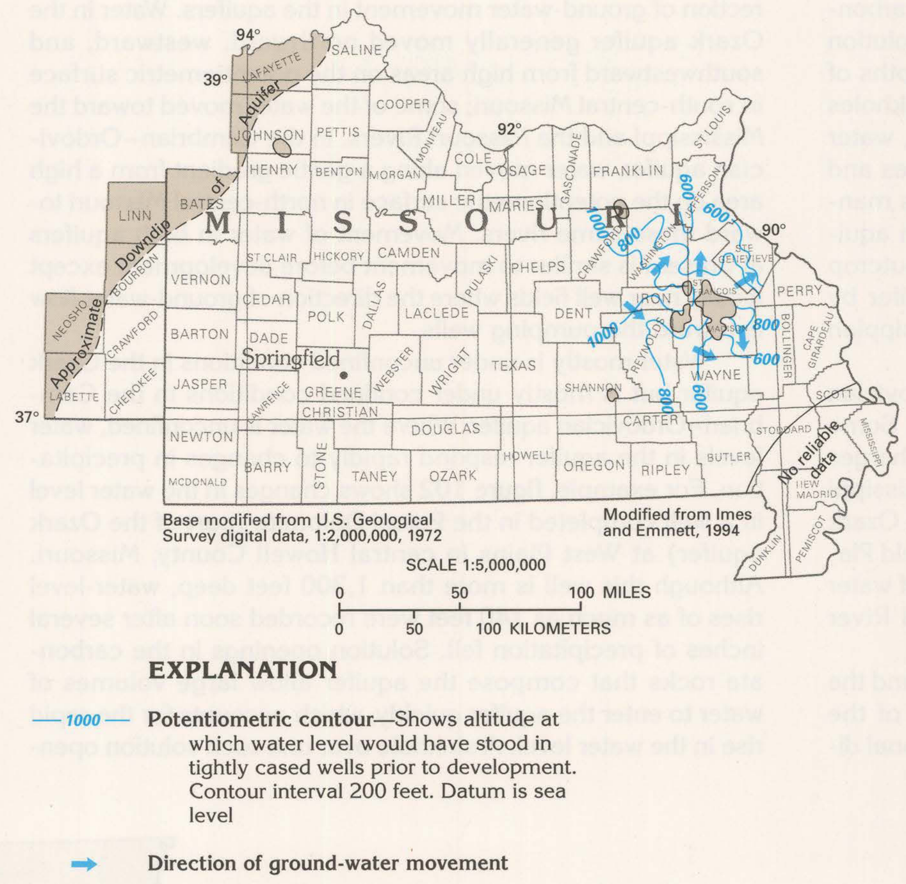


Figure 107. Water in the St. Francois aquifer generally moves along short flow paths from high altitudes on the potentiometric surface to nearby streams where it discharges as base flow.

SOLUTION FEATURES

Carbonate rocks, such as the limestone and dolomite that make up a large part of the Ozark Plateaus aquifer system, are readily dissolved where they are exposed at the land surface or are covered by a thin layer of soil. Small amounts of carbon dioxide are absorbed by precipitation that falls through the atmosphere. When the precipitation falls on the soil and percolates down through it to the water table, additional carbon dioxide is absorbed from decomposing organic matter in the soil. This absorption creates a weak carbonic acid, which partially dissolves the carbonate rocks. Initially, most of the rock material is dissolved along existing openings in the rock, such as joints and bedding planes. As the openings are enlarged, more of the acidic water is able to move more quickly through the aquifer; thus, the dissolution process and enlargement of the openings is accelerated. In some places, the openings are enlarged until streams flow in them and sediment transported in the streams erodes part of the rocks. If dissolution proceeds long enough, then karst topography, which is characterized by caves, sinkholes, and springs, develops on the carbonate rocks.

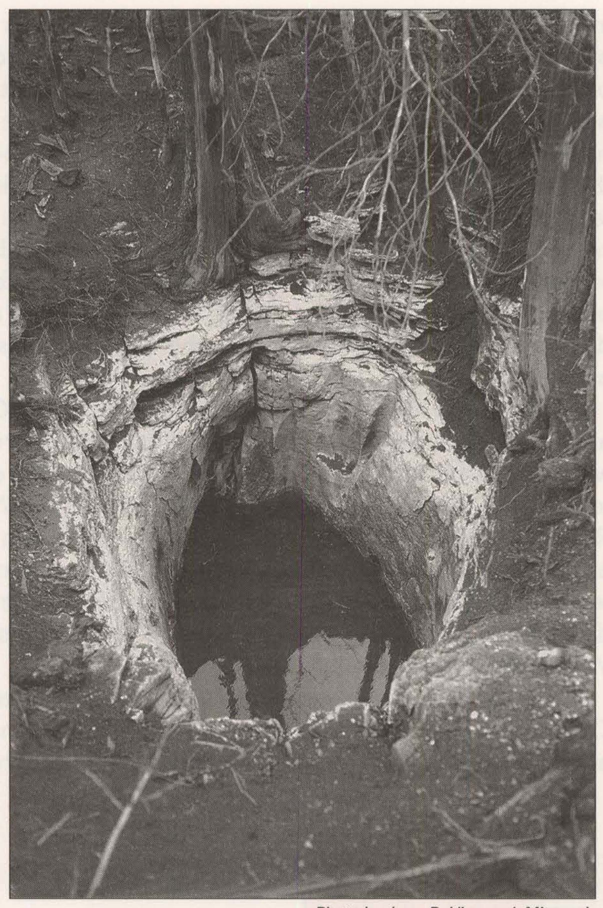


Photo by Jerry D. Vineyard, Missouri Division of Geology and Land Survey

Figure 108. Reversible sinkholes, such as this one, which is called Oval Sink and is located near Springfield, Missouri, allow surface runoff to enter carbonate-rock aquifers directly during most seasons of the year. Heavy rains can cause water levels in the aquifer and the sinkhole to rise until the sinkhole becomes a spring and discharges water from the aquifer to the land surface. Such sinkholes are known as estavelles.

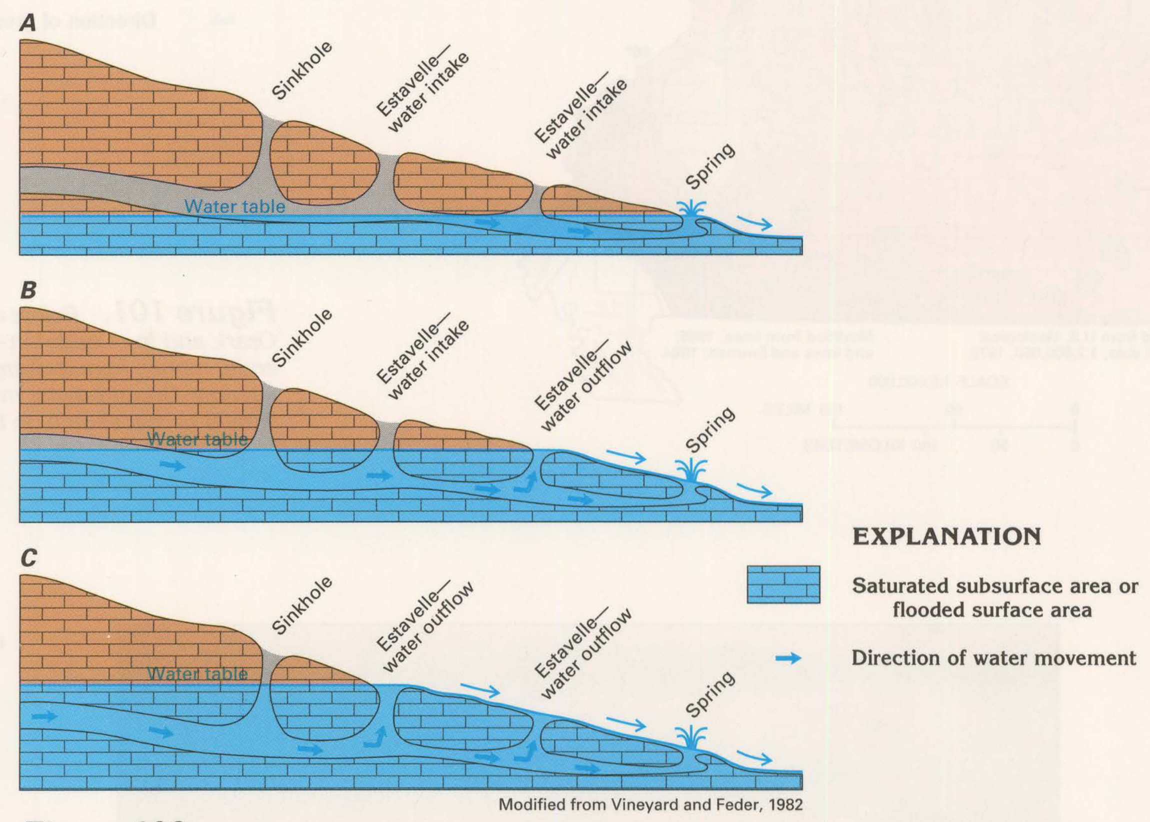


Figure 109. Estavelles, or reversible sinkholes, are recharge points through which water enters the aquifer when water levels are low (***A***). When water levels rise (***B***) in response to precipitation, the estavelle becomes a discharge point. Further rise in water levels (***C***) can cause flow to reverse in estavelles at higher altitudes.

