Groundwater Resources Program

Hydrogeology, Distribution, and Volume of Saline Groundwater in the Southern Midcontinent and Adjacent Areas of the United States

Scientific Investigations Report 2013–5017

U.S. Department of the Interior
U.S. Geological Survey

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By Noël I. Osborn, S. Jerrod Smith, and Christian H. Seger

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
kilometer (km)	0.6214	mile (mi)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
foot per year (ft/yr)	0.3048	meter per year (m/yr)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Hydrogeology, Distribution, and Volume of Saline Groundwater in the Southern Midcontinent and Adjacent Areas of the United States

By Noël I. Osborn, S. Jerrod Smith, and Christian H. Seger

Abstract

The hydrogeology, distribution, and volume of saline water in 22 aquifers in the southern midcontinent of the United States were evaluated to provide information about saline groundwater resources that may be used to reduce dependency on freshwater resources. Those aquifers underlie six States in the southern midcontinent—Arkansas, Kansas, Louisiana, Missouri, Oklahoma, and Texas—and adjacent areas including all or parts of Alabama, Colorado, Florida, Illinois, Kentucky, Mississippi, Nebraska, New Mexico, South Dakota, Tennessee, and Wyoming and some offshore areas of the Gulf of Mexico. Saline waters of the aquifers were evaluated by defining salinity zones; digitizing data, primarily from the Regional Aquifer-System Analysis Program of the U.S. Geological Survey; and computing the volume of saline water in storage.

The distribution of saline groundwater in the southern midcontinent is substantially affected by the hydrogeology and groundwater-flow systems of the aquifers. Many of the aquifers in the southern midcontinent are underlain by one or more aquifers, resulting in vertically stacked aquifers containing groundwaters of varying salinity. Saline groundwater is affected by past and present hydrogeologic conditions. Spatial variation of groundwater salinity in the southern midcontinent is controlled primarily by locations of recharge and discharge areas, groundwater-flow paths and residence time, mixing of freshwater and saline water, and interactions with aquifer rocks and sediments.

The volume calculations made for the evaluated aquifers in the southern midcontinent indicate that about 39,900 million acre-feet (acre-ft) of saline water is in storage. About 21,600 million acre-ft of the water in storage is slightly to moderately saline (1,000–10,000 milligrams per liter [mg/L] dissolved solids), and about 18,300 million acre-ft is very saline (10,000–35,000 mg/L dissolved solids). The largest volumes of saline water are in the coastal lowlands (about 16,300 million acre-ft), Mississippi embayment and Texas coastal uplands (about 12,000 million acre-ft), and Great Plains (about 8,170 million acre-ft) aquifer systems. Of the 22 aquifers evaluated in this report, the Maha aquifer in the Great Plains aquifer system contains both the largest total volume of saline water (about 6,280 million acre-ft) and the largest volume of slightly to moderately saline water (about 5,150 million acre-ft).

Introduction

Freshwater resources are under increasing stress from growing water-use demands and changes in climate (Federal Interagency Panel on Climate Change and Water Data and Information, 2011). In the southern midcontinent, the volume of fresh groundwater in storage is decreasing in response to groundwater withdrawals in many aquifer systems, such as the High Plains, the Mississippi River Valley alluvium, the coastal lowlands, and the Mississippi embayment aquifer systems (Reilly and others, 2008). Climate change and variability can affect water availability through changes in precipitation amount, intensity, and timing and changes in evapotranspiration (Brekke and others, 2009). These changes in precipitation and evaporation may affect surface-water runoff, streamflow, and reservoirs and may also affect groundwater recharge, discharge, and storage in aquifers (Gurdak and others, 2009). Advances in technology such as membrane filtration and reverse osmosis are reducing the cost of desalination (Anderson and Woosley, 2005). Because of increasing demand for freshwater supplies and decreasing costs of desalination, saline groundwater is being considered a source of water that could reduce dependency on freshwater resources (Alley, 2003; Galloway and others, 2003; Anderson and Woosley, 2005). The 2012 Texas State Water Plan recommends brackish groundwater desalination as a water-management strategy to meet at least some of the State's projected water needs; currently (2013), 34 municipal desalination facilities in Texas use brackish groundwater as a raw water source (Texas Water Development Board, 2013).

The term "saline groundwater," as used in this report, includes groundwater with dissolved-solids concentrations between 1,000 and 35,000 milligrams per liter (mg/L). Saline groundwater is considered slightly saline, moderately saline, or very saline if the groundwater has dissolved-solids concentrations of 1,000–3,000; greater than 3,000–10,000; and greater than 10,000–35,000 mg/L, respectively (table 1)

Table 1. Classification of groundwater based on dissolved-solids concentration.

[Modified from Winslow and Kister, 1956, p. 5; mg/L, milligrams per liter]

Class	Description	Dissolved-solids concentration (mg/L)
Fresh		Less than 1,000
Saline	Slightly saline	1,000–3,000
	Moderately saline	Greater than 3,000–10,000
	Very saline	Greater than 10,000–35,000
Brine		Greater than 35,000

(Winslow and Kister, 1956). Groundwater with dissolved-solids concentrations greater than 35,000 mg/L (the average concentration of seawater) is referred to as “brine”; groundwater with dissolved-solids concentrations less than 1,000 mg/L is referred to as “fresh.”

Saline groundwater is known to be present in the southern midcontinent of the United States (Krieger and others, 1957; Feth and others, 1965), but more information about the distribution and volume of saline aquifers is necessary to evaluate and develop saline-groundwater resources. The study described in this report was conducted as a pilot study through the U.S. Geological Survey (USGS) Groundwater Resources Program with the purpose of assessing and mapping saline aquifers in the southern midcontinent as potential water sources. Results of the study will help the USGS address the goals of the SECURE Water Act, Section 9507 (2009), to describe significant brackish aquifers located throughout the United States. (The SECURE Water Act does not define “brackish aquifers,” but the term “brackish” commonly refers to water with dissolved-solids concentrations between 1,000 and 10,000 mg/L [Freeze and Cherry, 1979; LBG-Guyton Associates and NRS Consulting Engineers, 2003], which fall within the saline-water classifications used herein). Information and maps in this report can be used in conjunction with geologic, hydrologic, chemical, climatic, and other types of information for regional planning activities. The regional-scale information provided in this report provides a framework for a systematic comparison of the saline-groundwater resources across the southern midcontinent region.

Early large-scale inventories of saline-groundwater resources of the United States include those of Krieger and others (1957) and Feth and others (1965). Surveys of saline groundwater in the southern midcontinent include those by Winslow and Kister (1956), who identified aquifers containing saline groundwater in Texas, and Winslow and others (1968), who presented information on the distribution, potential yield, aggregate sand thickness, and chemical analysis of saline groundwater in Louisiana. Core Laboratories, Inc. (1972), described a broad survey of principal saline aquifers in Texas; that survey includes a descriptive inventory of principal saline aquifers and their characteristics; geologic maps and sections, which illustrate aquifer location, thickness, structure, and salinity; and tables of supporting data. LBG-Guyton Associates and NRS Consulting Engineers (2003) evaluated the distribution and volume of groundwater containing between 1,000 and 10,000 mg/L of dissolved-solids concentrations in each major and minor aquifer in Texas.

Purpose and Scope

This report describes the hydrogeology, distribution, and volume of saline-groundwater resources in the southern midcontinent of the United States. Maps showing the thickness and dissolved-solids concentrations of saline water in 22 aquifers and tables listing the volume of saline water in each aquifer are provided. Methods used to compute the volume of saline water in each aquifer are described. The distribution and volume of saline groundwater are substantially affected by the hydrogeology and groundwater flow of the aquifers; therefore, the hydrogeology and groundwater-flow system of each aquifer are described in context with the occurrence of saline groundwater.

Approach

This study focused on regional aquifer systems studied by the USGS Regional Aquifer-System Analysis (RASA) Program between 1978 and 1995. The RASA Program defined regional hydrogeology and established a framework of background information of geology, hydrology, and geochemistry of the Nation’s important aquifer systems that could be used for regional assessment of groundwater resources and in support of detailed local studies (Sun and others, 1997). Reports from the RASA studies are well-suited for regional assessment of saline groundwater in the southern midcontinent because the RASA Program (1) assembled data from numerous local studies into regional databases and provided consistent and integrated information across political boundaries (such as States, municipalities, and special water-management districts); (2) provided comprehensive descriptions of the geologic, hydrologic, and geochemical characteristics of aquifer systems that are necessary for understanding the occurrence of saline groundwater; (3) produced regional maps including aquifer structure, thickness, sand percentage, hydrologic properties (such as porosity and transmissivity), and water chemistry; (4) used groundwater-flow and geochemical models to provide a quantitative understanding of regional flow in the aquifer systems; and (5) studied the largest aquifers in the southern midcontinent.

Several types of available geologic and hydrologic data were collected and compiled as part of the RASA Program. Data such as lithologic and geophysical logs, hydraulic heads, water chemistry, and aquifer properties were obtained from Federal, State, and private sources. The completeness, quality, and distribution of those data vary considerably. For example, subsurface data of water chemistry and hydrology typically are restricted to near-surface, freshwater aquifers and to deeper areas with oil and gas development. Although the distribution of data varied considerably, data were selected to represent the regional scope of the studies (Sun and Johnston, 1994).

Aquifers described in this report are in five regional aquifer systems defined by the RASA Program: the High Plains, Gulf Coast, Edwards-Trinity, Central Midwest, and Northern Midwest. The aquifers underlie six States in the southern midcontinent—Arkansas, Kansas, Louisiana, Missouri, Oklahoma, and Texas—and adjacent areas including all or parts of Alabama, Colorado, Florida, Illinois, Kentucky, Mississippi, Nebraska, New Mexico, South Dakota, Tennessee, and Wyoming and some offshore areas of the Gulf of Mexico (fig. 1).

Hydrogeologic features described in this report include 22 aquifers, permeable zones, and units (termed aquifers in this report) that are in 10 aquifer systems (table 2). An aquifer is defined as a geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield substantial quantities of water to wells and springs (Lohman and others, 1972) and may consist of fresh, saline, or brine water. An aquifer system is a grouping of aquifers and confining units that generally function together as an individual flow system (Miller and Appel, 1997).

Methods

Described in this section are the methods used to (1) define salinity zones used in the saline-groundwater assessment; (2) digitize data for dissolved-solids concentration, aquifer thickness, elevation, sand percentage, and porosity from published map reports; and (3) compute the volume of saline water in storage.

For the purpose of assessing the distribution and volume of saline groundwater, four salinity zones were defined by dissolved-solids concentrations of 1,000–3,000 mg/L; greater than 3,000–10,000 mg/L; greater than 10,000–20,000 mg/L; and greater than 20,000–35,000 mg/L. The salinity zones are comparable to the three saline-water classes defined by Winslow and Kister (1956) (table 1) except that the “very saline” class (greater than 10,000–35,000 mg/L dissolved-solids concentration) was divided into two zones (greater than 10,000–20,000 and greater than 20,000–35,000 mg/L dissolved-solids concentration) in this report to provide a more detailed assessment of very saline waters.

Contours representing dissolved-solids concentration, aquifer thickness, elevation, sand percentage, and porosity were digitized from published map reports. Control points and faults also were digitized when available. Digitization included large-format scanning of each map, registration of each map into geographic space, and manual tracing of point and line features into a geodatabase at a scale greater (finer) than the scale stated on each map. Aquifer-thickness maps were not available for two aquifers evaluated in this report (the lower aquifer units and upper aquifer unit in the Western Interior Plains aquifer system). For these aquifers, elevation contours representing the altitudes of the top and the base of each aquifer were digitized, and thickness was computed by subtracting continuous surfaces interpolated from digitized elevation contours. Each contour dataset was interpolated to a continuous surface (raster) at 1-kilometer resolution (cell size) by using the Topo to Raster tool (Esri, 2012a). If available, the control-point dataset was used as an additional input to the tool to guide interpolation between contours. The dissolved-solids-concentration raster was used as the input to the Contour List tool (Esri, 2012b) to generate selected additional contours needed to define the four salinity zones. The additional dissolved-solids concentration contours were then merged with the original mapped dissolved-solids-concentration contours. The merged dissolved-solids-concentration contours were converted to polygons (zones) by using the Feature to Polygon tool (Esri, 2012c) and were clipped to the aquifer-assessment areas, which were defined by the intersection of aquifer-thickness data coverage and dissolved-solids-concentration data coverage (areas where both thickness and dissolved-solids-concentration data were available). The resulting salinity zones were used to calculate rasters of mean aquifer thickness, mean sand percentage, and mean porosity by using the Zonal Statistics as Table tool (Esri, 2012d).

The volume of saline water in storage was computed for each salinity zone in each aquifer-assessment area by multiplying the salinity zone area, mean aquifer thickness or saturated thickness, mean porosity or specific-yield fraction, and mean sand-fraction values where available. Most of the saline groundwater described in this report flows under confined conditions, and the thickness used in the volumetric calculations for the confined salinity zones was calculated as the mean total aquifer thickness. Groundwater in the High Plains aquifer flows under unconfined conditions, and the mean 1996–97 saturated thickness of the High Plains aquifer was used in the volumetric calculations instead of the mean total aquifer thickness. Porosity data were not available for some aquifers, and for these aquifers, specific yield was used instead of porosity. In aquifers for which mapped data were available, mean thickness, porosity, and sand percentage were determined from interpolated raster files. In aquifers for which mapped data were not available, average values were obtained from the literature.

Limitations and Assumptions

Because of the regional scope of this study, only aquifers in regional aquifer systems (many of which underlie several States) were evaluated. A limitation of this study is that it does not include many of the smaller aquifers in the southern midcontinent. Additionally, only those aquifers with sufficient information on the distribution of dissolved-solids concentrations of saline water were evaluated for this study.