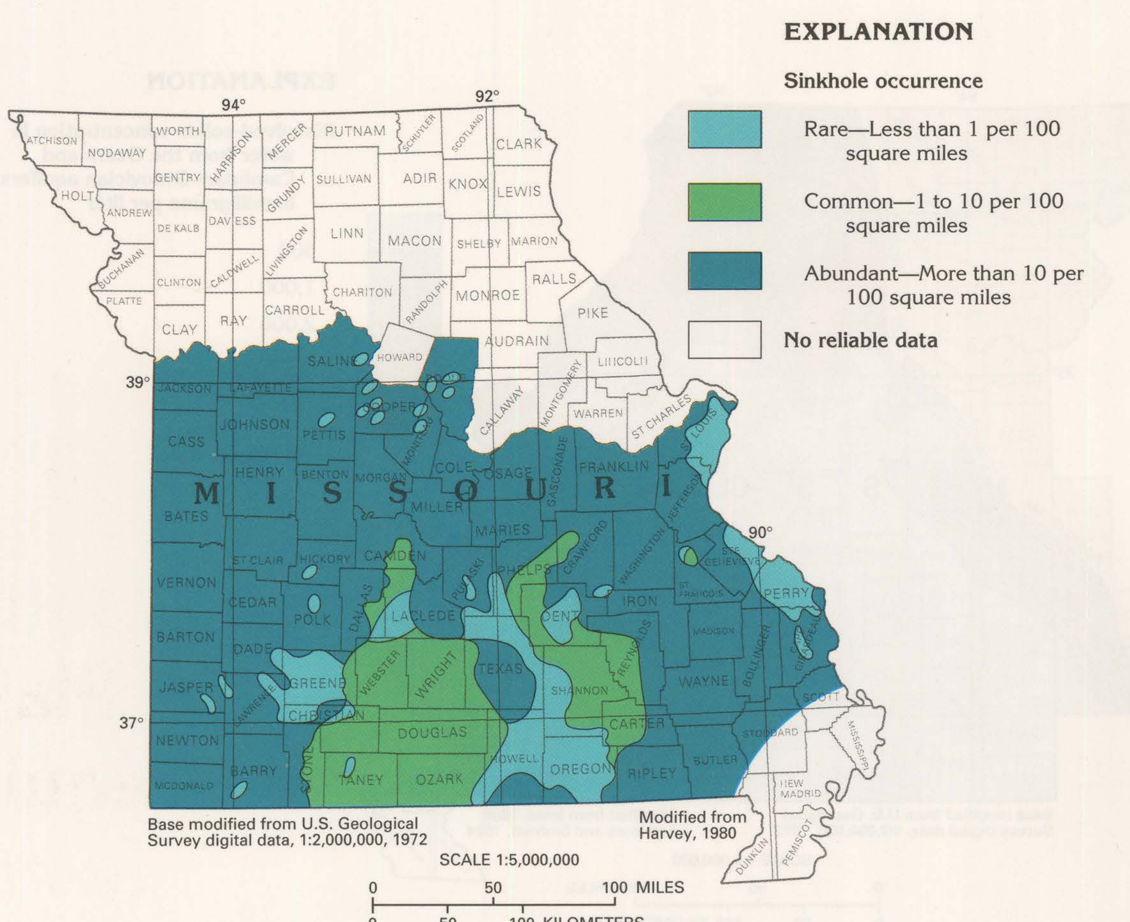
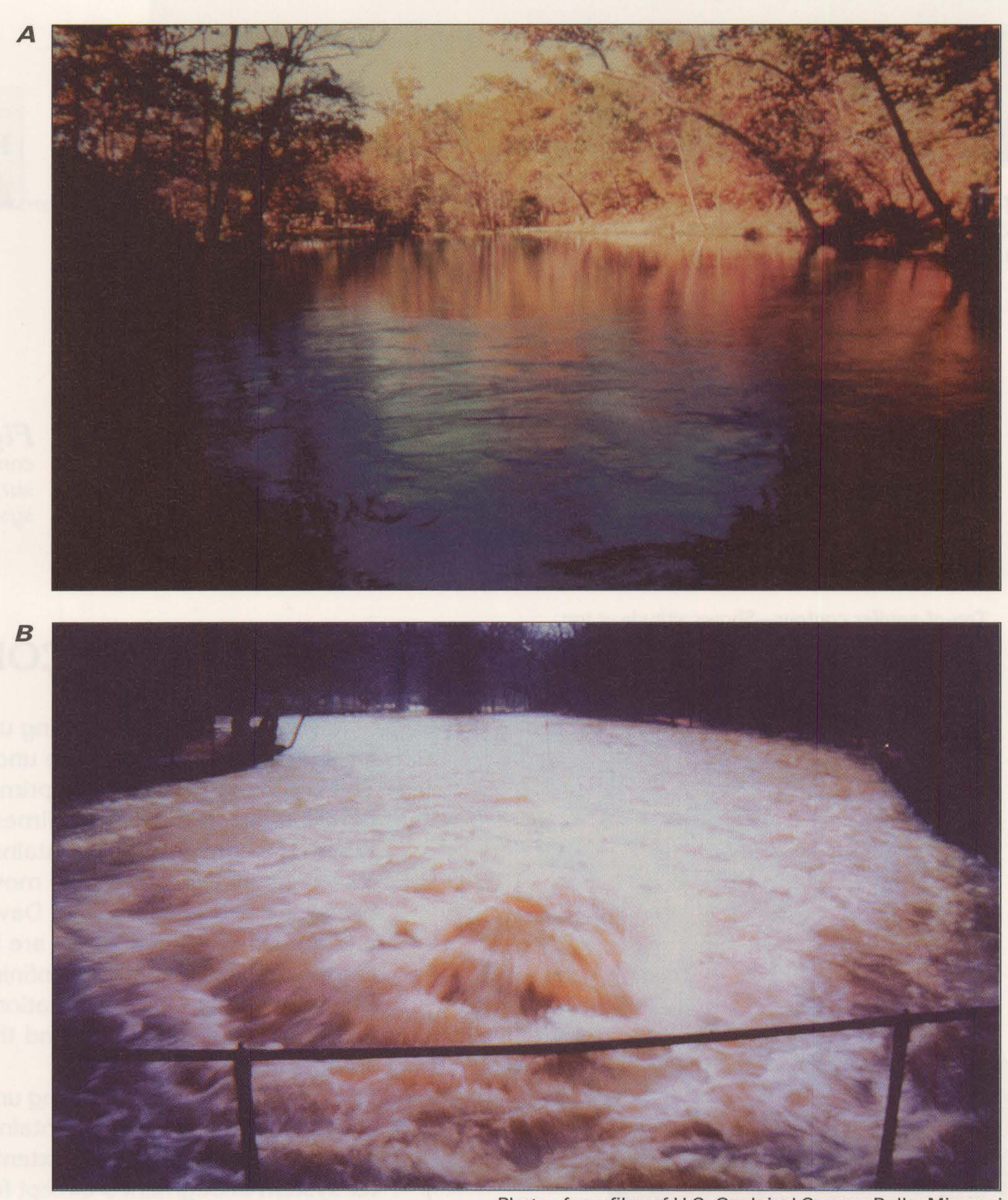


Figure 110. More sinkholes are developed in the carbonate rocks in south-central Missouri than elsewhere. This area is underlain by rocks that form the Ozark aquifer. The rocks of the Springfield Plateau aquifer in southwestern Missouri contain fewer sinkholes.



Photos from files of U.S. Geolgical Survey, Rolla, Missouri

Figure 111. Meramac Spring in Phelps County, Missouri, forms the headwaters of a small stream (***A***). The spring boil rose to about 4 feet above stream level (***B***) following a heavy rain in the spring catchment area.