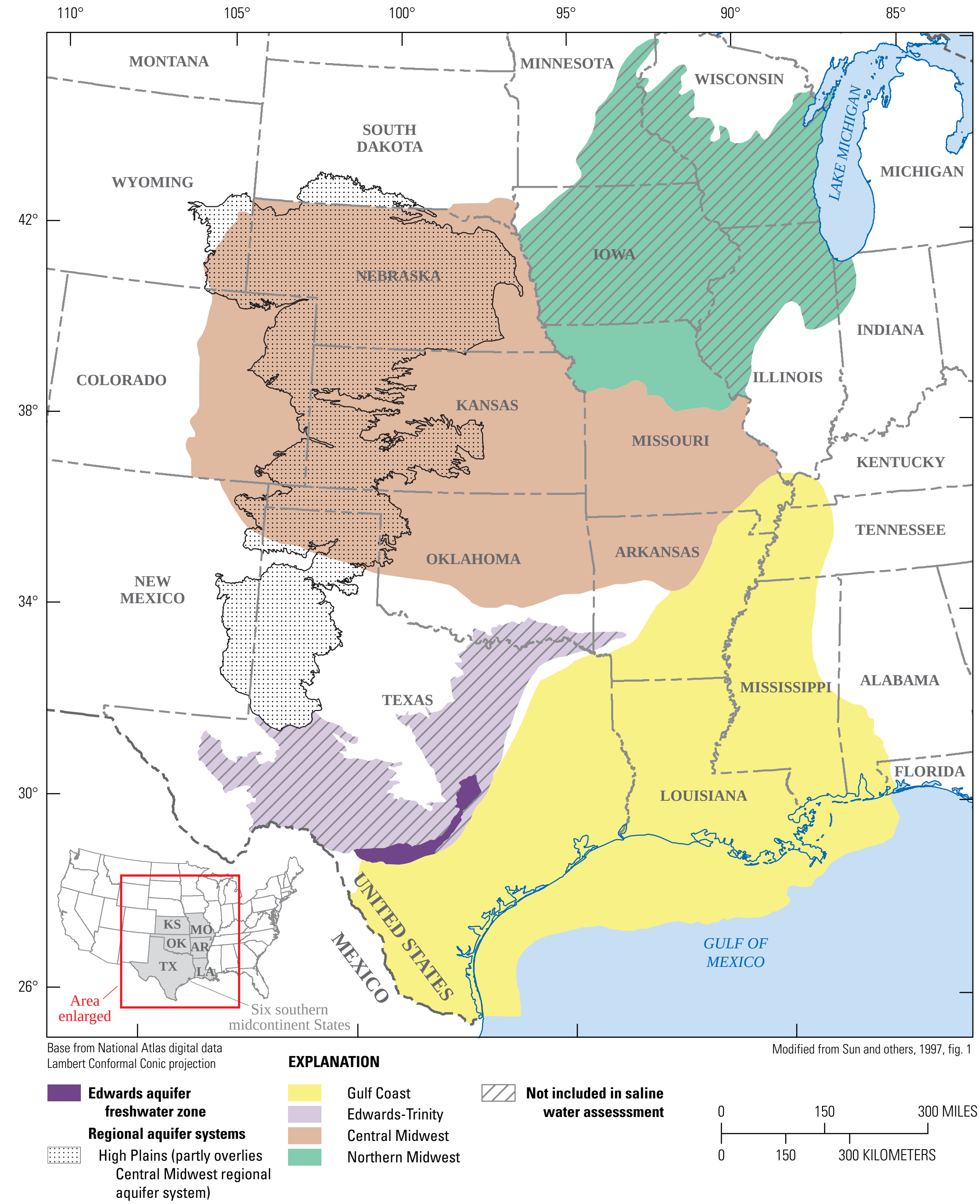

Figure 1. Regional aquifer systems in the southern midcontinent and adjacent areas, as defined in the U.S. Geological Survey Regional Aquifer-System Analysis Program.

Table 2. Regional aquifer systems, aquifer systems, and aquifers in the southern midcontinent and adjacent areas as defined in the U.S. Geological Survey Regional Aquifer-System Analysis Program.

Regional aquifer system	Aquifer system	Aquifer
High Plains	High Plains	High Plains
Gulf Coast	Coastal lowlands	Permeable zone A
		Permeable zone B
		Permeable zone C
		Permeable zone D
		Permeable zone E
	Mississippi embayment and Texas coastal uplands[1]	Mississippi River Valley alluvial
		Upper Claiborne
		Middle Claiborne
		Lower Claiborne-Upper Wilcox
		Middle Wilcox
		Lower Wilcox
		McNairy-Nacatoch
Edwards-Trinity	Edwards-Trinity	Edwards
Central Midwest	Great Plains	Maha
		Apishapa
	Western Interior Plains and Ozark Plateaus[2]	Upper aquifer unit and Springfield Plateau
		Lower aquifer units and Ozark
Northern Midwest	Mississippian	Mississippian
	Cambrian-Ordovician	Cambrian-Ordovician

[1]Mississippi embayment and Texas coastal uplands aquifer systems are mapped together in this report.

[2]Western Interior Plains and Ozark Plateaus aquifer systems are mapped together in this report.

The aquifer-assessment areas, which were determined on the basis of availability of both aquifer thickness and dissolved-solids-concentration data in the saline parts of the aquifers, usually are smaller than the actual extent of the aquifers. Although some of the maps in this report show dissolved-solids concentrations and thickness of parts of an aquifer containing freshwater (dissolved-solids concentrations less than 1,000 mg/L) or brine (dissolved-solids concentrations more than 35,000 mg/L), the maps in this report do not necessarily represent entire aquifers.

The regional-scale information provided in this report provides a framework for a systematic comparison of the saline-groundwater resources across the southern midcontinent region; however, this report does not provide detailed information on saline aquifers at a local level. Furthermore, to develop saline-groundwater resources, types of information not provided in this report (such as aquifer depth, well yields, water chemistry, and potential effects on freshwater aquifers) would be needed.

An assumption used in this study is that the volume of groundwater in storage does not change with time. In fact, the volume of groundwater in storage changes in response to both naturally occurring mechanisms, such as aquifer recharge and discharge to streams, and human-induced mechanisms such as groundwater withdrawals, deep-well injection, agricultural irrigation, and artificial recharge of water (Freeze and Cherry, 1979). Many of these mechanisms also have the potential to alter water chemistry. For example, groundwater withdrawals can induce the movement of saline water from underlying aquifers and from seawater into parts of aquifers that previously contained freshwater (Alley and others, 1999). In the southern midcontinent, activities by the petroleum industry have the potential to change the volume of water in storage and to alter water chemistry; for example, the petroleum industry withdraws large quantities of brine and saline water with production of oil and gas that are disposed of by injection into geologic units of Ordovician and Cambrian age (Jorgensen and Signor, 1981). Another common practice of the petroleum industry is waterflooding, a technique to recover hydrocarbons in old oil fields by injecting saline water into wells (Jorgensen and Signor, 1981).

Hydrogeology, Distribution, and Volume of Saline Groundwater

Several processes and factors affect the distribution and volume of saline-groundwater resources. The areal extent of an aquifer is controlled by hydrogeologic factors such as the types of rocks and sediments through which groundwater flow takes place, hydraulic properties, and the geologic history of those rocks and sediments. The volume of saline water in storage is by definition controlled by the areal extent, thickness, and porosity of an aquifer.

The chemical composition of groundwater is primarily determined by the mineralogy of rocks and sediments that compose an aquifer and by the length of time water is in contact with the minerals (Renken, 1998). Meteoric water, which enters groundwater-flow systems primarily as precipitation from rainfall, contains few dissolved solids (Renken, 1998). As meteoric water moves from recharge areas down the hydraulic gradient in aquifers, dissolved-solids concentrations generally increase as the residence time of groundwater increases and water-rock interactions (such as mineral dissolution, mineral precipitation, and ion exchange) progress (Hem, 1985; Siegel, 1989). Mixing of freshwater with saline water can occur by upward flow of saline groundwater from underlying geologic units, downward leakage through overlying units, and mixing of groundwater with surface water (Hem, 1985; Pettijohn, 1996; McMahon and others, 2007). Thus, the spatial variation of groundwater salinity is affected by factors and processes such as recharge sources, locations of recharge and discharge areas, groundwater residence time, water interactions with aquifer rock and sediments, and mixing of freshwater with saline water.

The following sections include a brief summary of the hydrogeology, groundwater-flow system, salinity, and processes that affect the water chemistry of each regional aquifer system. The sections also include maps showing the aquifer thickness and dissolved-solids concentrations of saline water of each aquifer-assessment area and the estimated volume of saline water in storage for each salinity zone.

High Plains Regional Aquifer System

The High Plains regional aquifer system, consisting of the High Plains aquifer, underlies 174,000 square miles (mi^2) in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (fig. 1). One of the largest aquifers in the Nation, the High Plains aquifer is the primary water supply for about 2.3 million people and also sustains more than one-quarter of the Nation's agricultural production (Gurdak and others, 2009). The High Plains aquifer is an unconfined aquifer that consists mainly of near-surface sand and gravel deposits of late Tertiary and Quaternary age. The principal rock-stratigraphic unit forming the High Plains aquifer is the Ogallala Formation of late Tertiary age (table 3), which consists of clays, silts, sands, and gravels deposited by streams that flowed eastward from the Rocky Mountains (Gutentag and others, 1984). Underlying the High Plains aquifer is bedrock of Permian to Cretaceous age that is in hydraulic connection with the High Plains aquifer in places (Ryder, 1996). The 1996–97 saturated thickness of the High Plains aquifer ranged from 0 feet to approximately 1,000 ft and averaged approximately 200 ft (Fischer and others, 2000) (fig. 2). The specific yield of the aquifer ranges from 3 to 35 percent and averages 15 percent (Weeks and others, 1988).

Recharge to the High Plains aquifer is by diffuse infiltration of precipitation, infiltration of irrigation water, focused infiltration of storm and irrigation water runoff through streambeds and other topographic depressions (such as playas), and upward flow of water from underlying aquifers (Gurdak and others, 2009). Groundwater in the High Plains aquifer flows regionally from west to east and discharges to streams and springs. Groundwater also is discharged by well withdrawals (Gutentag and others, 1984; Weeks and others, 1988; Gurdak and others, 2009).

Most water in the High Plains aquifer has dissolved-solids concentrations less than 500 mg/L, but dissolved-solids concentrations exceed 1,000 mg/L in the southern part of the aquifer in Texas and in small areas throughout the aquifer (fig. 2) (Weeks and others, 1988). In most areas of the High Plains aquifer, elevated dissolved-solids concentrations are caused by natural upward flow of saline groundwater from underlying geologic units and by pumping of high-capacity wells, which can induce or enhance upward flow of saline water from underlying geologic units (Weeks and others, 1988; Gurdak and others, 2009). The concentration of dissolved solids in groundwater exceeds 1,000 mg/L along parts of rivers connected to this aquifer because of irrigation practices. In stream valleys where the water table is near land surface, salts that accumulate in the soil owing to evapotranspiration are dissolved and flushed with irrigation water and transported to the aquifer (Weeks and others, 1988). An estimated 34.5 million acre-feet (acre-ft) of slightly saline water is stored in the aquifer-assessment area of the High Plains aquifer (table 4).

Table 3. Time-stratigraphic, rock-stratigraphic, and hydrogeologic units of the High Plains regional aquifer system.

[Modified from Gutentag and others, 1984, table 1; Fm, Formation; Gp, Group]

Time-stratigraphic unit		Rock-stratigraphic unit		Hydrogeologic unit
System	**Series**			
Quaternary	Holocene and Pleistocene	Valley-fill deposits		High Plains regional aquifer system
		Dune sand		
		Loess		
	Pleistocene	Unconsolidated alluvial deposits		
Tertiary	Miocene	Ogallala Fm		
		Arikaree Gp		
	Oligocene	White River Gp	Brule Fm	
Cretaceous	Upper and Lower Cretaceous	Undifferentiated rocks		
Jurassic	Upper and Middle Jurassic	Undifferentiated rocks		
Triassic	Upper Triassic	Dockum Gp		
Permian	Upper and Lower Permian	Undifferentiated rocks		

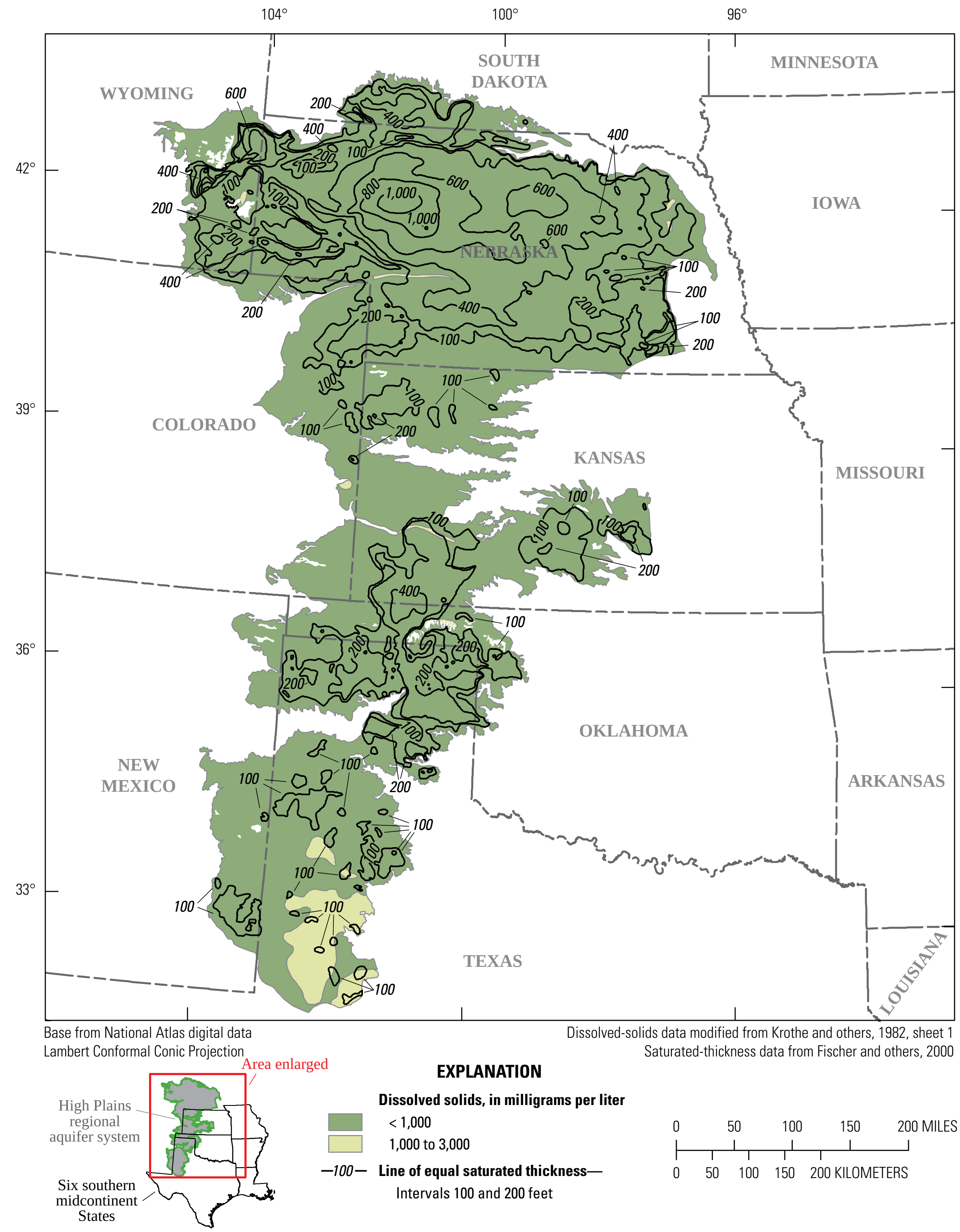

Figure 2. Dissolved-solids concentrations and 1996–97 saturated thickness in the aquifer-assessment area of the High Plains regional aquifer system.

Table 4. Estimated water volume of salinity zones in the aquifer-assessment area of the High Plains aquifer, High Plains regional aquifer system.

[mg/L, milligrams per liter; values may not sum to totals because of independent rounding]

Salinity zone, dissolved-solids concentration (mg/L)[1]	Area (million acres)	Mean 1996–97 saturated thickness (feet)[2]	Mean specific yield fraction[3]	Water volume (million acre-feet)
1,000–3,000	3.71	66.5	0.14	34.5

[1]Determined from dissolved-solids-concentration map (modified from Krothe and others, 1982, sheet 1).

[2]Computed from saturated thickness map (modified from Fischer and others, 2000).

[3]Computed from specific yield map (modified from Cederstrand and Becker, 1998).

Gulf Coast Regional Aquifer System

Aquifer Systems of the Gulf Coast Regional Aquifer System

The Gulf Coast regional aquifer system underlies an area of about 230,000 mi^2 onshore in parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Louisiana, Mississippi, Missouri, Tennessee, and Texas and an additional 60,000 mi^2 offshore (fig. 3) (Grubb, 1998). The Gulf Coast regional aquifer system consists of three aquifer systems: (1) the coastal lowlands, (2) the Mississippi embayment, and (3) the Texas coastal uplands. These three aquifer systems were further divided into seven aquifers, five permeable zones, and six confining units (table 5).