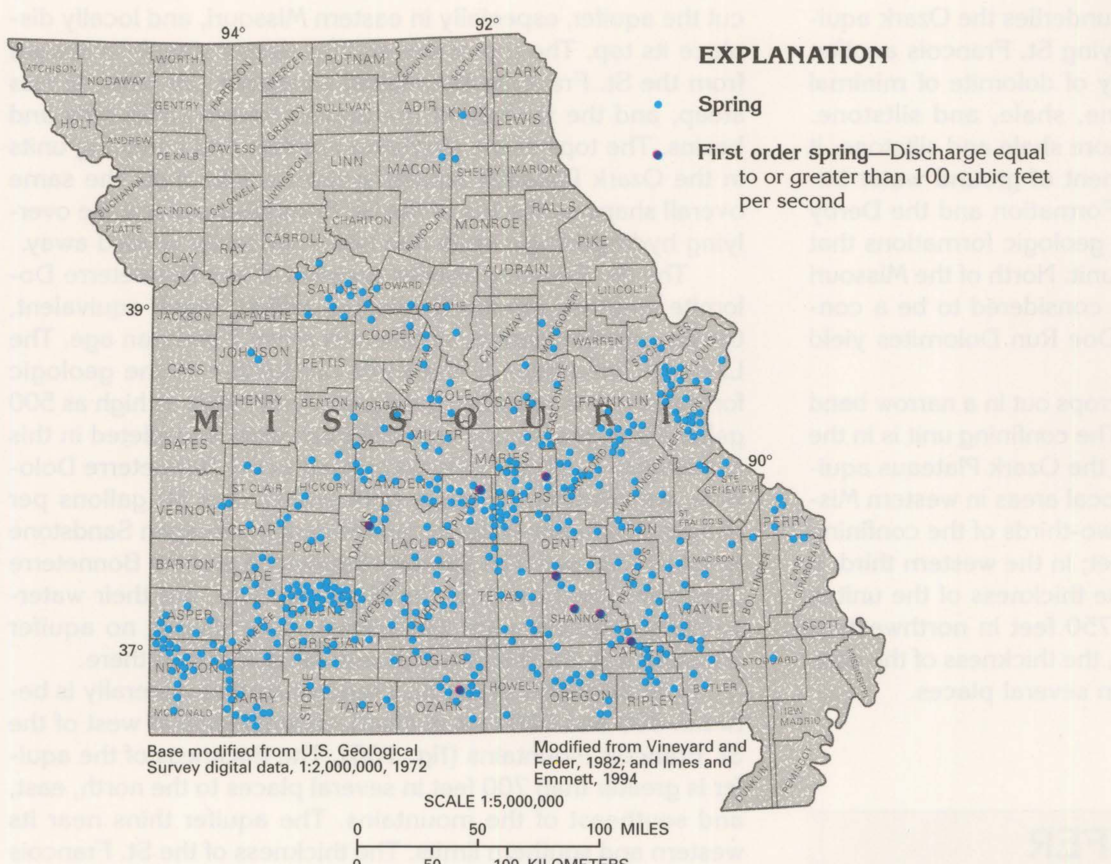


Figure 112. Most springs in Missouri issue from aquifers of the Ozark Plateaus aquifer system. All the springs that discharge 100 cubic feet of water per second or more issue from the Ozark aquifer.

Sinkholes

Sinkholes are closed, usually circular depressions in the land surface. Sinkholes form by dissolution of bedrock and are common where carbonate rocks are at or near land surface. Voids develop where part of the carbonate rock is dissolved and the subsequent collapse of overlying material creates a sinkhole. Many sinkholes form slowly and expand gradually. Sudden collapse of surface material into a sinkhole sometimes occurs as a result of a natural decline of ground-water levels or human activities, such as the diversion of surface water, withdrawal of ground water, or construction of surface water impoundments or heavy structures on the land surface. Such sudden collapse is called catastrophic collapse and can result in severe damage to property or endanger human or animal life.

All or part of the flow of small streams might enter a sinkhole. Sinkholes commonly are connected to a subsurface network of caves, pipes, and other types of solution openings, all of which channel large volumes of ground water. Thus, sinkholes have important effects on ground and surface water. Large sinkholes may be occupied by ponds or lakes. Some sinkholes, such as the one shown in **figure 108**, are reversible; that is, water may flow into the sinkhole at times and out of it at other times. Such a sinkhole is called an estavelle. The relation of the water table to flow into and out of a reversible sinkhole is shown by the diagram in **figure 109**. During periods of normal or less-than-normal precipitation, water levels in the aquifer are low, and surface water enters the aquifer quickly and directly through the estavelles (**fig. 109*A***). However, flow can be reversed (**fig. 109*B***), and an estavelle can function as a spring when water levels in the aquifer rise during periods of excessive precipitation. As water levels continue to rise (**fig. 109*C***), flow can be reversed in additional estavelles.

Sinkholes are abundant to common in much of the area where the carbonate rocks that compose the Ozark Plateaus aquifer system are at or near the land surface (**fig. 110**). Most of the areas where more than 10 sinkholes per 100 square miles have been mapped are underlain by the Ozark aquifer (compare **figs. 95** and **110**). Most sinkholes that have formed by sudden collapse are in the area underlain by the Ozark aquifer. However, a large area of abundant sinkholes near Springfield, Missouri, and smaller, isolated areas of abundant sinkholes to the north and west of Springfield are underlain by the Springfield Plateau aquifer.

Springs

Springs are openings through which ground water discharges to the land surface. The sizes of the springs and the volume of water they discharge vary. Some springs are small seeps where only small volumes of water issue slowly from the aquifer; others, such as Meramac Spring in Missouri (**fig. 111*A***), are large enough to form the headwaters of streams. Following heavy rains in the catchment area of the spring, a boil can develop on the surface of a stream where the spring discharges through the streambed (**fig. 111*B***). Although springs may discharge from an aquifer that contains water under unconfined, or water-table, conditions, such springs tend to be small, their discharges vary greatly, and their flows tend to cease during periods of low rainfall. In contrast, springs that issue from aquifers that contain water under confined conditions tend to be unaffected by seasonal variations in precipitation. This is because the flows of such springs are supplied by a large replenishment area, in some cases as large as several tens or hundreds of square miles. Springs are common in areas of karst topography, such as that which has developed on the carbonate rocks of the Ozark and the Springfield Plateau aquifers.

Missouri has eight first-order springs, or springs that have a flow that is greater than or equal to 100 cubic feet per second. The location of these springs is shown in **figure 112**, along with the location of smaller springs. All the first-order springs and most of the smaller springs mapped issue from the Ozark aquifer (compare **figs. 95** and **112**). Some springs, however, issue from the Springfield Plateau and the Cambrian-Ordovician aquifers. The springs are fed by conduits that developed by partial dissolution of the limestone and dolomite that compose the aquifers. Fractures and joints in the carbonate rocks also channel water to the springs. Water from many springs is used to supply fish hatcheries, and some springs are used as a partial source of municipal water supply. The chemical quality of spring water usually is suitable for most purposes, but the water is susceptible to contamination because in many places, the springs are connected to sinkholes by networks of solution openings. Thus, any contaminants that enter the aquifer can be quickly transported to a spring, as in the case of the sewage lagoon at West Plains, Missouri, discussed previously.

FRESH GROUND-WATER WITHDRAWALS

Total fresh ground-water withdrawals from the Ozark Plateaus aquifer system during 1990 were 330 million gallons per day, 8 million gallons per day of which was withdrawn in Kansas. About 139 million gallons per day was withdrawn for agricultural purposes, the principal use (**fig. 113**). About 88 million gallons per day was used for public supply, and about 53 million gallons per day was withdrawn for industrial, mining, and thermoelectric power uses. Withdrawals for domestic and commercial supplies were about 50 million gallons per day.

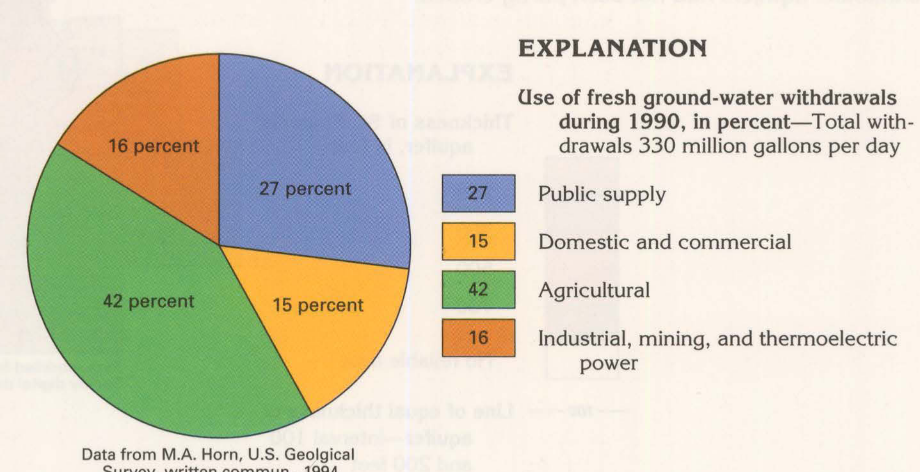


Figure 113. More water was withdrawn from the Ozark Plateaus aquifer system during 1990 for agricultural supply, primarily irrigation, than for other uses.