Sediments composing the Gulf Coast regional aquifer systems were deposited mostly during Quaternary and Tertiary times. Deposition of these sediments was in fluvial, deltaic, or shallow marine environments, resulting in an interbedded sequence of sand, silt, and clay with some gravel, lignite, and limestone (Williamson and Grubb, 1997). The sediments that compose these aquifers and confining units generally dip toward the Gulf of Mexico and become thicker and less permeable downdip (Grubb, 1998). Excess fluid pressure (termed “geopressure”) developed as sediments were buried more rapidly than fluids could be expelled from compacting sediments (Grubb, 1998). Gulf Coast sediments thin over uplifted structural features, such as the Sabine uplift, and thicken in depressions, such as the Mississippi embayment (Grubb, 1998). The relation of hydrogeologic units of the Texas coastal uplands aquifer system and the coastal lowlands aquifer system is illustrated in figure 4.

Simulation of groundwater flow in the aquifer systems indicates that regional groundwater flow prior to withdrawal of groundwater (predevelopment) generally was from areas of high water-level altitude toward major rivers or broad extensive areas at low land-surface elevation (Grubb, 1998); however, large-scale groundwater withdrawals throughout the Gulf Coast regional aquifer systems have lowered hydraulic heads, which has caused changes in recharge and discharge, flow velocity, flow direction and magnitude, and land-surface subsidence (Williamson and Grubb, 1997). Large-scale development of groundwater resources in the freshwater part of the aquifer system has changed flow patterns in the saline part and induced flow updip toward pumping centers (Williamson and Grubb, 1997).

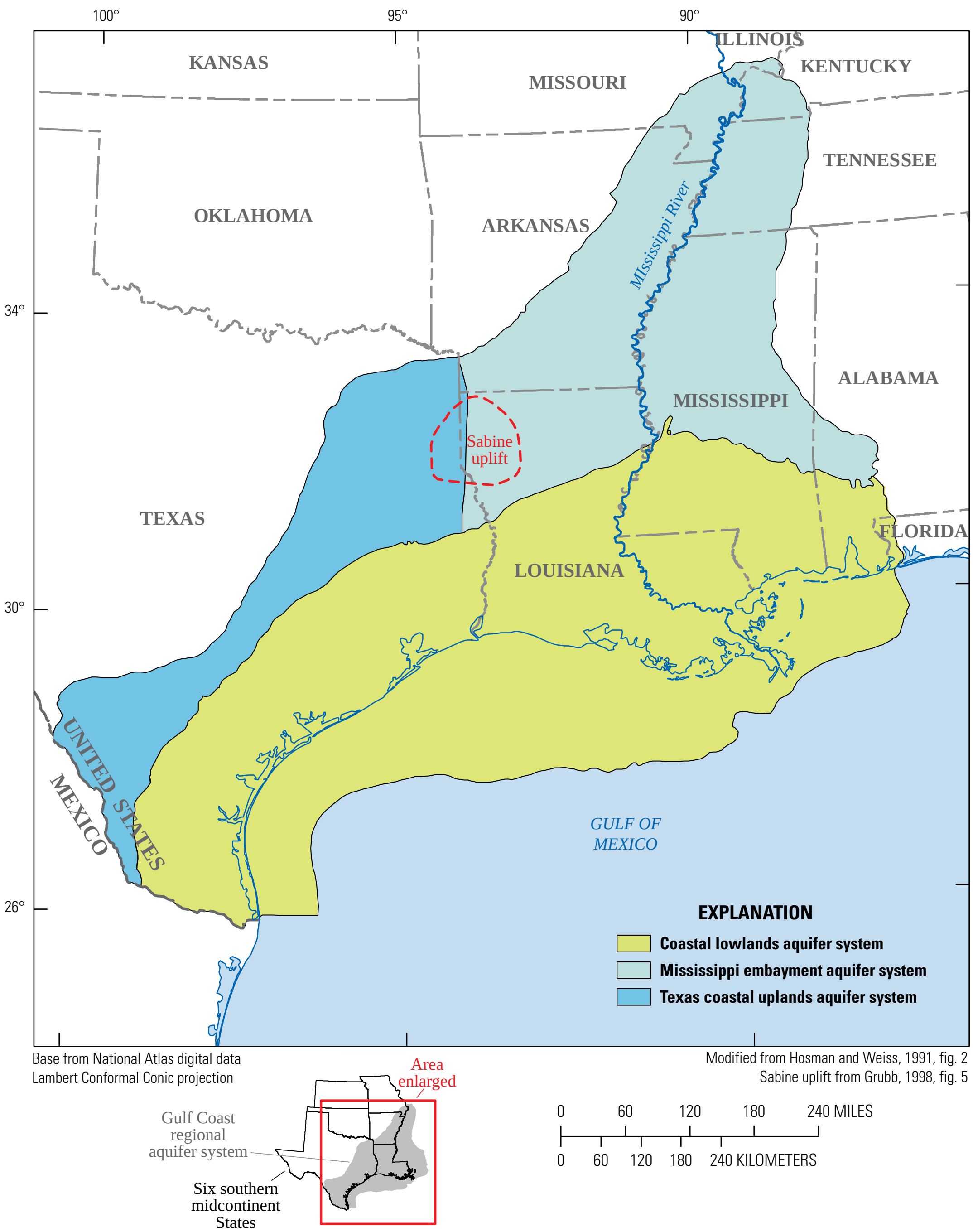

Figure 3. Aquifer systems in the Gulf Coast regional aquifer system.

Table 5. Time-stratigraphic, rock-stratigraphic, and hydrogeologic units of the Gulf Coast regional aquifer system.

[Modified from Grubb, 1998, table 1]

Coastal lowlands aquifer system

Time-stratigraphic unit		Rock-stratigraphic unit	Hydrogeologic unit	
System	Series			
Quaternary	Holocene		Permeable zone A	Coastal lowlands aquifer system
	Pleistocene			
			Permeable zone B	
Tertiary	Pliocene			
			Permeable zone C	
	Miocene		Zone D confining unit	
			Permeable zone D	
			Zone E confining unit	
			Permeable zone E	
	Oligocene and Eocene	Vicksburg and Jackson Groups		
			Vicksburg-Jackson confining unit	

Mississippi embayment aquifer system

Time-stratigraphic unit		Rock-stratigraphic unit	Hydrogeologic unit	
System	Series			
Quaternary	Holocene and Pleistocene	Alluvium	Mississippi River Valley alluvial aquifer	Mississippi embayment aquifer system
	Oligocene and Eocene	Vicksburg and Jackson Groups	Vicksburg-Jackson confining unit	
Tertiary	Eocene	Claiborne Group	Upper Claiborne aquifer	
			Middle Claiborne confining unit	
			Middle Claiborne aquifer	
			Lower Claiborne confining unit	
			Lower Claiborne-upper Wilcox aquifer	
		Wilcox Group	Middle Wilcox aquifer	
	Paleocene		Lower Wilcox aquifer	
		Midway Group	Midway confining unit[1]	
Cretaceous	Upper Cretaceous		McNairy-Nacatoch aquifer[1]	

Texas coastal uplands aquifer system

Hydrogeologic unit	
Not present	
Vicksburg-Jackson confining unit	
Upper Claiborne aquifer	Texas coastal uplands aquifer system
Middle Claiborne confining unit	
Middle Claiborne aquifer	
Lower Claiborne confining unit	
Lower Claiborne-upper Wilcox aquifer	
Middle Wilcox aquifer	
Not present	
Midway confining unit	

[1]Included in the Mississippi embayment aquifer system by Grubb (1984), Hosman and Weis (1991), and Renken (1998).

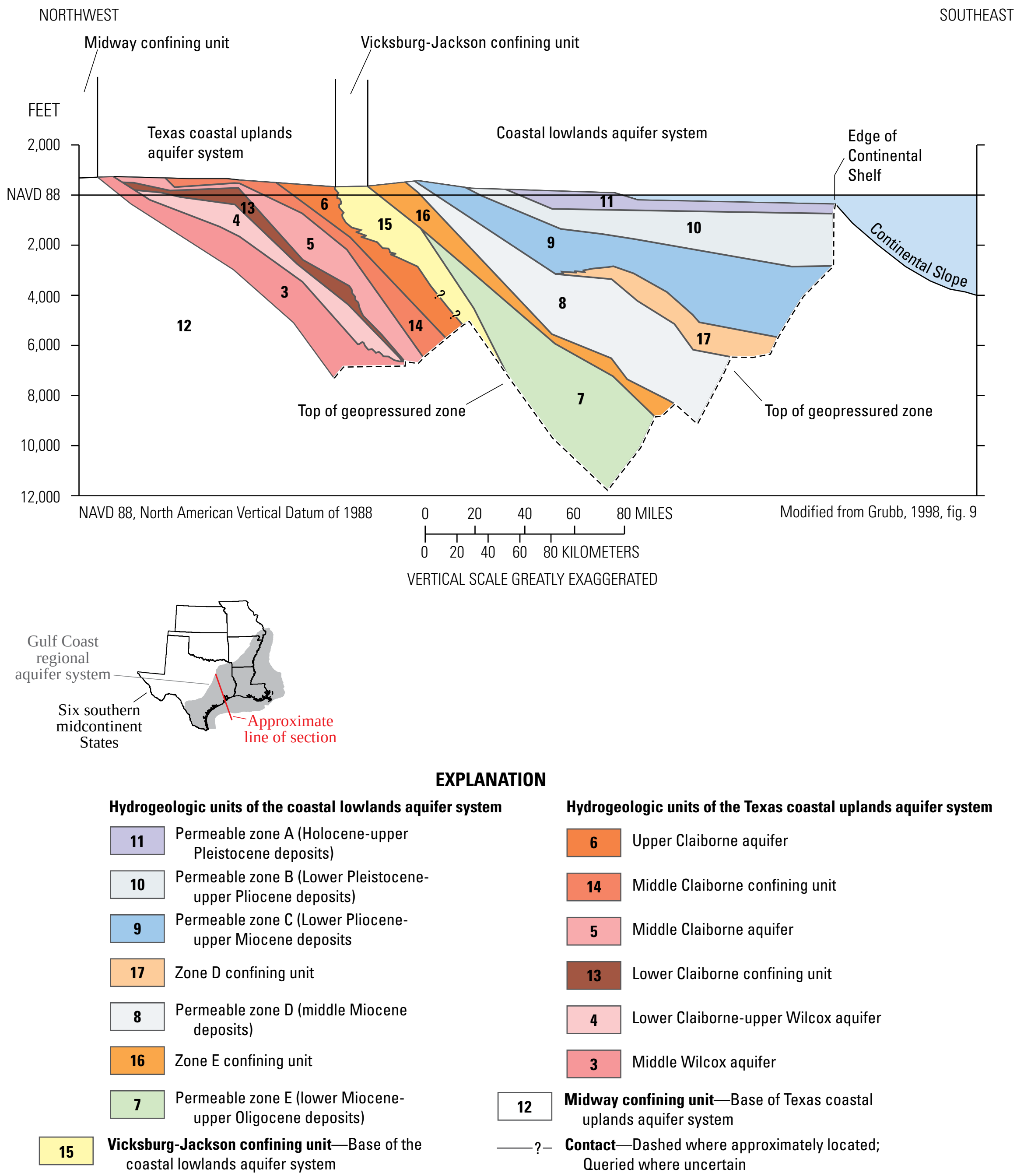

Figure 4. Generalized section from the western boundary of the Gulf Coast regional aquifer system in Texas to the Continental Slope showing relation of hydrogeologic units of the Texas coastal uplands aquifer system, the coastal lowlands aquifer system, and the geopressured zone.

Coastal Lowlands Aquifer System

The coastal lowlands aquifer system underlies an area of about 160,000 mi^2, including both onshore and offshore areas (fig. 3). This aquifer system consists mostly of interbedded sands and clays of Oligocene age and younger (Weiss, 1992). The average thickness of these sediments is approximately 6,000 ft, with a maximum thickness of more than 18,000 ft offshore from southern Louisiana (Weiss, 1992). Because the interbedded sand and clay beds of the coastal lowlands aquifer system are not regionally extensive, these sediments were divided vertically into five aquifers (termed “permeable zones A, B, C, D, and E”) and two confining units on the basis of distinct changes in vertical hydraulic head gradients and local lithology (Weiss, 1992) (figs. 5–9, table 5). The coastal lowlands aquifer system overlies the Tertiary hydrogeologic units of the Mississippi embayment and the Texas coastal uplands aquifer systems and is separated from these hydrogeologic units by the regionally extensive Vicksburg-Jackson confining unit (Weiss, 1992). The Vicksburg-Jackson confining unit is the base of the coastal lowlands aquifer system except where the geopressured zone is present, and in those areas, the geopressured zone is considered to be the base of the coastal lowlands aquifer system (Grubb, 1998) (fig. 4).

Water in the coastal lowlands aquifer system is unconfined in outcrop areas, but most of the aquifer system is confined (Ryder, 1996). The aquifer system is recharged primarily by infiltration of precipitation that falls on topographically high aquifer-outcrop areas. Additional recharge occurs in areas where groundwater withdrawals have reversed the groundwater-flow direction, causing water to flow from streams into the aquifers. Natural discharge occurs by evapotranspiration, flow into streams, and upward flow to shallow aquifers in coastal areas or in the Gulf of Mexico (Ryder, 1996). Model simulations by Grubb (1998) indicated that regional predevelopment groundwater flow in the coastal lowlands aquifer system generally was from areas of high water-level altitudes between the major rivers and adjacent to the outcrop band of the Vicksburg-Jackson confining unit to the major rivers and to regional discharge areas parallel to the shoreline.

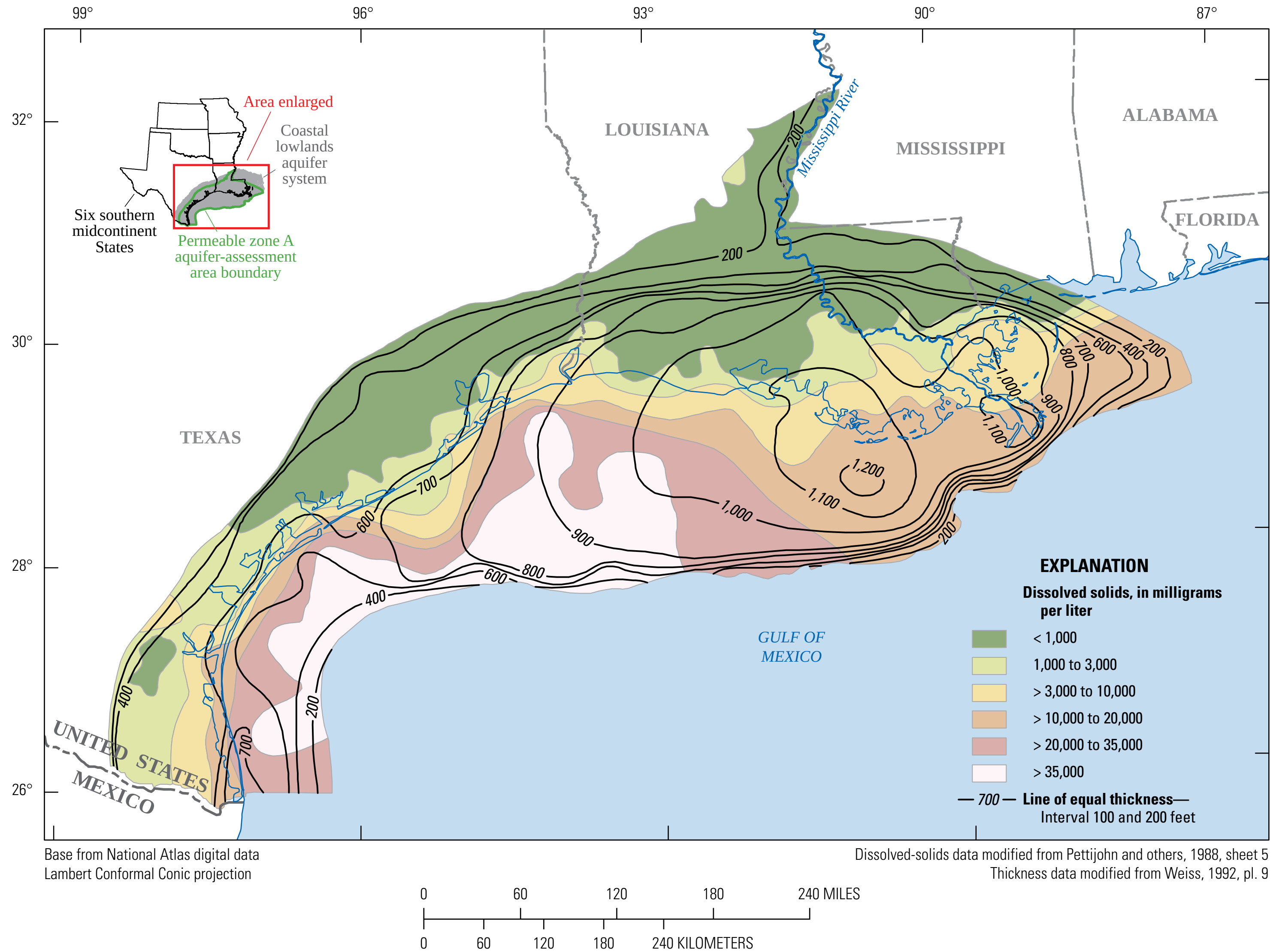

Figure 5. Dissolved-solids concentrations and thickness in the aquifer-assessment area of permeable zone A in the coastal lowlands aquifer system, Gulf Coast regional aquifer system.