MISSISSIPPIAN AQUIFER

The Mississippian aquifer is the uppermost aquifer in Paleozoic rocks in northern Missouri. The aquifer extends over all of Missouri north of the Missouri River (**fig. 114**) except for small areas near the Mississippi and the Missouri Rivers where the rocks that compose the aquifer have been removed by erosion. Stratigraphically equivalent rocks south of the Missouri River are considered to be part of the Springfield Plateau aquifer, which is the uppermost aquifer of the Ozark Plateaus aquifer system. The Mississippian and the Springfield Plateau aquifers possibly are hydraulically connected in the Saline–Chariton–Howard–Cooper County area but are hydraulically separate elsewhere. Because this connection is poorly known, the aquifers are considered to have separate ground-water flow systems in this report.

The Mississippian aquifer is so named because it consists of limestone of Mississippian age. The Keokuk, the Burlington, the Fern Glen, the Sedalia, and the Chouteau Limestones compose the aquifer; of these formations, the Keokuk and the Burlington are the principal water-yielding rocks. Both formations consist of crystalline limestone and yield water primarily from solution cavities. In most places, the aquifer is overlain by a confining unit of Pennsylvanian shale and sandstone and is everywhere underlain by a confining unit of Mississippian shale.

The thickness of the Mississippian aquifer averages about 200 feet but locally exceeds 400 feet in northwestern Missouri (**fig. 115**). The aquifer is thickest in part of the Forest City Basin, which is a structural downwarp that extends northward into Iowa, and is thinnest near the Mississippi and the Missouri Rivers where it has been dissected or partially removed by erosion.

Ground-water movement in the Mississippian aquifer can be inferred from a map of the potentiometric surface of the aquifer (**fig. 116**). The map was prepared by using the earliest water levels available for wells completed in the aquifer, in order to represent conditions before the aquifer was developed. Recharge to the aquifer is mostly from precipitation that falls on areas where the aquifer is exposed at the land surface or is overlain by a thin blanket of younger rocks or glacial deposits, or both. Locally, the Mississippian aquifer receives some recharge by vertical leakage from the overlying glacial drift aquifers or the deeper Cambrian–Ordovician aquifer where the hydraulic head in the Mississippian aquifer is less than that of the adjacent aquifers. Most of the water in the Mississippian aquifer moves along flow paths that are of short or intermediate length from the three high areas on the potentiometric surface toward small to large streams, into which it discharges as base flow (**fig. 116**). The irregular shape of the potentiometric surface largely reflects the topography of the area.

The chemical quality of the water in the Mississippian aquifer varies considerably. The aquifer contains freshwater only in the eastern one-third of its extent (**fig. 117**); elsewhere, it contains slightly saline to very saline water. Dissolved-solids concentrations of water from the aquifer generally are greatest where the aquifer is overlain by a thick confining unit and least where it is unconfined or overlain by a thin or leaky confining unit. In southern Carroll and Chariton Counties and western Howard County, the aquifer contains water with dissolved-solids concentrations of greater than 10,000 milligrams per liter. This very saline water is thought to have entered the Mississippian aquifer either by upward leakage from the underlying Cambrian–Ordovician aquifer or by the discharge of eastward-moving saline water from the upper aquifer unit of the Western Interior Plains aquifer system.

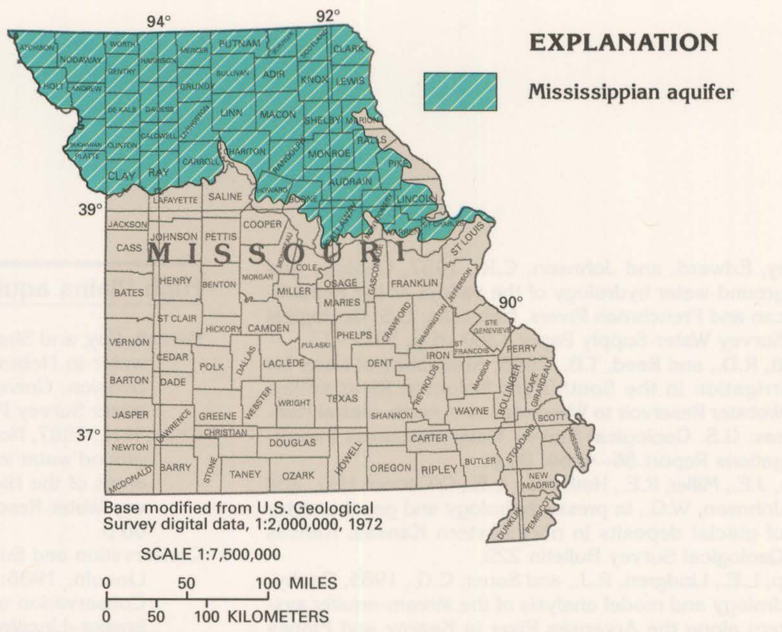


Figure 114. The Mississippian aquifer underlies most of northern Missouri except where it has been locally removed by erosion.

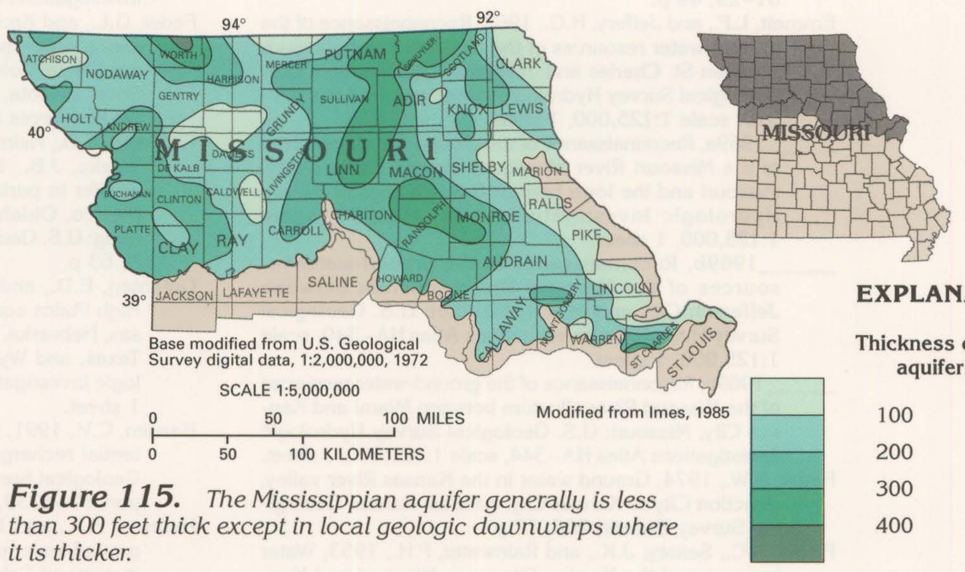


Figure 115. The Mississippian aquifer generally is less than 300 feet thick except in local geologic downwarps where it is thicker.

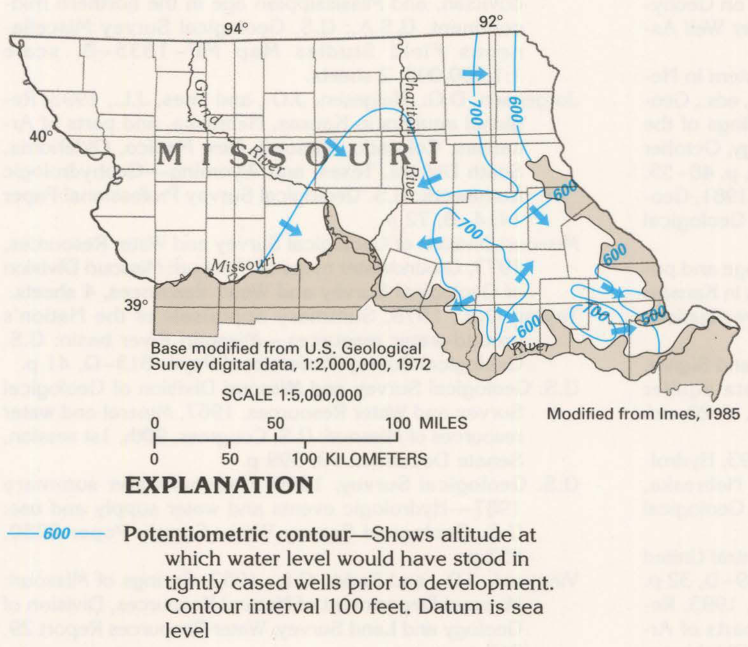


Figure 116. Water in the Mississippian aquifer moves locally from recharge areas that are highs on the potentiometric surface toward streams where it discharges as base flow. No regional direction of flow can be defined for the aquifer.