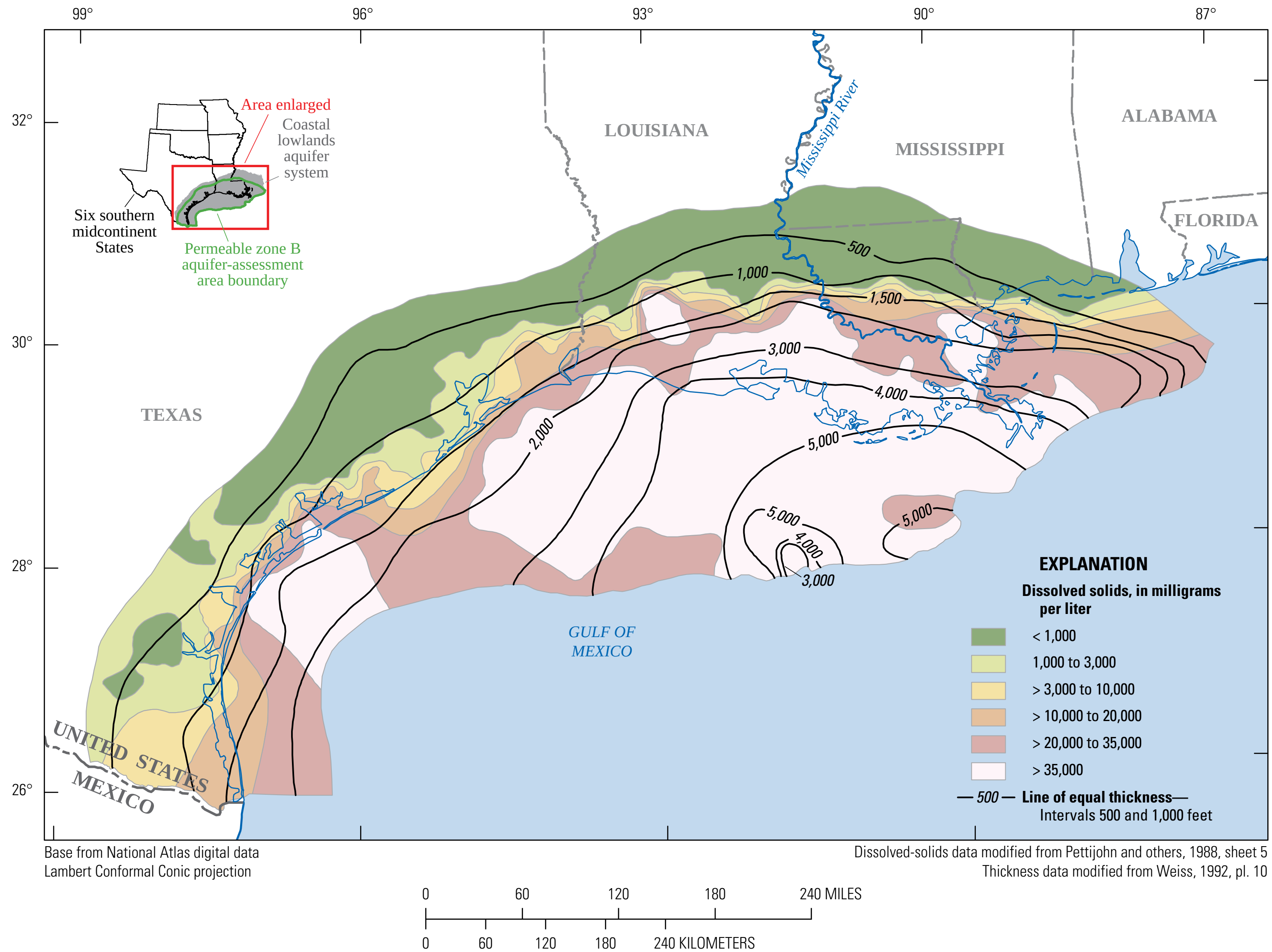

Figure 6. Dissolved-solids concentrations and thickness in the aquifer-assessment area of permeable zone B in the coastal lowlands aquifer system, Gulf Coast regional aquifer system.

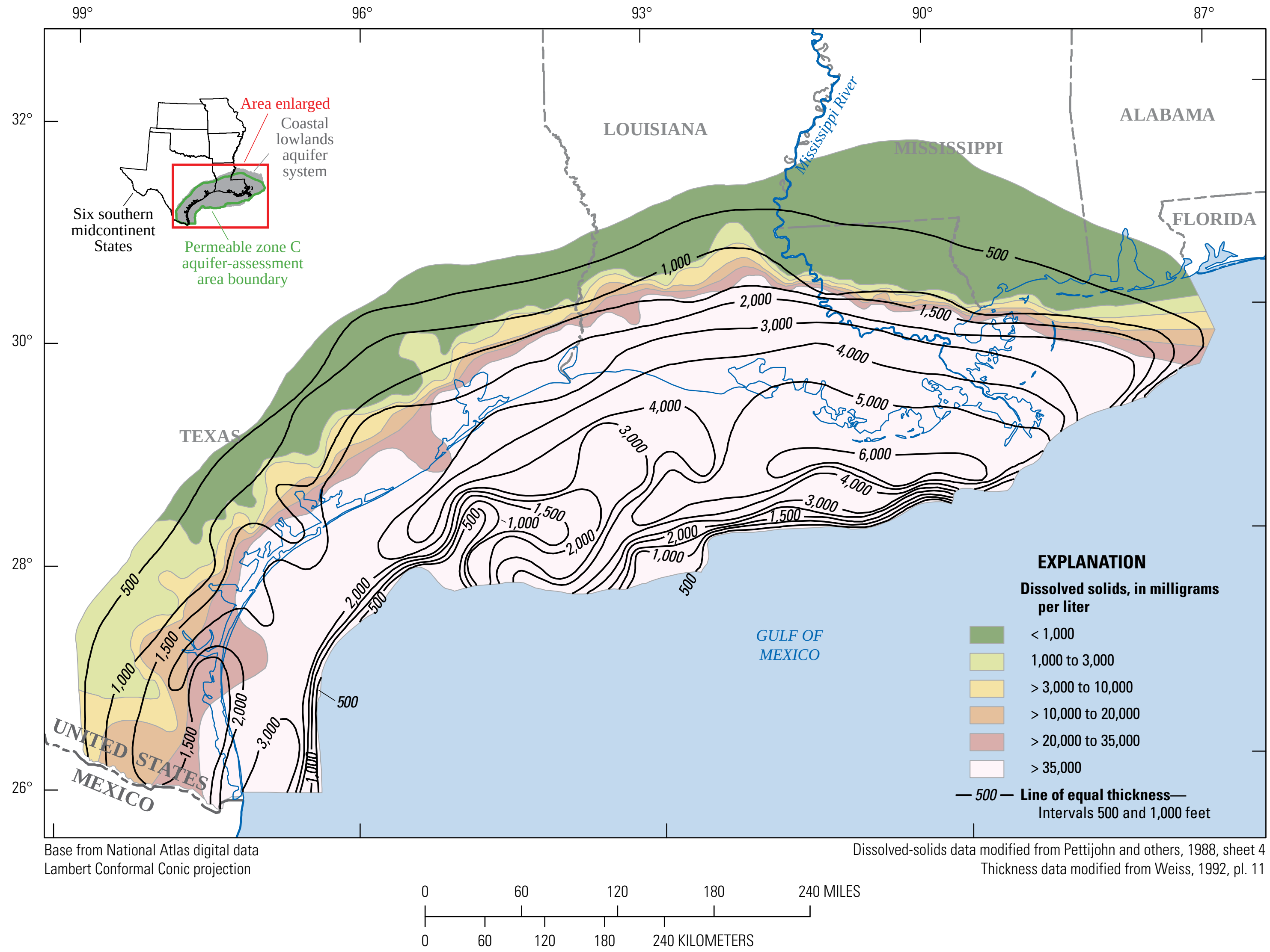

Figure 7. Dissolved-solids concentrations and thickness in the aquifer-assessment area of permeable zone C in the coastal lowlands aquifer system, Gulf Coast regional aquifer system.

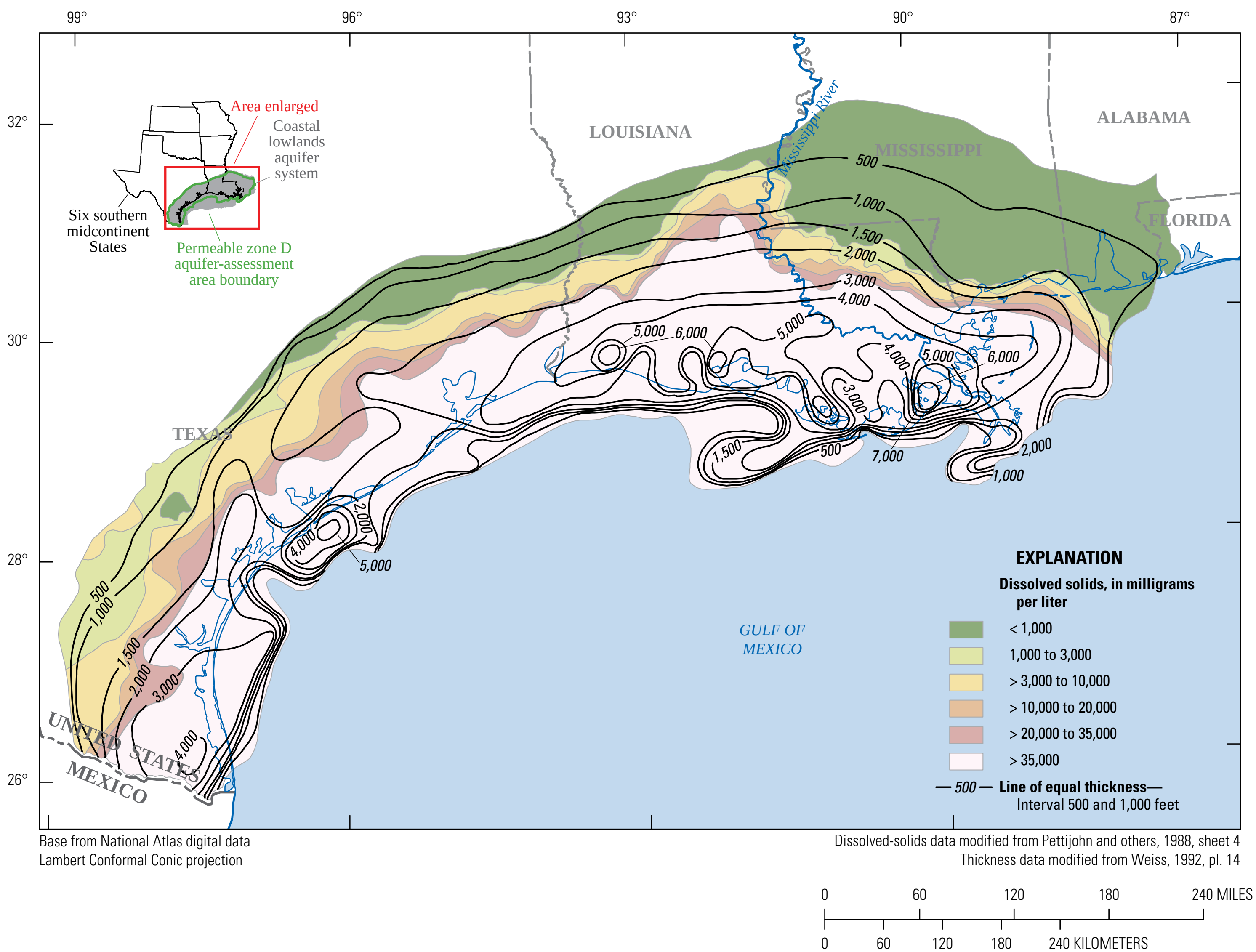

Figure 8. Dissolved-solids concentrations and thickness in the aquifer-assessment area of permeable zone D in the coastal lowlands aquifer system, Gulf Coast regional aquifer system.

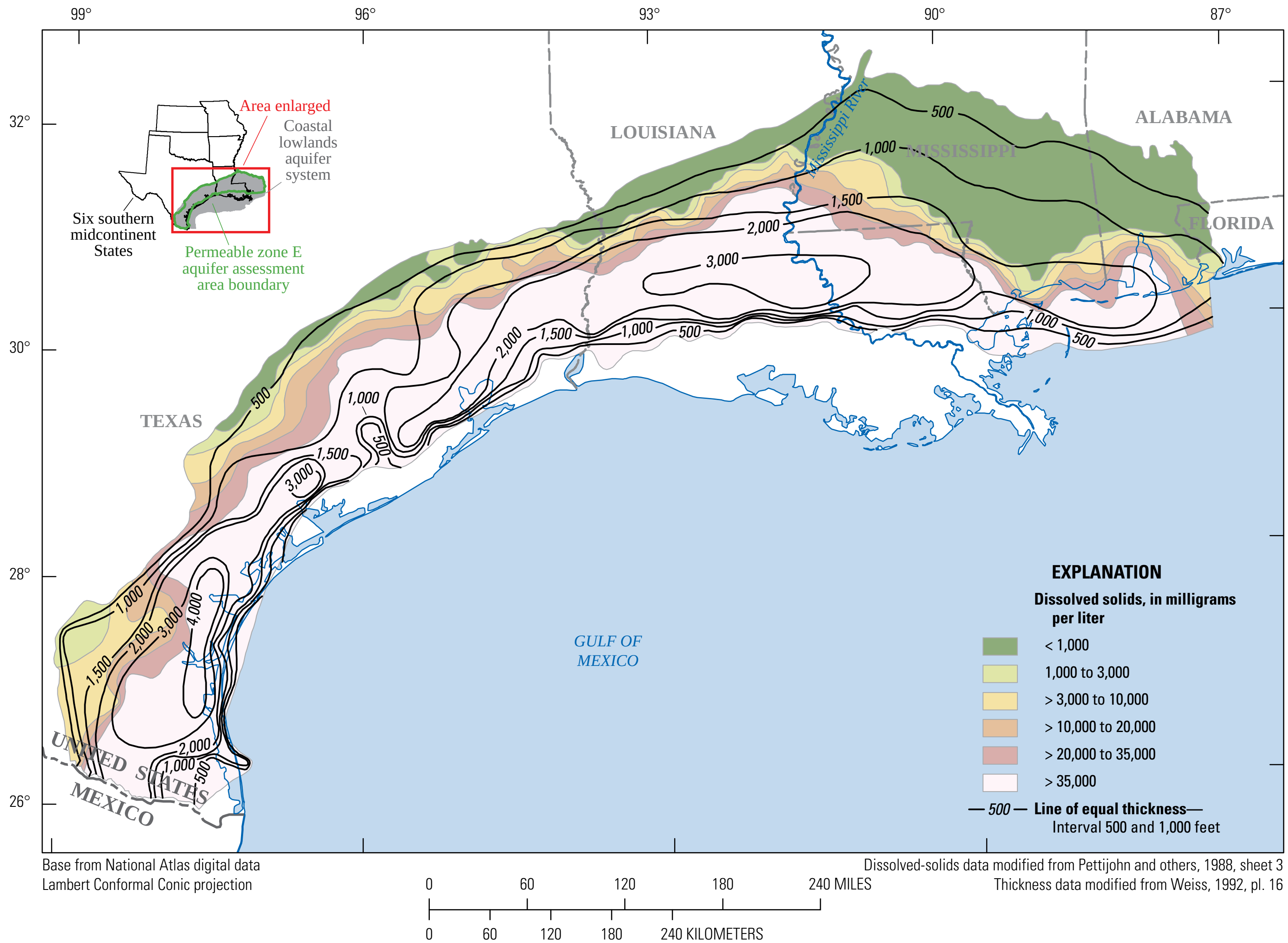

Figure 9. Dissolved-solids concentrations and thickness in the aquifer-assessment area of permeable zone E in the coastal lowlands aquifer system, Gulf Coast regional aquifer system.

Mississippi Embayment and Texas Coastal Uplands Aquifer Systems

The Mississippi embayment and Texas coastal uplands aquifer systems underlie about 188,000 mi^2 in parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Louisiana, Mississippi, Missouri, Tennessee, and Texas (fig. 3). The Mississippi embayment and Texas coastal uplands aquifer systems consist of thick sequences of Cenozoic deposits. The maximum thickness of the Mississippi embayment aquifer system is approximately 6,000 ft, and the maximum thickness of the Texas coastal uplands aquifer system is approximately 7,000 ft (Ackerman, 1996). The Mississippi embayment and Texas coastal uplands aquifer systems are contiguous and share many of the same hydrogeologic units. Furthermore, the saline-groundwater flow systems of the two aquifer systems are interconnected. For these reasons, the saline groundwaters in both aquifer systems are mapped and evaluated together in this report.

The aquifers in the Mississippi embayment and laterally equivalent Texas coastal uplands aquifer systems typically consist of one or more massive sand beds and are separated by confining units of regionally extensive clay beds (Grubb, 1998). The aquifers in the Texas coastal uplands aquifer system typically are thicker and contain more sand than equivalent aquifers in the Mississippi embayment aquifer system (Grubb, 1998). The regional hydrogeologic units in the combined Mississippi embayment and Texas coastal uplands aquifer systems, from youngest to oldest, are (1) Mississippi River Valley alluvial aquifer, (2) Vicksburg-Jackson confining unit, (3) upper Claiborne aquifer, (4) middle Claiborne confining unit, (5) middle Claiborne aquifer, (6) lower Claiborne confining unit, (7) lower Claiborne-upper Wilcox aquifer, (8) middle Wilcox aquifer, (9) lower Wilcox aquifer, (10) Midway confining unit, and (11) McNairy-Nacatoch aquifer (table 5). The Mississippi embayment aquifer system contains all of these hydrogeologic units; the Texas coastal uplands aquifer system contains all of the hydrogeologic units except the Mississippi River Valley alluvial aquifer, the lower Wilcox aquifer, and the McNairy-Nacatoch aquifer. Maps of dissolved-solids concentrations and thickness of aquifers in the Mississippi embayment and Texas coastal uplands aquifer systems are shown in figures 10–16.

The Mississippi River Valley alluvial aquifer consists of alluvial and terrace deposits of Quaternary age and is age equivalent with permeable zone A in the coastal lowlands aquifer system (Hosman and Weiss, 1991) but is separated from the coastal lowlands aquifer by the Vicksburg-Jackson confining unit (Ackerman, 1996). The Mississippi River Valley alluvial aquifer overlies aquifers and confining units of Tertiary age (table 5) and consists of deposits of gravel, sand, and clay, which commonly grade upward from gravel and coarse sand at the base to fine sand overlain by silt and clay at the surface (Pettijohn, 1996).

The Mississippi River Valley alluvial aquifer is exposed at land surface throughout its areal extent. Regionally, the alluvial aquifer is unconfined, but locally it is confined under a layer of silt, clay, and fine-grained sand (Ackerman, 1996). The alluvial aquifer is absent on Crowleys Ridge (fig. 10), an erosional remnant of Tertiary strata, which acts as a barrier to regional groundwater flow (Ackerman, 1996). In areas where the Mississippi River Valley alluvial aquifer overlies or is incised into the underlying Tertiary aquifers, there is upward flow of groundwater from the underlying aquifers (Pettijohn, 1996).

The Vicksburg-Jackson confining unit, consisting of massive clay beds, separates the Mississippi River Valley alluvial aquifer and aquifers and confining units in the underlying Claiborne Group (table 5). The Claiborne Group contains a thick sequence of massive sand beds separated by thick, extensive marine clay beds (Hosman and Weiss, 1991). The upper Claiborne aquifer consists of interbedded fine sand, silt, and clay. The aquifer is as thick as 2,400 ft in southeastern Texas and generally less than 300 ft thick in the Mississippi embayment. The middle Claiborne aquifer underlies the middle Claiborne confining unit and consists primarily of the Sparta Sand. The middle Claiborne aquifer has a large sand content in the Mississippi embayment, where the aquifer generally contains more than 60 percent sand. The lower Claiborne confining unit hydraulically separates the underlying lower Claiborne-upper Wilcox aquifer from the middle Claiborne aquifer. The lower Claiborne-upper Wilcox aquifer consists primarily of the Carrizo Sand or its equivalent Meridian Sand Member of the Tallahatta Formation, which is a massive and extensive sand (Hosman and Weiss, 1991). In the central part of the Mississippi embayment, the lower Claiborne-upper Wilcox aquifer merges with the middle Claiborne aquifer where the clay of the lower Claiborne confining unit changes to sand facies. The middle Claiborne and lower Claiborne-upper Wilcox aquifers are not present over the Sabine uplift, in an area of about 7,000–9,000 mi^2 centered on the Texas-Louisiana State boundary (figs. 12–13), owing to lack of deposition or erosion (Grubb, 1998).

The middle Wilcox aquifer generally consists of thin interbedded sand, silt, and clay, but in the northern part of the Mississippi embayment, the middle Wilcox aquifer contains massive sand beds (Hosman and Weiss, 1991; Grubb, 1998). The aquifer is more than 80 percent sand throughout most of the northern part of the Mississippi embayment, but the sand content gradually decreases to the southeast where it is less than 40 percent throughout a large part of southern Mississippi (Grubb, 1998). The lower Wilcox aquifer occurs in only the Mississippi embayment aquifer system (table 5). The aquifer is generally less than 400 ft thick but thickens southward to more than 1,200 ft in central Mississippi (Hosman and Weiss, 1991). The Midway confining unit is the basal confining unit of most of the Mississippi embayment and Texas coastal uplands aquifer systems (fig. 4, table 5) (Grubb, 1998; Hosman and Weiss, 1991).

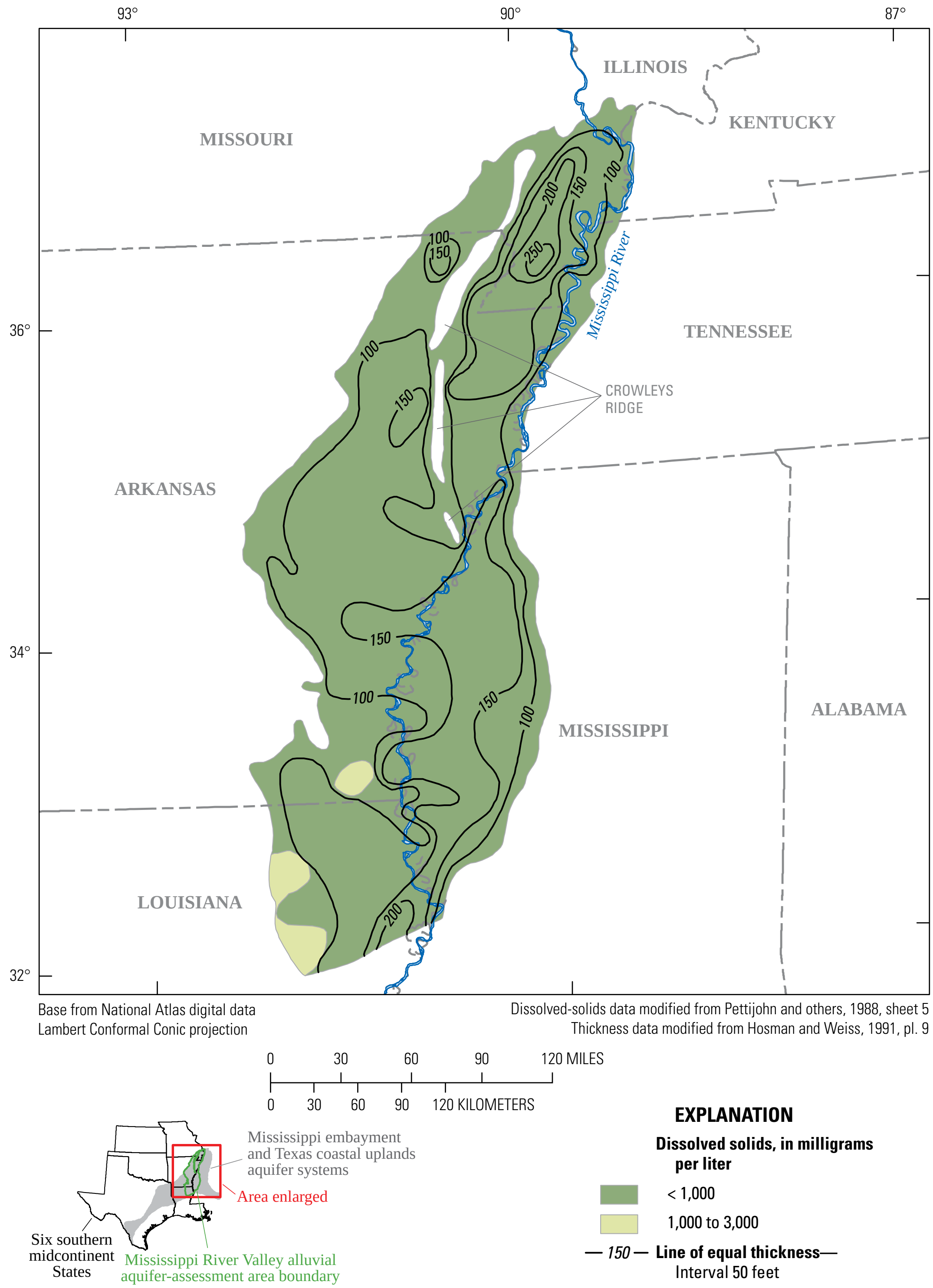

Figure 10. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the Mississippi River Valley alluvial aquifer in the Mississippi embayment and Texas coastal uplands aquifer systems, Gulf Coast regional aquifer system.

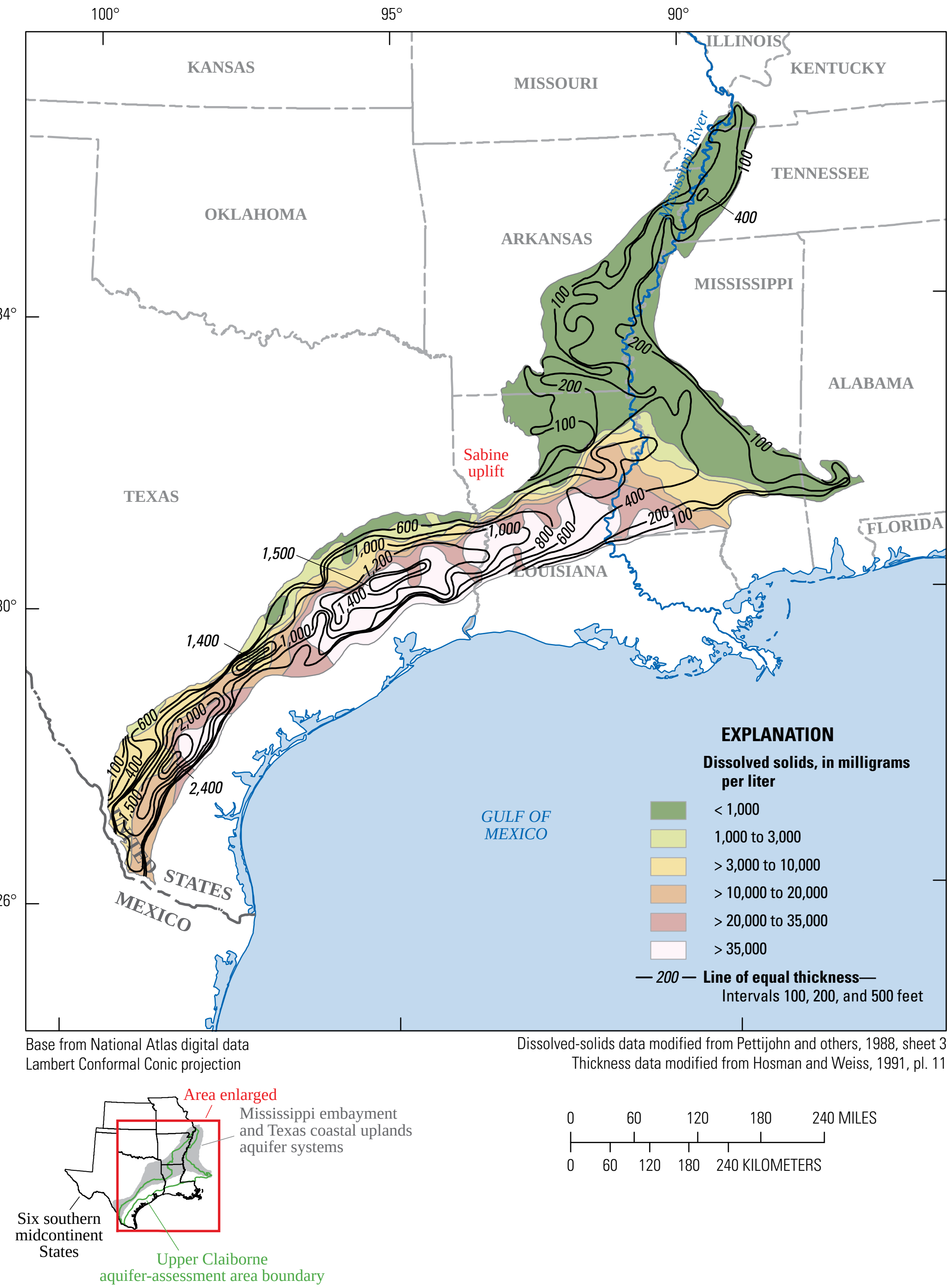

Figure 11. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the upper Claiborne aquifer in the Mississippi embayment and Texas coastal uplands aquifer systems, Gulf Coast regional aquifer system.