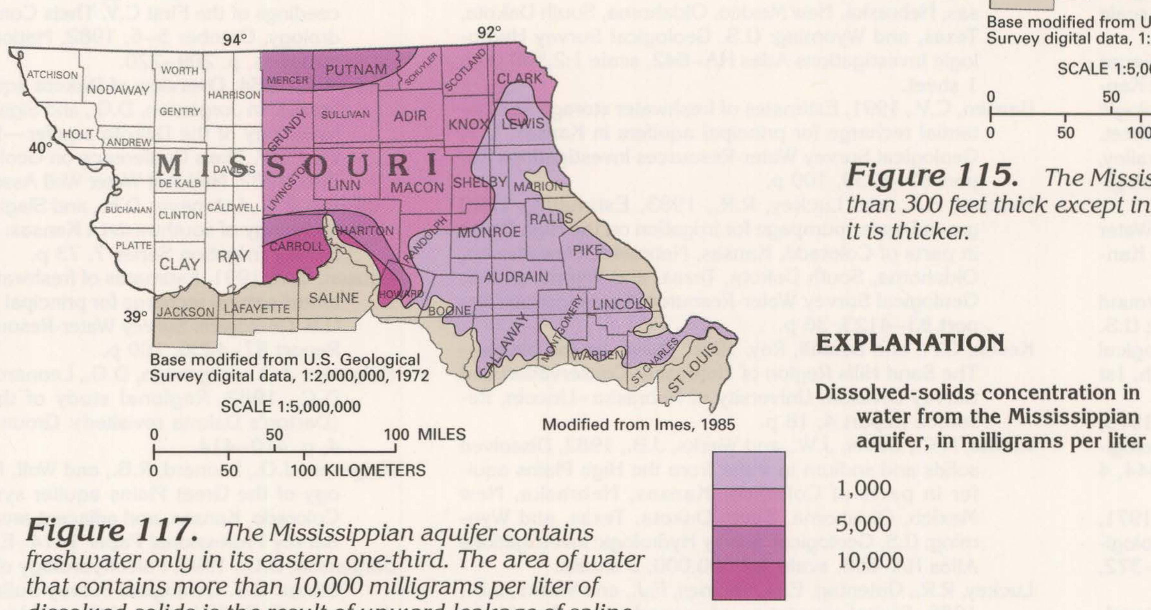


Figure 117. The Mississippian aquifer contains freshwater only in its eastern one-third. The area of water that contains more than 10,000 milligrams per liter of dissolved solids is the result of upward leakage of saline water from deeper aquifers.

Mississippian aquifer

WESTERN INTERIOR PLAINS AQUIFER SYSTEM

The Western Interior Plains aquifer system underlies most of Kansas, the eastern and southern parts of Nebraska, and a small area in west-central Missouri (**fig. 118**). The aquifer system consists of water-yielding dolomite, limestone, and sandstone that are stratigraphically equivalent to aquifers of the Ozark Plateaus aquifer system. However, in contrast to the Ozark Plateaus system, the Western Interior Plains aquifer system contains no freshwater.

The Western Interior Plains aquifer system consists of lower aquifer units in rocks of Ordovician and Cambrian age, a shale confining unit of Mississippian and Devonian age, and an upper aquifer unit of Mississippian limestone. The thickness of the aquifer system (including the confining unit) ranges from less than 500 feet to more than 3,000 feet in Segment 3 (**fig. 119**). The aquifer system is thin or absent on structural uplifts and is thickest in downwarps. For example, the thick area in southwestern Kansas is on the northern flank of the Anadarko Basin, and the thick area along the Missouri River is on the southern flank of the Forest City Basin. The aquifer system is thin or missing in western Nebraska and central Kansas atop the Chadron and the Cambridge Arches and the central Kansas Uplift and is locally thin or absent in eastern Kansas on the Nemaha Uplift.

Regional ground-water movement in the aquifer system is southeastward to eastward. Much of the water discharges from the aquifer system in the transition zone between the Western Interior Plains and the Ozark Plateaus aquifer systems. The location of this transition zone and the merging of ground-water flow in these two aquifer systems are discussed in the section of this report that describes the relation of the Ozark Plateaus aquifer system to adjacent aquifers. Saline ground water from the Western Interior Plains aquifer system discharges to springs and streams in Henry and Saline Counties, Missouri. Water is thought to move very slowly through the aquifer system.

Dissolved-solids concentrations of water in the Western Interior Plains aquifer system are greater than 1,000 milligrams per liter everywhere. In thick, deeply buried parts of the aquifer system, dissolved-solids concentrations of more than 200,000 milligrams per liter have been reported. The large concentrations are due, in part, to the slow movement of ground water in the aquifer system. The slower the water moves, the longer it is in contact with aquifer minerals and the more mineral material it is able to dissolve.

Little water is withdrawn from the Western Interior Plains aquifer system because the aquifer system is deeply buried and contains highly mineralized water. Locally, deeply buried parts of the aquifer system contain oil and gas, and some brine that is a by-product of hydrocarbon production is injected into disposal wells, which are completed in permeable parts of the system.

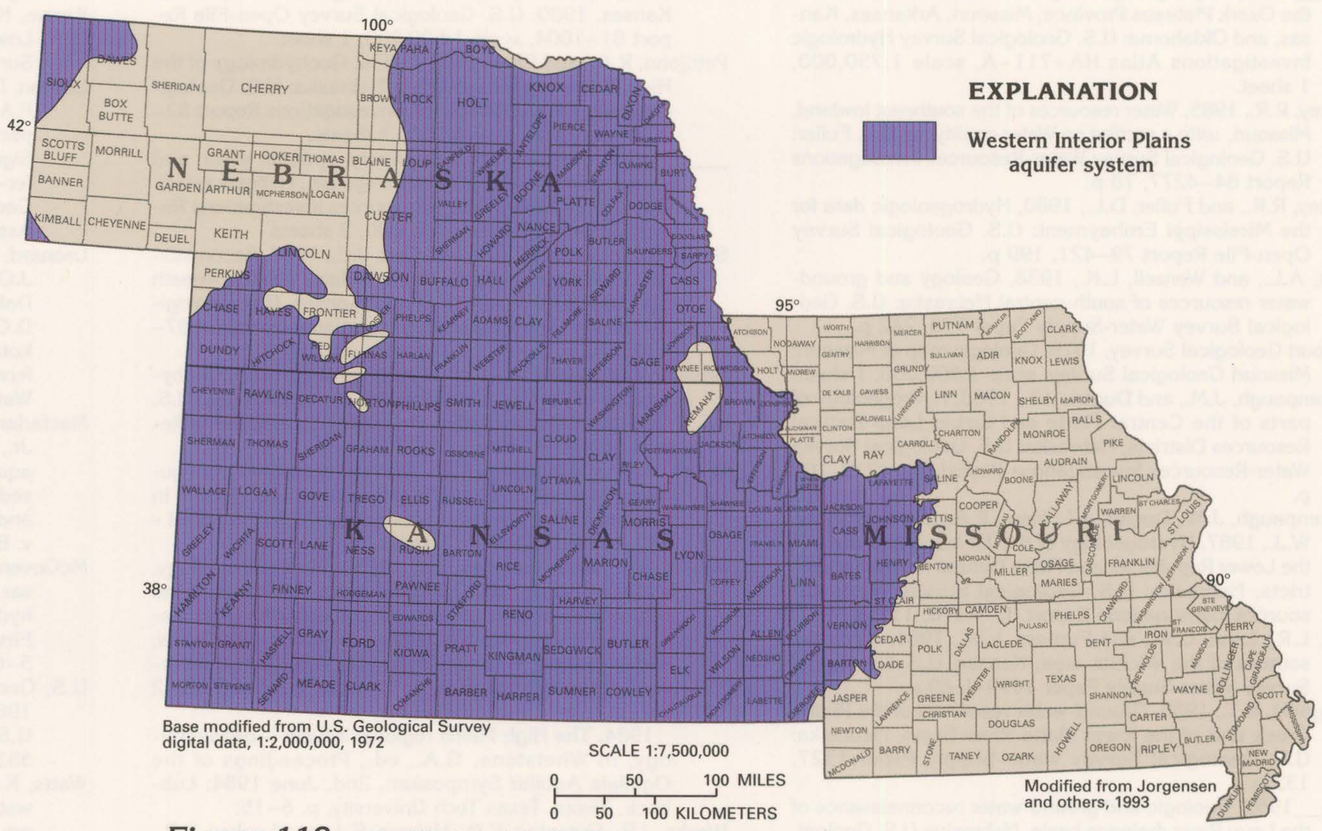


Figure 118. The Western Interior Plains aquifer system extends over large parts of Kansas and Nebraska and a small part of Missouri.

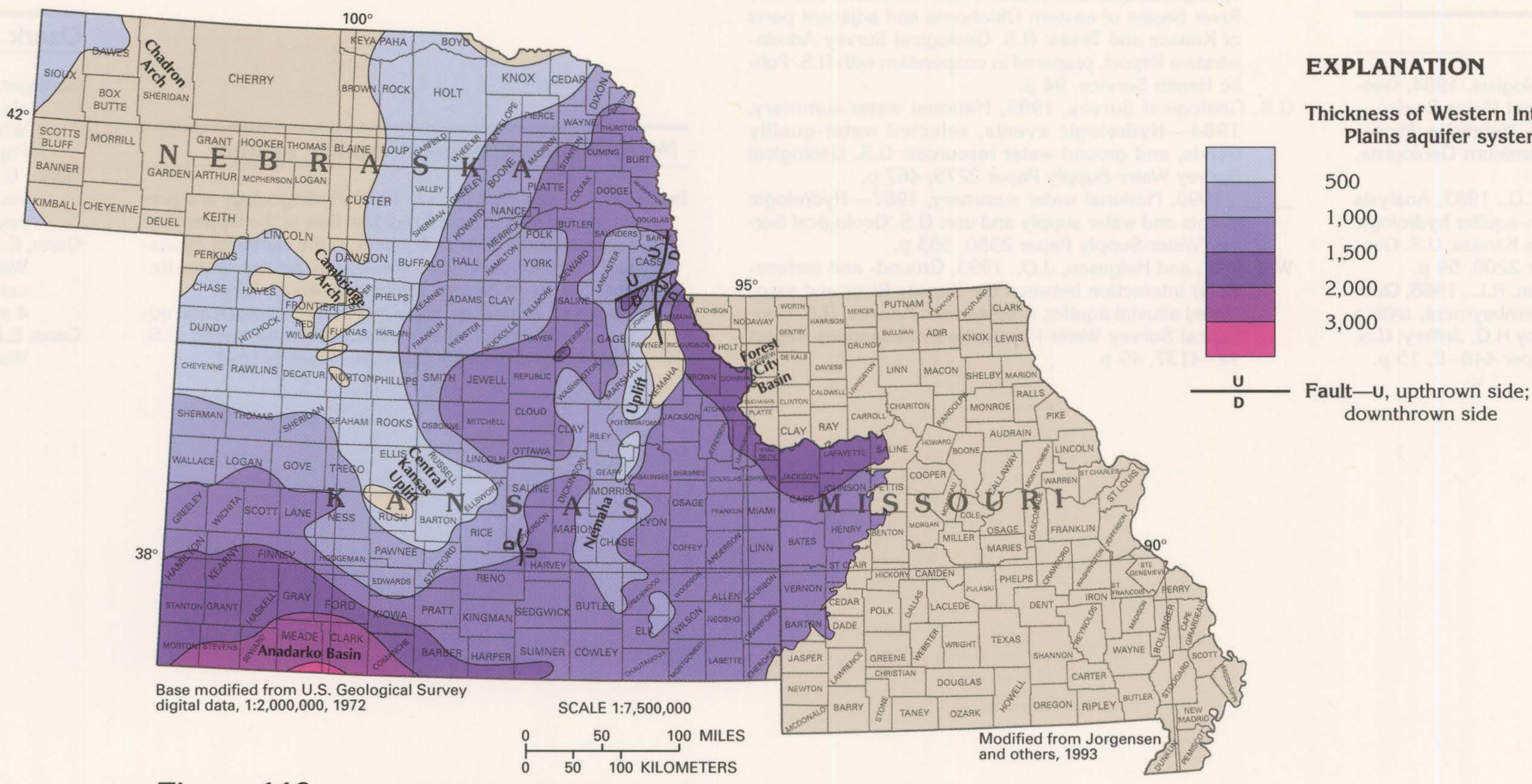


Figure 119. The aquifer system is thick along the flanks of major structural downwarps and is thin or absent on structural uplifts.

Western Interior Plains aquifer system

References

Regional summary

American Association of Petroleum Geologists, 1984, Geological Highway Map, Northern Great Plains Region—North Dakota, South Dakota, Iowa, Nebraska, Minnesota: American Association of Petroleum Geologists, scale 1:900,000, 1 sheet.

———1986, Geological Highway Map, Mid-Continent Region: Kansas, Missouri, Oklahoma, Arkansas: American Association of Petroleum Geologists, scale 1:900,000, 1 sheet.

Burchett, R.R., comp., 1986, Bedrock geologic map of Nebraska: Nebraska Geological Survey, scale 1:1,000,000, 1 sheet.

Ebanks, W.J., Jr., Brady, L.L., Heckel, P.H., O'Connor, M.G., Sanderson, G.A., West, R.R., and Wilson, F.W., 1979, The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—Kansas: U.S. Geological Survey Professional Paper 1110–Q, 30 p.

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

Gebert, W.A., Graczyk, D.J., and Krug, W.R., 1987, Average annual runoff in the United States, 1951–80: U.S. Geological Survey Hydrologic Investigations Atlas HA–170, scale 1:7,500,000, 1 sheet.

Imes, J.L., 1985, The ground-water flow system in northern Missouri with emphasis on the Cambrian–Ordovician aquifer: U.S. Geological Survey Professional Paper 1305, 61 p.

Imes, J.L., and Emmett, L.F., 1994, Geohydrology of the Ozark Plateaus aquifer system in parts of Missouri, Arkansas, Oklahoma, and Kansas: U.S. Geological Survey Professional Paper 1414–D, 127 p.

Jorgensen, D.G., Helgesen, J.O., and Imes, J.L., 1993, Regional aquifers in 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.

Kansas Geological Survey, 1964, Geologic map of Kansas: Kansas Geological Survey, scale 1:500,000, 1 sheet.

Lugn, A.L., and Wenzel, L.K., 1938, Geology and ground-water resources of south-central Nebraska: U.S. Geological Survey Water-Supply Paper 779, 242 p.

Missouri Geological Survey, 1979, Geologic map of Missouri: Missouri Geological Survey, scale 1:500,000, 1 sheet.

Solley, W.B., Pierce, R.R., and Perlman, H.A., 1993, Estimated use of water in the United States in 1990: U.S. Geological Survey Circular 1081, 76 p.

U.S. Geological Survey, 1985, National water summary 1984—Hydrologic events, selected water-quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 467 p.

———1986, National water summary 1985—Hydrologic events and surface-water resources: U.S. Geological Survey Water-Supply Paper 2300, 506 p.

———1990, National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 553 p.

Surficial aquifer system

American Association of Petroleum Geologists, 1984, Geological Highway Map, Northern Great Plains Region—North Dakota, South Dakota, Iowa, Nebraska, Minnesota: American Association of Petroleum Geologists, scale 1:900,000, 1 sheet.

Barker, R.A., Dunlap, L.E., and Sauer, C.G., 1983, Analysis and computer simulation of stream-aquifer hydrology, Arkansas River Valley, southwestern Kansas: U.S. Geological Survey Water-Supply Paper 2200, 59 p.

Boswell, E.H., Cushing, E.M., and Hosman, R.L., 1968, Quaternary aquifers in the Mississippi embayment, *with a discussion on* Quality of the water, by H.G. Jeffery: U.S. Geological Survey Professional Paper 448–E, 15 p.

Bradley, Edward, and Johnson, C.R., 1957, Geology and ground-water hydrology of the valleys of the Republican and Frenchman Rivers, Nebraska: U.S. Geological Survey Water-Supply Paper 1360–H p. 589–713.

Burnett, R.D., and Reed, T.B., 1986, Availability of water for irrigation in the South Fork Solomon River valley, Webster Reservoir to Waconda Lake, north-central Kansas: U.S. Geological Survey Water-Resources Investigations Report 86–4064, 89 p.

Denne, J.E., Miller, R.E., Hathaway, L.E., O'Connor, H.G., and Johnson, W.G., in press, Hydrology and geochemistry of glacial deposits in northeastern Kansas: Kansas Geological Survey Bulletin 229.

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

Ellis, M.J., 1981, Analysis of stream-aquifer system interrelationships in the Big Blue and Little Blue River Basins in Gage and Jefferson Counties, Nebraska: U.S. Geological Survey Water-Resources Investigations Report 81–29, 49 p.

Emmett, L.F., and Jeffery, H.G., 1968, Reconnaissance of the ground-water resources of the Missouri River alluvium between St. Charles and Jefferson City, Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–315, scale 1:125,000, 1 sheet.

———1969a, Reconnaissance of the ground-water resources of the Missouri River alluvium between Kansas City, Missouri and the Iowa border: U.S. Geological Survey Hydrologic Investigations Atlas HA-336, scale 1:125,000, 1 sheet.

———1969b, Reconnaissance of the ground-water resources of the Missouri River alluvium between Jefferson City and Miami, Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–340, scale 1:125,000, 1 sheet.

———1969c, Reconnaissance of the ground-water resources of the Missouri River alluvium between Miami and Kansas City, Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–344, scale 1:125,000, 1 sheet.

Fader, S.W., 1974, Ground water in the Kansas River valley, Junction City to Kansas City, Kansas: Kansas Geological Survey Bulletin 206, 12 p.

Fishel, V.C., Searcy, J.K., and Rainwater, F.H., 1953, Water resources of the Kansas City area, Missouri and Kansas: U.S. Geological Survey Circular 273, 52 p.

Fuller, D.L., Knight, R.D., and Harvey, D.J., 1967, Ground water, *in* Mineral and water resources of Missouri: U.S. Geological Survey and Missouri Division of Geological Survey and Water Resources, U.S. Congress, 90th, 1st Session, Senate Document 19, p. 281–313.