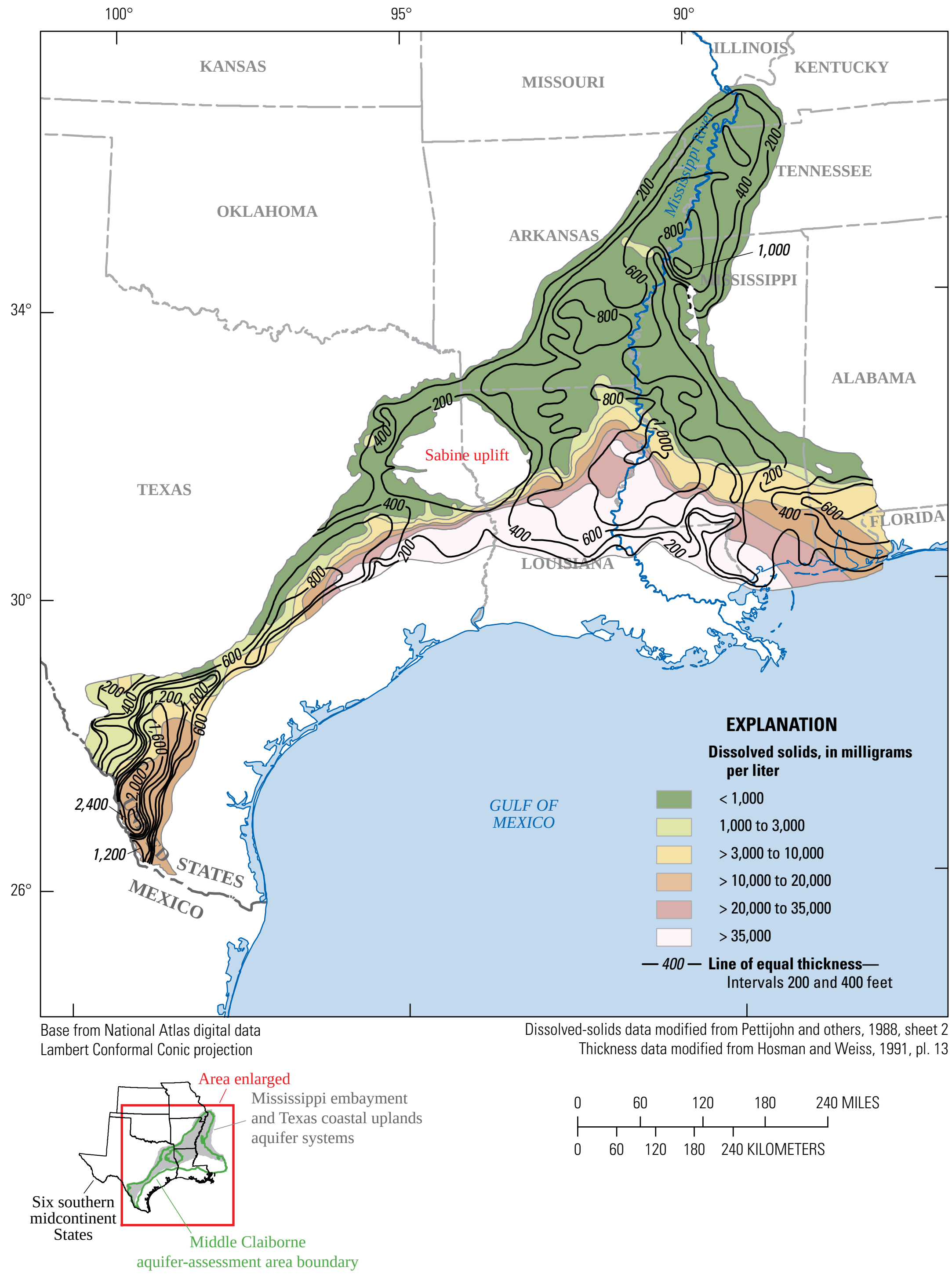

Figure 12. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the middle Claiborne aquifer in the Mississippi embayment and Texas coastal uplands aquifer systems, Gulf Coast regional aquifer system.

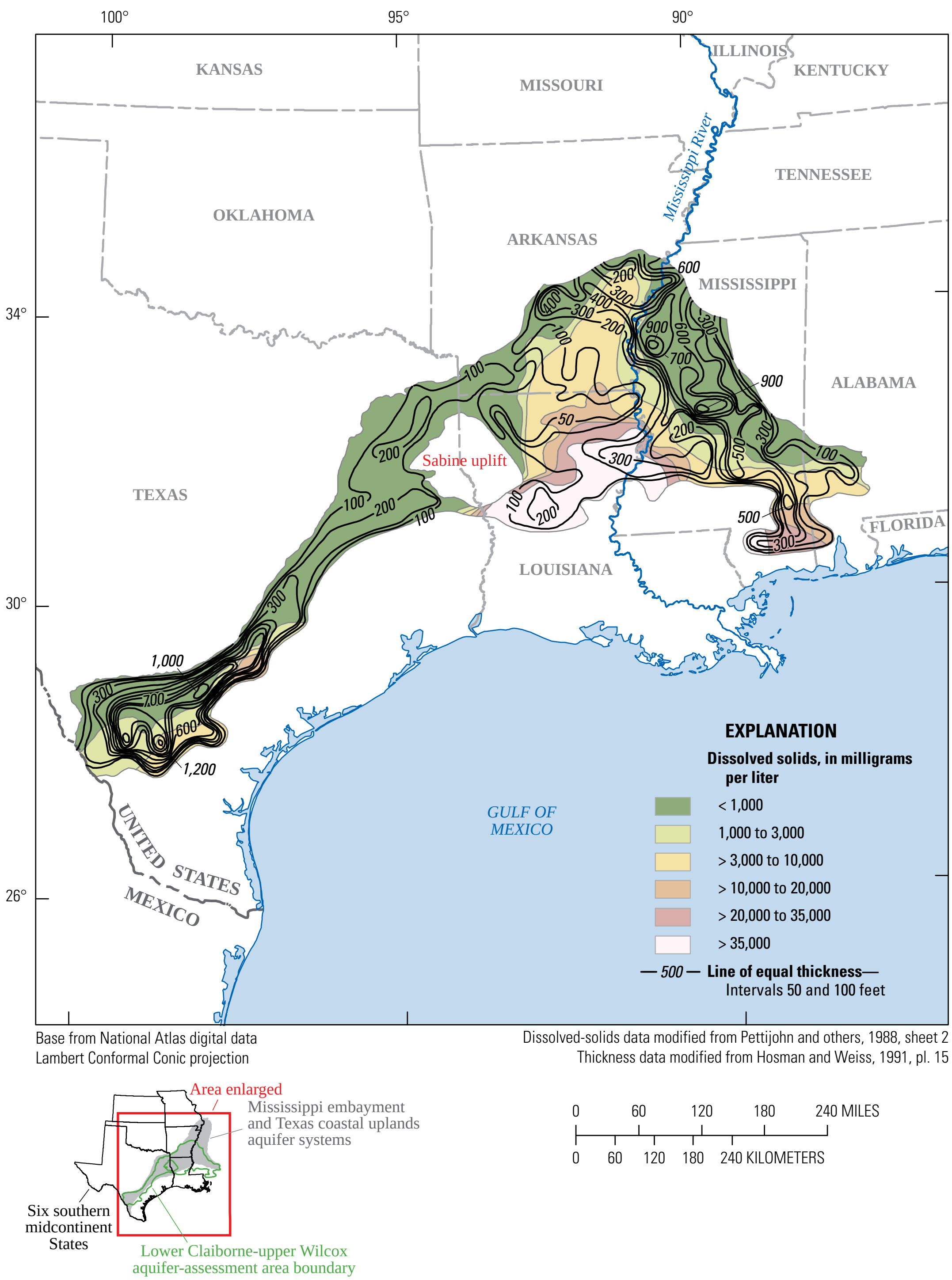

Figure 13. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the lower Claiborne-upper Wilcox aquifer in the Mississippi embayment and Texas coastal uplands aquifer systems, Gulf Coast regional aquifer system.

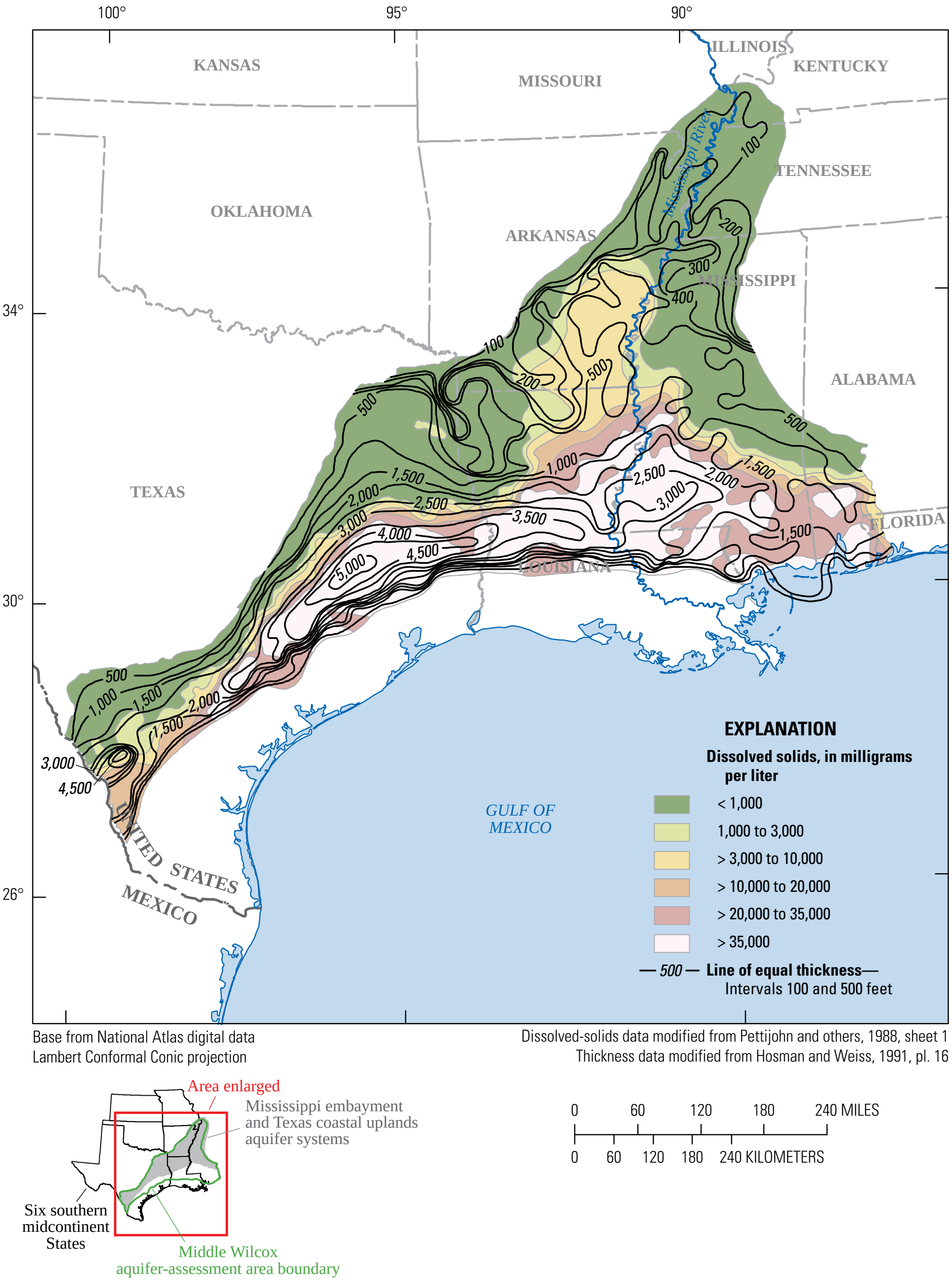

Figure 14. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the middle Wilcox aquifer in the Mississippi embayment and Texas coastal uplands aquifer systems, Gulf Coast regional aquifer system.

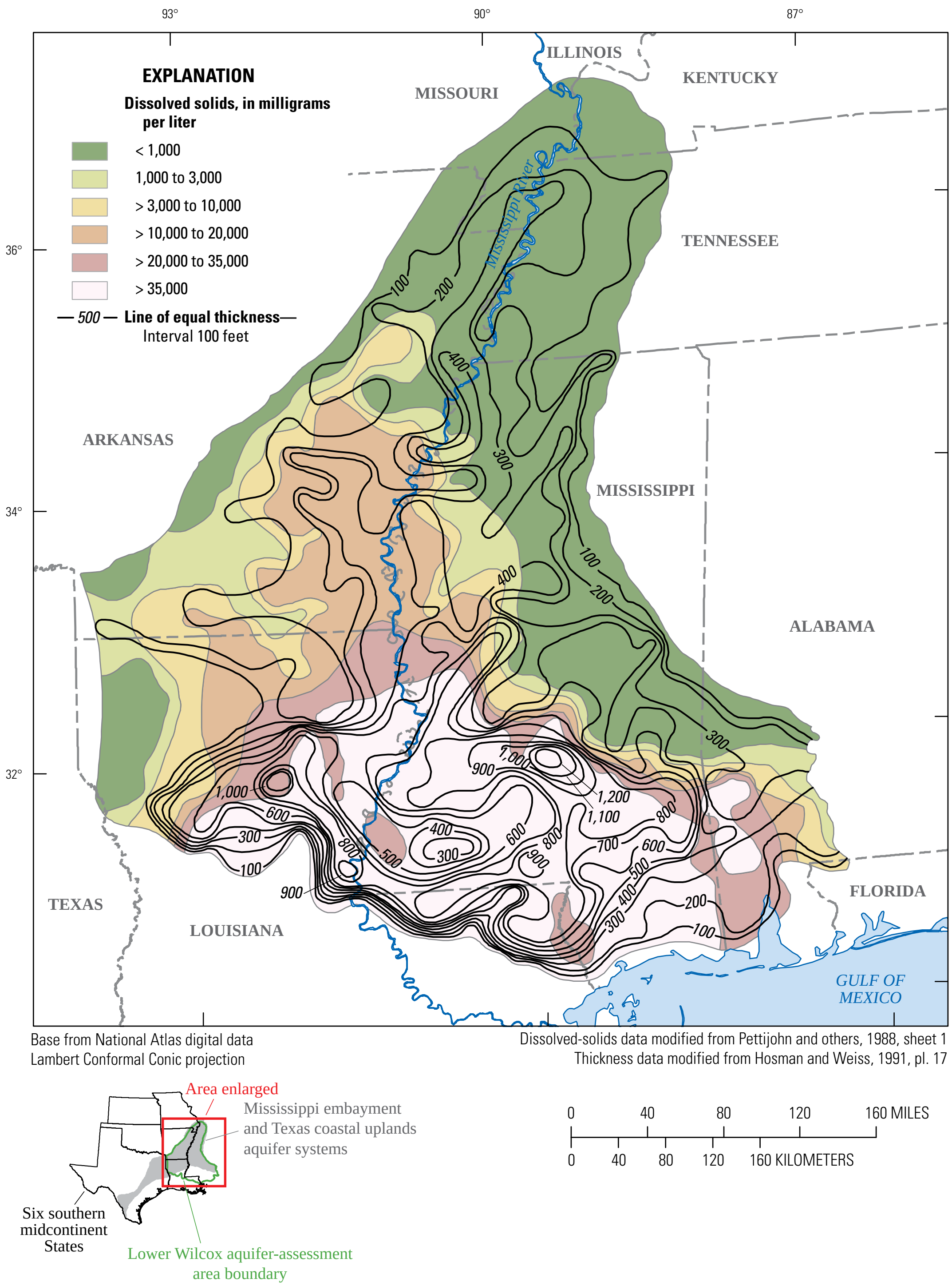

Figure 15. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the lower Wilcox aquifer in the Mississippi embayment and Texas coastal uplands aquifer systems, Gulf Coast regional aquifer system.

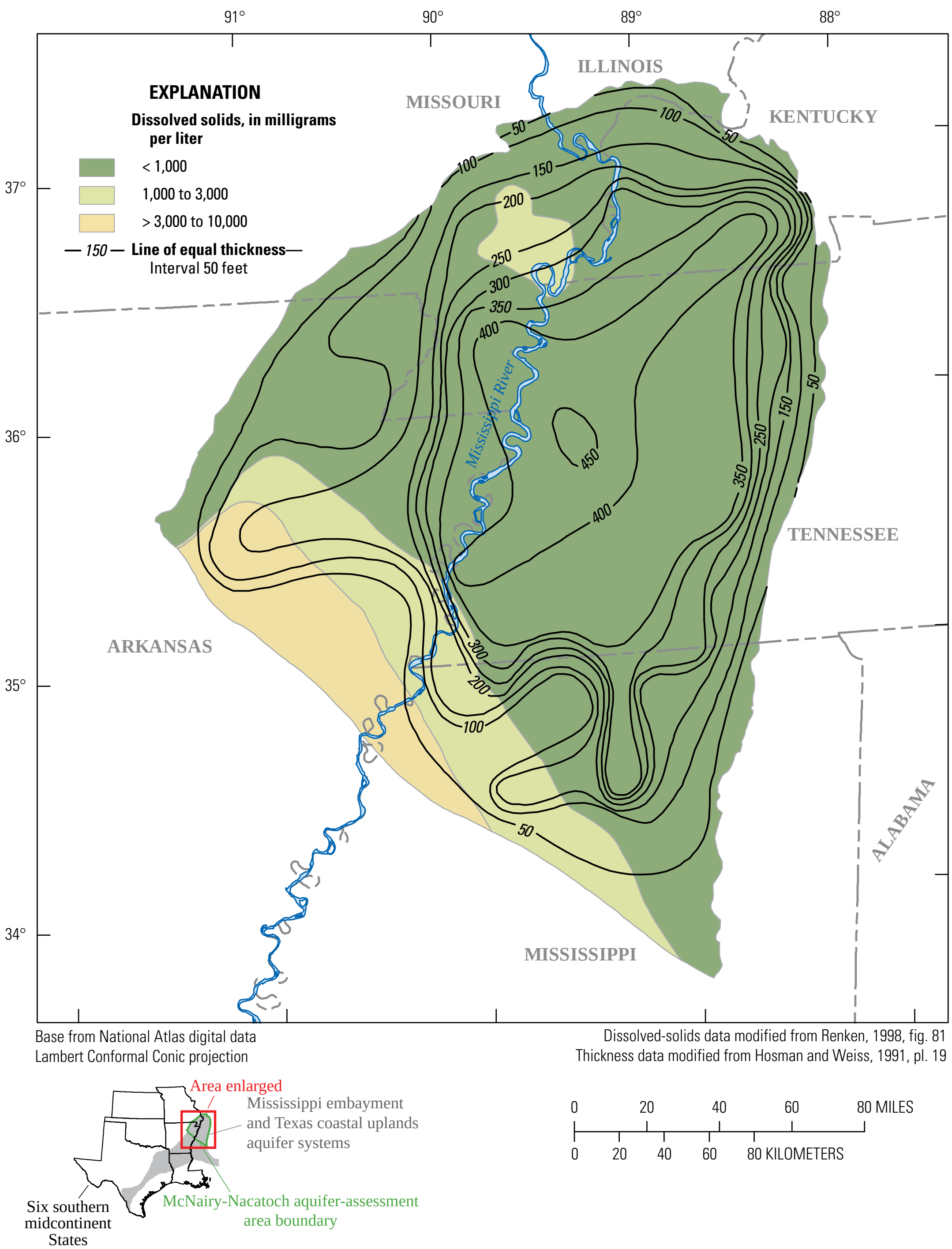

Figure 16. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the McNairy-Nacatoch aquifer of the Mississippi embayment and Texas coastal uplands aquifer systems, Gulf Coast regional aquifer system.

The McNairy-Nacatoch aquifer, of Upper Cretaceous age, is the lowermost hydrogeologic unit in the Gulf Coast regional aquifer system (table 5). This aquifer consists of sand, minor gravel, and clay deposited in a deltaic environment (Renken, 1998), which by way of a facies change, grades downdip to clay, marl, and limestone (Brahana and Mesko, 1988).

Aquifers in the Mississippi embayment aquifer system are recharged by infiltration of precipitation on aquifer-outcrop areas, which are generally along the perimeter of the aquifer system. Groundwater discharge is to pumping wells, to incised rivers and streams, and as upward leakage to shallower aquifers (Renken, 1998). Regional groundwater flow is downdip toward the axis of the Mississippi embayment and then southward toward the Gulf of Mexico (Pettijohn, 1996). Groundwater flow is generally toward the streams; however, high streamflow or sustained pumping can locally reverse the hydraulic gradients and induce recharge from the streams to the aquifer, especially near the Mississippi River (Hosman and Weiss, 1991). Aquifers in the Texas coastal upland aquifer system are recharged by infiltration of precipitation on topographically high aquifer-outcrop areas. Groundwater discharge is to pumping wells, to evapotranspiration, to streams in outcrop areas, and as upward leakage to shallower aquifers in downdip areas (Ryder, 1996).

Groundwater Chemistry of the Gulf Coast Regional Aquifer System

Groundwater in the Gulf Coast regional aquifer system is generally fresh in and near outcrop areas of the aquifers and permeable zones. Dissolved-solids concentrations generally increase downdip toward the Gulf of Mexico and toward principal discharge areas. The deeper parts of the aquifers and permeable zones contain brine with dissolved-solids concentrations that can exceed 100,000 mg/L (Grubb, 1998) (figs. 5–16).

The major chemical and physical processes that affect water chemistry of the aquifers in the Gulf Coast regional aquifer system are water-rock interactions (leaching of soluble salts from the unsaturated zone, alteration of albite and other silicate minerals, cation exchange, and dissolution of evaporites) and mixing of freshwater with upward flow of saline water from underlying units (Pettijohn, 1996). The primary water type in aquifer outcrop areas and updip areas near the outcrops, where median dissolved-solids concentrations are less than 1,000 mg/L, typically is calcium bicarbonate or a mixture of calcium bicarbonate and sodium bicarbonate (Pettijohn, 1996). The major processes controlling the water chemistry in these outcrop and updip areas are leaching of soluble salts from the unsaturated zone and alteration of silicates (Pettijohn, 1996). In middip areas, where the median concentration of dissolved solids ranges from 1,000 mg/L to 3,000 mg/L, the primary water types are either sodium bicarbonate or a mixture of sodium bicarbonate and calcium bicarbonate, and the major processes controlling water chemistry are upward flow from underlying deposits, dissolution of residual evaporite crystals, and alteration of silicates (Pettijohn, 1996). In middip to downdip areas, where the median concentration of dissolved solids ranges from 3,000 mg/L to 10,000 mg/L, the primary water types are either sodium bicarbonate or sodium chloride, or a mixture of the two, and the major processes are dissolution of evaporites and alteration of silicates (Pettijohn, 1996). In downdip areas, where the concentration of dissolved solids exceeds 10,000 mg/L, the primary water type is sodium chloride, and the major processes controlling water chemistry are dissolution of halite in salt domes and upward flow from underlying deposits (Pettijohn, 1996). The major process controlling chemistry of the brine, with dissolved-solids concentrations greater than 35,000 mg/L, is dissolution of halite in salt domes (Williamson and Grubb, 1997). Dissolution of halite occurs in areas where salt domes penetrate a permeable zone or aquifer at depths greater than approximately 4,000 ft. At depths less than approximately 4,000 ft, salt domes commonly are sealed by relatively impervious cap rocks, and thus dissolution of halite is minimal (Pettijohn, 1996).

Mixing of water by upward flow from underlying units is the most likely process causing slightly saline water in the Mississippi River Valley alluvial aquifer in a few small areas in northeast Louisiana and southeast Arkansas (fig. 10) (Pettijohn, 1996). Slightly saline water in the McNairy-Nacatoch aquifer in a small area in southeastern Missouri, southwestern Kentucky, and northwestern Tennessee (fig. 16) is the result of upward flow of water from the underlying Ozark Plateaus aquifer system (Renken, 1998). In local areas near the Gulf Coast, groundwater withdrawals have caused lowering of water levels in and near pumping centers and have induced the movement of seawater into parts of aquifers that previously contained freshwater (Grubb, 1998).

Saline-Water Volume of the Gulf Coast Regional Aquifer System

About 28,300 million acre-ft of saline water is estimated to be in the aquifer-assessment areas of the Gulf Coast regional aquifer system. The coastal lowlands aquifer system contains about 16,300 million acre-ft of saline water (table 6), and the Mississippi embayment and Texas coastal upland aquifer systems contain about 12,000 million acre-ft of saline water (table 7). Gulf Coast aquifers with the largest estimated volumes of saline water are permeable zone B (5,040 million acre-ft) and the middle Wilcox aquifer (4,700 million acre-ft) (tables 6 and 7).

Table 6. Estimated water volume of salinity zones in aquifer-assessment areas of the coastal lowlands aquifer system, Gulf Coast regional aquifer system.

[mg/L, milligrams per liter; values may not sum to totals because of independent rounding]

Salinity zone, dissolved-solids concentration (mg/L)[1]	Area (million acres)	Mean thickness (feet)[2]	Mean sand fraction[3]	Mean porosity fraction[4]	Water volume (million acre-feet)
Permeable zone A					
1,000–3,000	9.88	685	0.53	0.28	1,000
3,000–10,000	9.17	865	0.47	0.28	1,040
10,000–20,000	13.8	862	0.32	0.28	1,070
20,000–35,000	9.09	798	0.31	0.28	630
TOTAL					3,740
Permeable zone B					
1,000–3,000	7.33	725	0.56	0.28	833
3,000–10,000	5.03	1,010	0.45	0.28	640
10,000–20,000	6.4	1,320	0.35	0.28	828
20,000–35,000	15.0	2,420	0.27	0.28	2,740
TOTAL					5,040
Permeable zone C					
1,000–3,000	5.61	836	0.43	0.28	565
3,000–10,000	4.38	1,180	0.37	0.28	535
10,000–20,000	4.03	1,460	0.34	0.28	560
20,000–35,000	4.80	1,720	0.39	0.28	902
TOTAL					2,560
Permeable zone D					
1,000–3,000	5.30	905	0.45	0.28	604
3,000–10,000	7.82	1,420	0.36	0.28	1,120
10,000–20,000	3.00	1,600	0.39	0.28	524
20,000–35,000	3.62	1,850	0.41	0.28	769
TOTAL					3,020
Permeable zone E					
1,000–3,000	3.00	909	0.35	0.28	267
3,000–10,000	5.06	1,160	0.34	0.28	559
10,000–20,000	3.64	1,370	0.33	0.28	461
20,000–35,000	4.46	1,590	0.34	0.28	675
TOTAL					1,960
TOTAL	Coastal lowlands aquifer system				16,300

[1]Determined from dissolved-solids-concentration maps (modified from Pettijohn and others, 1988).

[2]Computed from thickness maps (modified from Weiss, 1992).

[3]Computed from sand-percentage maps (modified from Weiss, 1992).

[4]Computed from average porosities compiled by Core Laboratories, Inc. (1972).

Table 7. Estimated water volume of salinity zones in aquifer-assessment areas of the Mississippi embayment and Texas coastal uplands aquifer systems, Gulf Coast regional aquifer system.

[mg/L, milligrams per liter; values may not sum to totals because of independent rounding; NA, data not available]

Salinity zone, dissolved-solids concentration (mg/L)[1]	Area (million acres)	Mean thickness (feet)[2]	Mean sand fraction[3]	Mean porosity fraction[4]	Water volume (million acre-feet)
Mississippi River Valley alluvial aquifer					
1,000–3,000	0.506	91	NA	[5]0.28	12.9
TOTAL					12.9
Upper Claiborne aquifer					
1,000–3,000	4.04	615	0.47	0.30	345
3,000–10,000	7.51	722	0.47	0.30	767
10,000–20,000	5.53	942	0.51	0.30	794
20,000–35,000	5.09	852	0.44	0.30	578
TOTAL					2,480
Middle Claiborne aquifer					
1,000–3,000	7.95	629	0.58	0.30	860
3,000–10,000	7.97	664	0.46	0.30	728
10,000–20,000	8.36	838	0.41	0.30	870
20,000–35,000	5.08	498	0.37	0.30	283
TOTAL					2,740
Lower Claiborne-upper Wilcox aquifer					
1,000–3,000	8.07	337	0.69	0.24	451
3,000–10,000	10.30	206	0.68	0.24	344
10,000–20,000	2.94	183	0.67	0.24	86.1
20,000–35,000	2.35	176	0.66	0.24	65.1
TOTAL					946
Middle Wilcox aquifer					
1,000–3,000	7.47	1,190	0.44	0.24	934
3,000–10,000	10.6	1,010	0.40	0.24	1,040
10,000–20,000	5.10	1,640	0.43	0.24	868
20,000–35,000	11.8	1,730	0.38	0.24	1,860
TOTAL					4,700
Lower Wilcox aquifer					
1,000–3,000	6.24	197	0.67	0.24	198
3,000–10,000	6.02	213	0.63	0.24	194
10,000–20,000	8.53	251	0.65	0.24	334
20,000–35,000	5.50	423	0.56	0.24	313
TOTAL					1,040
McNairy-Nacatoch aquifer					
1,000–3,000	2.35	126	0.81	[6]0.25	60.0
3,000–10,000	1.38	53	0.81	[6]0.25	14.8
TOTAL					74.8
TOTAL	Mississippi embayment and Texas coastal uplands aquifer systems				12,000

[1]Determined from dissolved-solids-concentration maps (modified from Pettijohn and others, 1988; Renken, 1998).

[2]Computed from thickness maps (modified from Hosman and Weiss, 1991).

[3]Computed from sand-percentage maps (modified from Hosman and Weiss, 1991).

[4]Computed from average porosities compiled by Core Laboratories, Inc. (1972).

[5]Specific yield from Ackerman (1996).

[6]Average porosity from Emmons (1921).

Edwards-Trinity Regional Aquifer System

The Edwards-Trinity regional aquifer system underlies a 77,000-mi^2 area that extends from western Texas into southeastern Oklahoma and southwestern Arkansas (fig. 1). This regional aquifer system consists of three major aquifers: the Edwards, Trinity, and Edwards-Trinity aquifers (Ryder, 1996), but there only was sufficient information to map the distribution of saline groundwater in the Edwards aquifer in south-central Texas (fig. 17).