Gann, E.E., Harvey, E.J., Barks, J.M., and Fuller, D.L.,1973, Water resources of northwestern Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–444, 4 sheets.

Gann, E.E., Harvey, E.J., Jeffery, H.G., and Fuller, D.L., 1971, Water resources of northeastern Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–372, 4 sheets.

Gillespie, J.B., and Hargadine, G.D., 1981, Saline ground-water discharge to the Smoky Hill River between Salina and Abilene, central Kansas: U.S. Geological Survey Water-Resources Investigations Report 81–43, 71 p.

Goeke, J.W., Peckenpaugh, J.M., Cady, R.E., and Dugan, J.T., 1992, Hydrology of parts of the Twin Platte and Middle Republican Natural Resources Districts, southwestern Nebraska: Nebraska Water Survey Paper 70, 89 p.

Hosman, R.L., and Weiss, J.S., 1991, Geohydrologic units of the Mississippi embayment and Texas coastal uplands aquifer systems, south-central United States: U.S. Geological Survey Professional Paper 1416–B, 19 p.

Imes, J.L., 1985, The ground-water flow system in northern Missouri with emphasis on the Cambrian–Ordovician aquifer: U.S. Geological Survey Professional Paper 1305, 61 p.

———1990, Major geohydrologic units in and adjacent to the Ozark Plateaus Province, Missouri, Arkansas, Kansas, and Oklahoma: U.S. Geological Survey Hydrologic Investigations Atlas HA–711–A, scale 1:750,000, 1 sheet.

Luckey, R.R., 1985, Water resources of the southeast lowland, Missouri, *with a section on* Water quality, by D.L. Fuller: U.S. Geological Survey Water-Resources Investigations Report 84–4277, 78 p.

Luckey, R.R., and Fuller, D.L., 1980, Hydrogeologic data for the Mississippi Embayment: U.S. Geological Survey Open-File Report 79–421, 199 p.

Lugn, A.L., and Wenzell, L.K., 1938, Geology and ground-water resources of south-central Nebraska: U.S. Geological Survey Water-Supply Paper 779, 242 p.

Missouri Geological Survey, 1979, Geologic map of Missouri: Missouri Geological Survey, scale 1:500,000, 1 sheet.

Peckenpaugh, J.M., and Dugan, J.T., 1983, Hydrogeology of parts of the Central Platte and Lower Loup Natural Resources Districts, Nebraska: U.S. Geological Survey Water-Resources Investigations Report 83–4219, 100 p.

Peckenpaugh, J.M., Dugan, J.T., Kern, R.A., and Schroeder, W.J., 1987, Hydrogeology of the Tri-basin and parts of the Lower Republican and Platte Natural Resources Districts, Nebraska: U.S. Geological Survey Water-Resources Investigations Report 87–4176, 117 p.

Petri, L.R., Lane, C.W., and Furness, L.W., 1961, Water resources of the Wichita area, Kansas: U.S. Geological Survey Water-Supply Paper 1499–I, 69 p.

Sniegocki, R.T., 1955, Ground-water resources of the Prairie Creek unit of the lower Platte River Basin, Nebraska: U.S. Geological Survey Water-Supply Paper 1327, 133 p.

———1959, Geologic and ground-water reconnaissance of the Loup River drainage basin, Nebraska: U.S. Geological Survey Water-Supply Paper 1493, 106 p.

Taylor, O.J., 1978, Summary appraisals of the Nation's ground-water resources—Missouri River Basin: U.S. Geological Survey Professional Paper 813–Q, 41 p.

Ward, P.E., 1961, Geology and ground-water features of salt springs, seeps, and plains in the Arkansas and Red River Basins of eastern Oklahoma and adjacent parts of Kansas and Texas: U.S. Geological Survey Administrative Report, prepared in cooperation with U.S. Public Health Service, 94 p.

U.S. Geological Survey, 1985, National water summary, 1984—Hydrologic events, selected water-quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 467 p.

———1990, National water summary, 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 553 p.

Wolf, R.G., and Helgesen, J.O., 1993, Ground- and surface-water interaction between the Kansas River and associated alluvial aquifer, northeastern Kansas: U.S. Geological Survey Water-Resources Investigations Report 92–4137, 49 p.

High Plains aquifer

Bentall, Ray, and Shaffer, F.B., 1979, Availability and use of water in Nebraska, 1975: Conservation and Survey Division, University of Nebraska–Lincoln, Nebraska Water Survey Paper 48, 121 p.

Chen, H.H., 1987, Nonpoint-source agricultural chemicals in ground water in Nebraska—Preliminary results for six areas of the High Plains aquifer: U.S. Geological Survey Water-Resources Investigations Report 86–4338, 68 p.

Conservation and Survey Division, University of Nebraska–Lincoln, 1986: The groundwater atlas of Nebraska: Conservation and Survey Division, University of Nebraska–Lincoln, Resource Atlas 4, 32 p.

Dugan, J.T., 1984, Hydrologic characteristics of Nebraska soils: U.S. Geological Survey Water-Supply Paper 2222, 19 p.

Dugan, J.T., McGrath, Timothy, and Zelt, R.B., 1994, Water-level changes in the High Plains aquifer—Pre-development to 1992: U.S. Geological Survey Water-Resources Investigations Report 94–4027, 56 p.

Feder, G.L., and Krothe, N.C., 1981, Results of a reconnaissance water-quality sampling program of the Ogallala aquifer in Colorado, Kansas, Nebraska, Oklahoma, South Dakota, and Texas: U.S. Geological Survey Water-Resources Investigations Report 81–65, 7 p.

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., and Weeks, J.B., 1980, Water table in the High Plains aquifer in 1978 in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–642, scale 1:2,500,000, 1 sheet.

Hansen, C.V., 1991, Estimates of freshwater storage and potential recharge for principal aquifers in Kansas: U.S. Geological Survey Water-Resources Investigations Report 87–4230, 100 p.

Heimes, F.J., and Luckey, R.R., 1983, Estimating 1980 ground-water pumpage for irrigation on the High Plains in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Water-Resources Investigations Report 83–4123, 36 p.

Keech, C.F., and Bentall, Ray, 1988, Dunes on the plains—The Sand Hills Region of Nebraska: Conservation and Survey Division, University of Nebraska–Lincoln, Resource Report 4, 18 p.

Krothe, N.C., Oliver, J.W., and Weeks, J.B., 1982, Dissolved solids and sodium in water from the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–658, scale 1:2,500,000, 2 sheets.

Luckey, R.R., Gutentag, E.D., Heimes, F.J., and Weeks, J.B., 1986, Digital simulation of ground-water flow in 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–D, 57 p.

Luckey, R.R., Gutentag, E.D., and Weeks, J.B., 1981, Water-level and saturated-thickness changes, predevelopment to 1980, in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–652, scale 1:2,500,000, 2 sheets.

McGrath, Timothy, and Dugan, J.T., 1993, Water-level changes in the High Plains aquifer—Predevelopment to 1991: U.S. Geological Survey Water-Resources Investigations Report 93–4088, 53 p.

Pabst, M.E., and Stullken, L.E., 1984, Altitude and configuration of the water table in the High Plains aquifer of Kansas, 1980: U.S. Geological Survey Open-File Report 81–1004, scale 1:500,000, 1 sheet.

Pettijohn, R.A., and Chen, H.H., 1983a, Geohydrology of the High Plains aquifer system in Nebraska: U.S. Geological Survey Water-Resources Investigations Report 82–502, map, scale 1:175,000, 3 sheets.

———1983b, Hydraulic conductivity, specific yield, and pumpage—High Plains aquifer system, Nebraska: U.S. Geological Survey Water-Resources Investigations Report 82–4014, scale 1:175,000, 3 sheets.

Stullken, L.E., Stamer, J.K., and Carr, J.E., 1987, Reconnaissance of water quality in the High Plains aquifer beneath agricultural lands, south-central Kansas, U.S. Geological Survey Water-Resources Investigations Report 87–4003, 25 p.

Stullken, L.E., Watts, K.R., and Lindgren, R.J., 1985, Geohydrology of the High Plains aquifer, western Kansas: U.S. Geological Survey Water- Resources Investigations Report 85–4198, 86 p.

Watts, K.R., and Stullken, L.E., 1985, Generalized configuration of the base of the High Plains regional aquifer in Kansas: U.S. Geological Survey Open-File Report 81–344, scale 1:500,000, 1 sheet.

Weeks, J.B., and Gutentag, E.D., 1981, Bedrock geology, altitude of base, and 1980 saturated thickness of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–648, scale 1:2,500,000, 2 sheets.

———1984, The High Plains regional aquifer—geohydrology, *in* Whetstone, G.A., ed., Proceedings of the Ogallala Aquifer Symposium, 2nd, June 1984: Lubbock, Texas, Texas Tech University, p. 6–15.

Weeks, J.B., Gutentag, E.D., Heimes, F.J., and Luckey, R.R., 1988, Summary of the High Plains Regional Aquifer-System Analysis in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400–A, 30 p.

Mississippi embayment aquifer system

Brahana, J.V., and Mesko, T.O., 1988, Hydrogeology and preliminary assessment of regional flow in the Upper Cretaceous and adjacent aquifers in the northern Mississippi Embayment: U.S. Geological Survey Water-Resources Investigations Report 87–4000, 65 p.

———in press, Hydrology of the McNairy–Nacatoch and adjacent aquifers in the Mississippi Embayment: U.S. Geological Survey Professional Paper 1416–L.

Hosman, R.L., and Weiss, J.L., 1991, Geohydrologic units of the Mississippi embayment and Texas coastal uplands aquifer systems, south-central United States: U.S. Geological Survey Professional Paper 1416–B, 19 p.

Mesko, T.O., 1988, Subsurface geology of Paleozoic, Mesozoic, and Cenozoic units in southeast Missouri: U.S. Geological Survey Miscellaneous Investigations Series, Map I–1875, scale 1:1,000,000, 2 sheets.

———1990, Geohydrology and water quality of Cenozoic and Mesozoic units in southeast Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–719, scale 1:1,000,000, 2 sheets.

Williamson, A.K., Grubb, H.F., and Weiss, J.L., 1990, Ground-water flow in the Gulf Coast aquifer systems, south-central United States—A preliminary analysis: U.S. Geological Survey Water-Resources Investigations Report 89–4071, 124 p.

Great Plains aquifer system

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.

Darton, N.H., 1905, Preliminary report on the geology and underground water resources of the Central Great Plains: U.S. Geological Survey Professional Paper 32, 433 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, October 5–6, 1982, National Water Well Association, p. 209–220.

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, October 5–6, 1982, National Water Well Association, p. 48–55.

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

Hansen, C.V., 1991, Estimates of freshwater storage and potential natural recharge for principal aquifers in Kansas: U.S. Geological Survey Water-Resources Investigations Report 87–4230, 100 p.

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.

Helgesen, J.O., Leonard, R.B., and Wolf, R.J., 1993, Hydrology of the Great Plains aquifer system in Nebraska, Colorado, Kansas, and adjacent areas: U.S. Geological Survey Professional Paper 1414–E, 80 p.

Jorgensen, D.G., 1993, Paleohydrology of the central United States: U.S. Geological Survey Bulletin 1989–D, 32 p.

Jorgensen, D.G., Helgesen, J.O., and Imes, J.L., 1993, Regional aquifers in 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., Leonard, R.B., Signor, D.C., and Helgesen, J.O., 1986, Central Midwest regional aquifer-system study, *in* Sun, R.J., ed., Regional Aquifer-System Analysis program of the U.S. Geological Survey—Summary of projects, 1978–84: U.S. Geological Survey Circular 1002, p. 132–140.

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.

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.

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, October 5–6, 1982, National Water Well Association, p. 221–228.

Leonard, R.B., Signor, D.C., Jorgensen, D.G., and Helgesen, J.O., 1984, Geohydrology and hydrochemistry of the Dakota aquifer, central United States, *in* Jorgensen, D.G., and Signor, D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5–6, 1982, National Water Well Association, p. 229–237.

Macfarlane, P.A., Doveton, J.M., Feldman, H.R., Bulter, J.J., Jr., Combes, J.M., and Collins, J.R., 1994, Aquifer/aquitard units of Kansas—Methods of delineation and sedimentary architecture effects on ground-water flow and flow properties: Journal of Sedimentary Research, v. B64, no. 4, p. 464–480.

McGovern, H.E., 1984, Overview of Dakota aquifer in Kansas, *in* Jorgensen, D.G., and Signor, D.G., eds., Geohydrology of the Dakota aquifer—Proceedings of the First C.V. Theis Conference on Geohydrology, October 5–6, 1982, National Water Well Association, p. 58–61.

U.S. Geological Survey, 1990, National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 553 p.

Watts, K.R., 1985, Potential hydrologic effects of ground-water withdrawals from the Dakota aquifer, southwestern Kansas: U.S. Geological Survey Water-Supply Paper 2304, 47 p.

Ozark Plateaus aquifer system

Bedinger, M.S., and Sniegocki, R.T., 1976, Summary appraisals of the Nation's ground-water resources—Arkansas-White-Red region: U.S. Geological Survey Professional Paper 813–H, 31 p.

Gann, E.E., Harvey, E.J., and Miller, D.E., 1976, Water resources of south-central Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–550, 4 sheets.

Gann, E.E., Harvey, E.J., Barks, J.M., and Fuller, D.L, 1973, Water resources of northwestern Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–444, 4 sheets.

Gann, E.E., Harvey, E.J., Jeffery, H.G., and Fuller, D.L., 1971, Water resources of northeastern Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–372, 4 sheets.

Gann, E.E., Harvey, E.J., Barks, J.M., Fuller, D.L., and Miller, D.E., 1974, Water resources of west-central Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–491, 4 sheets.

Harvey, E.J., 1980, Ground water in the Springfield–Salem Plateaus of southern Missouri and northern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 80–101, 60 p.

Imes, J.L., 1985, The ground-water flow system in northern Missouri with emphasis on the Cambrian–Ordovician aquifer: U.S. Geological Survey Professional Paper 1305, 61 p.

———1990a, Major geohydrologic units in and adjacent to the Ozark Plateaus Province, Missouri, Arkansas, Kansas, and Oklahoma: U.S. Geological Survey Hydrologic Investigations Atlas HA–711A, scale 1:750,000, 1 sheet.

———1990b, Major geohydrologic units in and adjacent to the Ozark Plateaus Province, Missouri, Arkansas, Kansas, and Oklahoma—Springfield Plateau aquifer: U.S. Geological Survey Hydrologic Investigations Atlas HA–711G, scale 1:750,000, 3 sheets.

———1990c, Major geohydrologic units in and adjacent to the Ozark Plateaus Province, Missouri, Arkansas, Kansas, and Oklahoma—St. Francois aquifer: U.S. Geological Survey Hydrologic Investigations Atlas HA–711C, scale 1:750,000, 2 sheets.

Imes, J.L., and Emmett, L.F., 1994, Geohydrology of the Ozark Plateaus aquifer system in parts of Missouri, Arkansas, Oklahoma, and Kansas: U.S. Geological Survey Professional Paper 1414–D, 127 p.

Jorgensen, D.G., Helgesen, J.O., Leonard, R.B., and Signor, D.C., 1986, Equivalent freshwater head and dissolved-solids concentration of water in rocks of Cambrian, Ordovician, and Mississippian age in the northern midcontinent, U.S.A.: U.S. Geological Survey Miscellaneous Field Studies Map MF–1835–B, scale 1:1,000,000, 2 sheets.

Jorgensen, D.G., Helgesen, J.O., and Imes, J.L., 1993, Regional aquifers in 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.

Missouri Division of Geological Survey and Water Resources, 1973, Groundwater maps of Missouri: Missouri Division of Geological Survey and Water Resources, 4 sheets.

Taylor, O.J., 1978, Summary appraisals of the Nation's ground-water resources—Missouri River basin: U.S. Geological Survey Professional Paper 813–Q, 41 p.

U.S. Geological Survey and Missouri Division of Geological Survey and Water Resources, 1967, Mineral and water resources of Missouri: U.S. Congress, 90th, 1st session, Senate Document 19, 399 p.

U.S. Geological Survey, 1990, National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 553 p.

Vineyard, J.D., and Feder, G.L., 1982, Springs of Missouri: Missouri Department of Natural Resources, Division of Geology and Land Survey, Water Resources Report 29, 212 p.

Mississippian aquifer

Gann, E.E., Harvey, E.J., Barks, J.M., and Fuller, D.L., 1973, Water resources of northwestern Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–444, 4 sheets.

Gann, E.E., Harvey, E.J., Jeffery, H.G., and Fuller, D.L., 1971, Water resources of northeastern Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–372, 4 sheets.

Imes, J.L., 1985, The ground-water flow system in northern Missouri with emphasis on the Cambrian–Ordovician aquifer: U.S. Geological Survey Professional Paper 1305, 61 p.

Jorgensen, D.G., Helgesen, J.O., Leonard, R.B., and Signor, D.C., 1986, Equivalent freshwater head and dissolved-solids concentration of water in rocks of Cambrian, Ordovician, and Mississippian age in the northern midcontinent, U.S.A.: U.S. Geological Survey Miscellaneous Field Studies Map MF–1835–B, scale 1:1,000,000, 2 sheets.

Western Interior Plains aquifer system

Jorgensen, D.G., Helgesen, J.O., and Imes, J.L., 1993, Regional aquifers in 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.

Wolf, R.J., Hansen, C.V., McGovern, H.E., and Spinazola, J.M., 1990, Geohydrologic systems in Kansas with emphasis on systems in Upper Cambrian through Lower Cretaceous rocks: U.S. Geological Survey Hydrologic Investigations Atlas HA–722A, scales 1:1,500,000 and 1:2,000,000, 2 sheets.