Extensively faulted, fractured, and cavernous carbonate rocks of Cretaceous age make up the Edwards aquifer (Ryder, 1996). The aquifer is composed of limestone and dolostone of the Georgetown Formation and Edwards Group (table 8) (Ryder, 1996). The Trinity aquifer, composed of the less permeable and clay-rich Glen Rose Limestone (table 8), underlies and is adjacent to the Edwards aquifer to the north (Barker and Ardis, 1996). The arc-shaped Edwards aquifer is generally coincident with a region of northeastward-trending faults known as the Balcones fault zone (fig. 17) (Ryder, 1996). Thickness of the Edwards aquifer ranges from less than 300 ft in the northeast to about 800 ft in the southwest and averages about 550 ft. The effective porosity of the Edwards aquifer generally ranges from 2 to 14 percent and averages approximately 6 percent (Maclay, 1995).

Recharge to the Edwards aquifer is primarily from losses from streams that cross the aquifer outcrop (recharge zone), by infiltration of precipitation in the recharge zone, and by inflow from the adjacent Trinity aquifer (Maclay, 1995; Barker and Ardis, 1996; Lambert and others, 2010). Groundwater flows from the recharge zone in a downdip direction to the south and southeast into the confined parts of the aquifer. The freshwater flow is subsequently diverted by northeastward-trending faults to the east and northeast through solutionally enlarged fractures and is discharged from springs and pumping wells (Maclay and Land, 1988; Maclay, 1995; Barker and Ardis, 1996; Lambert and others, 2010).

The freshwater zone of the Edwards aquifer (fig. 1) is bounded to the south and southeast by a zone of transition from freshwater to saline water containing groundwater with dissolved-solids concentrations ranging from 1,000 mg/L to 10,000 mg/L. Fresh groundwater enters the freshwater/saline-water transition zone from the freshwater zone in the western part of the Edwards aquifer. Relatively low-permeability rocks in the freshwater/saline-water transition zone allow small flows toward the northeast, where groundwater discharges to the freshwater zone in the eastern part of the aquifer (Lambert and others, 2010). The freshwater/saline-water transition zone is separated downdip from a saline-water zone, with dissolved-solids concentration greater than 10,000 mg/L, by faults that offset permeable layers of the aquifer and restrict groundwater flows across them. Dissolved-solids concentrations in the saline-water zone rapidly increase downdip toward the Gulf of Mexico from 10,000 mg/L to more than 250,000 mg/L (Maclay and Land, 1988).

Water chemistry of the Edwards aquifer is controlled primarily by geologic processes that occurred in late Tertiary time, when the deeply buried aquifer, saturated with brine, was uplifted and faulted. Large volumes of freshwater began to infiltrate the aquifer in the fault zone that previously had been isolated from meteoric conditions, allowing freshwater to mix with older brine and saline water (Maclay, 1995). Groundwater flow from the adjacent Trinity aquifer also may mix with water in the freshwater/saline-water transition zone, a hypothesis supported by helium-isotope data (Hunt and others, 2010). Isotope and geochemical data from wells indicate that water in the freshwater/saline-water transition zone is mostly meteoric water that likely has been recharged from the freshwater zone in the recent geologic past (less than tens of thousands of years) in a hydraulically active flow system (Groschen and Buszka, 1997). Isotope data from deep wells in the saline-water zone indicate that the older water has been thermally altered in reactions with carbonate rocks and is in a hydraulically stagnant flow system (Groschen and Buszka, 1997).

Only the slightly and moderately saline waters of the freshwater/saline-water transition zone were mapped in the Edwards aquifer assessment area (fig. 17) because insufficient water chemistry data were available to map saline water with dissolved-solids concentrations greater than 10,000 mg/L. An estimated 49.1 million acre-ft of slightly to moderately saline water is stored in the Edwards aquifer (table 9).

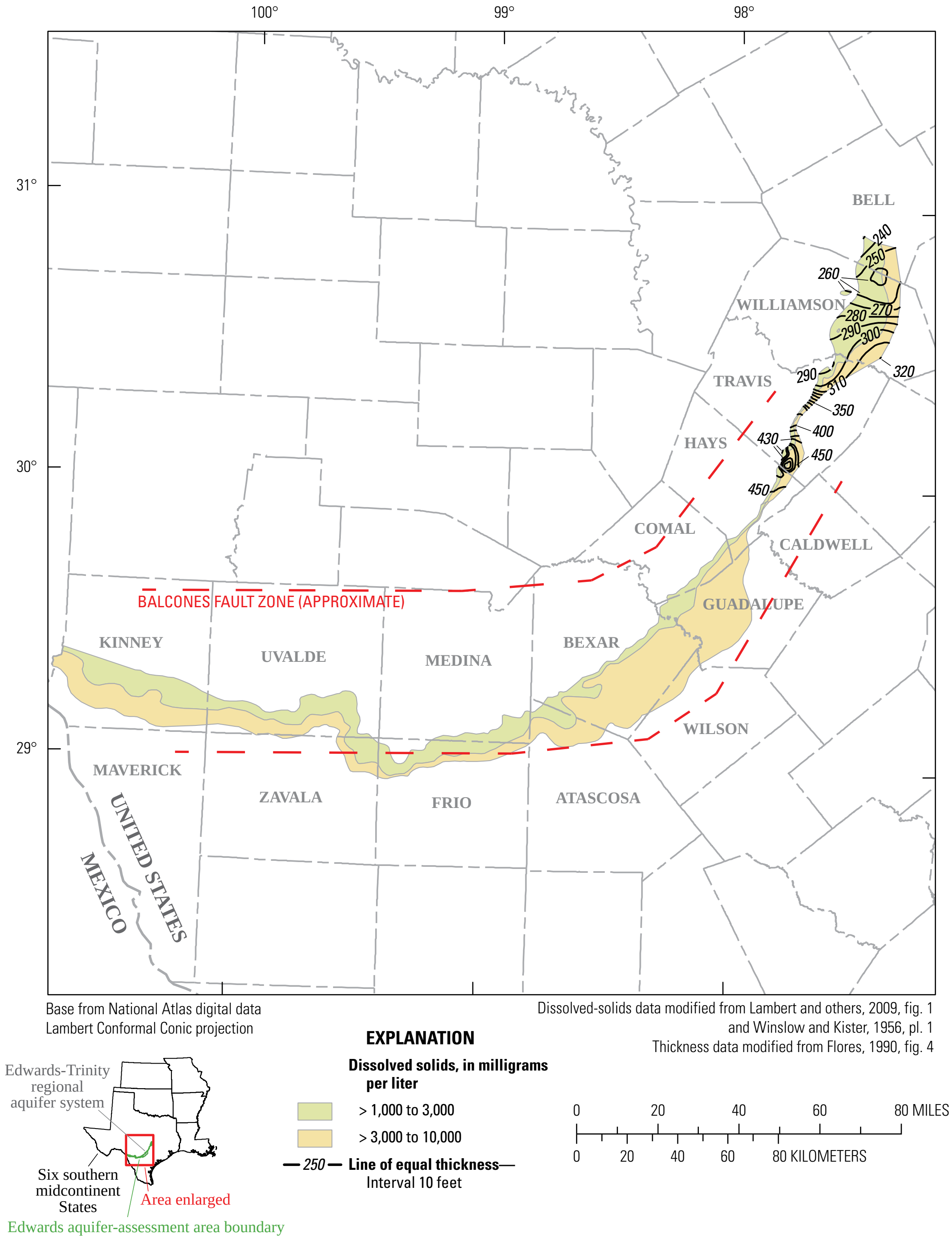

Figure 17. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the Edwards aquifer, Edwards-Trinity regional aquifer system.

Table 8. Time-stratigraphic, rock-stratigraphic, and hydrogeologic units of the Edwards aquifer, Edwards-Trinity regional aquifer system.

[From Maclay and Land, 1988, fig. 3; Ls, Limestone; Fm, Formation; Gp, Group]

<table>
<tr><th colspan="2">Time-stratigraphic unit</th><th colspan="2" rowspan="2">Rock-stratigraphic unit</th><th rowspan="2">Hydro-geologic unit</th></tr>
<tr><th>System</th><th>Stage</th></tr>
<tr><td rowspan="7">Cretaceous</td><td rowspan="3">Washitan Stage</td><td rowspan="3"></td><td>Buda Ls</td><td rowspan="2">Confining unit</td></tr>
<tr><td>Del Rio Clay</td></tr>
<tr><td>Georgetown Fm</td><td rowspan="3">Edwards aquifer</td></tr>
<tr><td rowspan="2">Fredericksburgian Stage</td><td rowspan="2">Edwards Gp</td><td>Pearson Fm</td></tr>
<tr><td>Kainer Fm</td></tr>
<tr><td rowspan="2">Trinitian Stage</td><td rowspan="2">Glen Rose Ls</td><td>Upper Glen Rose</td><td>Confining unit</td></tr>
<tr><td>Lower Glen Rose</td><td>Trinity aquifer</td></tr>
</table>

Table 9. Estimated water volume of salinity zones in the aquifer-assessment area of the Edwards aquifer, Edwards-Trinity regional aquifer system.

[Only saline waters with dissolved-solids concentrations of 1,000–10,000 mg/L were evaluated; mg/L, milligrams per liter; values may not sum to totals because of independent rounding]

Salinity zone, dissolved-solids concentration (mg/L)[1]	Area (million acres)	Mean thickness (feet)[2]	Mean porosity fraction[3]	Water volume (million acre-feet)
1,000–3,000	0.644	443	0.06	17.1
3,000–10,000	0.952	561	0.06	32.0
TOTAL				49.1

[1]Determined from dissolved-solids-concentration maps (modified from Flores, 1990; Lambert and others, 2009) and well data (modified from Groschen and Buszka, 1997).

[2]Computed from thickness map (modified from Flores, 1990).

[3]Maclay, 1995.

Central Midwest Regional Aquifer System

The Central Midwest regional aquifer system underlies a 370,000-mi^2 area in all of Kansas and Nebraska and parts of Arkansas, Colorado, Missouri, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming (fig. 1). The regional aquifer system consists of three aquifer systems: Great Plains, Western Interior Plains, and Ozark Plateaus (fig. 18) (Jorgensen and others, 1996). The regional aquifer system is divided into two subregions based on groundwater-flow systems: the Plains subregion, consisting of the Great Plains aquifer system, the Western Interior Plains confining system, and the Western Interior Plains aquifer system; and the Ozark subregion, consisting of the Ozark Plateaus aquifer system (fig. 18) (Jorgensen and others, 1996). The Great Plains confining system and the High Plains regional aquifer system (fig. 1) overlie most of the Great Plains aquifer system (fig. 19). The High Plains regional aquifer system is described in the section "High Plains Regional Aquifer System."

The rock-stratigraphic units of the Western Interior Plains aquifer system in the Plains subregion are approximately age equivalent to those of the Ozark Plateaus aquifer system in the Ozark subregion. Rocks of the upper aquifer unit in the Western Interior Plains aquifer system are age equivalent to the Mississippian rocks of the Springfield Plateau aquifer, and rocks of the lower aquifer units in the Western Interior Plains aquifer system are age equivalent to rocks of the Ozark aquifer, the St. Francois confining unit, and the St. Francois aquifer in the Ozark Plateaus aquifer system (tables 10 and 11) (Jorgensen and others, 1996).

Although the Western Interior Plains and Ozark Plateaus aquifer systems consist of age-equivalent rock-stratigraphic units, the two aquifer systems have separate groundwater-flow systems (Jorgensen and others, 1996). Regional groundwater flow in the Western Interior Plains aquifer system is generally eastward, and a large component of groundwater flow in the Ozark Plateaus aquifer system is westward. Eastward-flowing saline groundwater from the Western Interior Plains aquifer system converges with the westward-flowing fresh groundwater from the Ozark Plateaus aquifer system in a broad, topographically low area that extends from northeastern Oklahoma into central Missouri and then flows vertically upward to streams or to overlying rock units (fig. 19) (Jorgensen and others, 1996). The shared boundary between the two flow systems is a transition zone between freshwater and saline water. Because the Western Interior Plains and Ozark Plateaus aquifer systems share the transition zone between freshwater and saline water, saline groundwaters in both systems are mapped and evaluated together in this report.

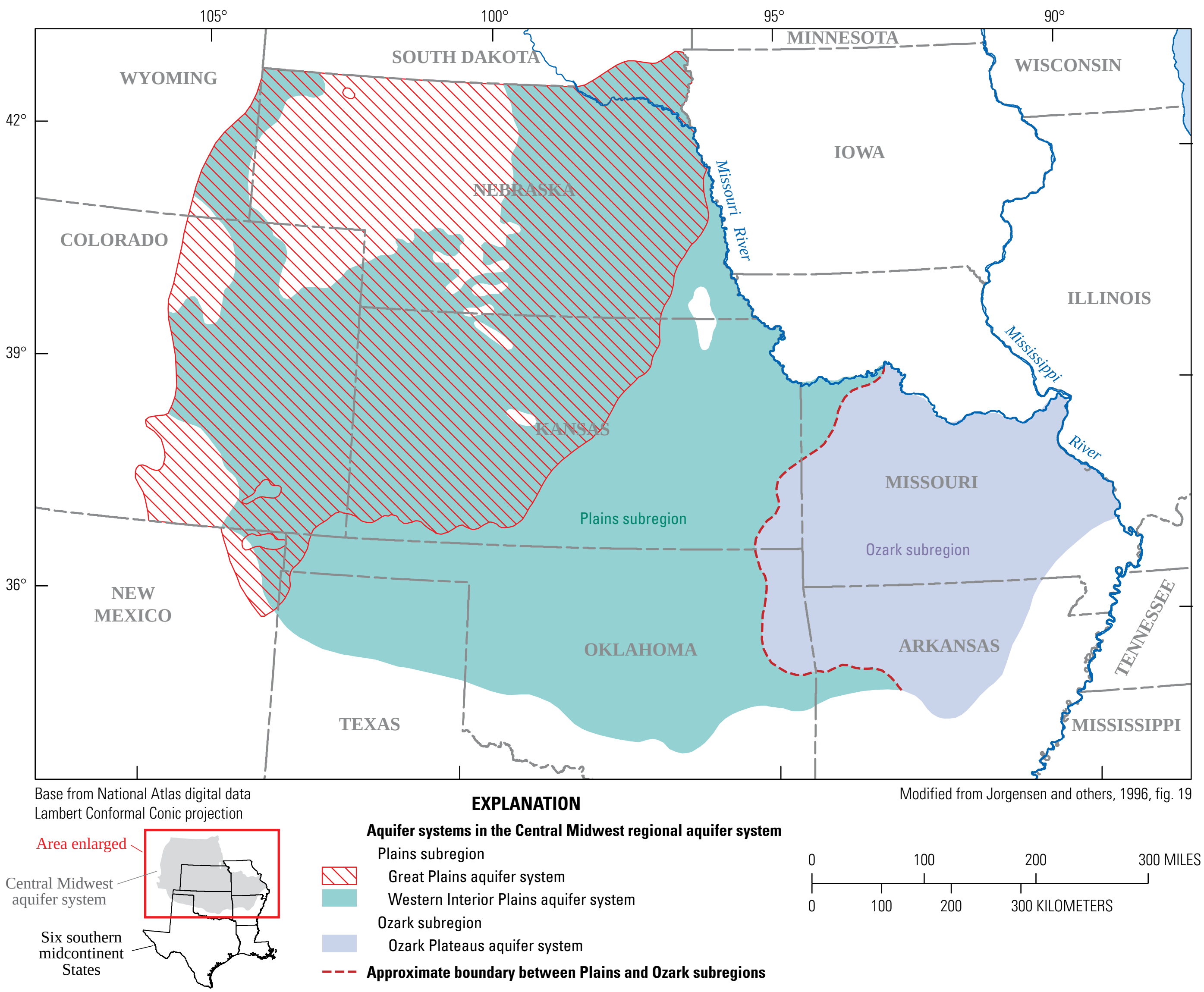

Figure 18. Aquifer systems in the Central Midwest regional aquifer system.

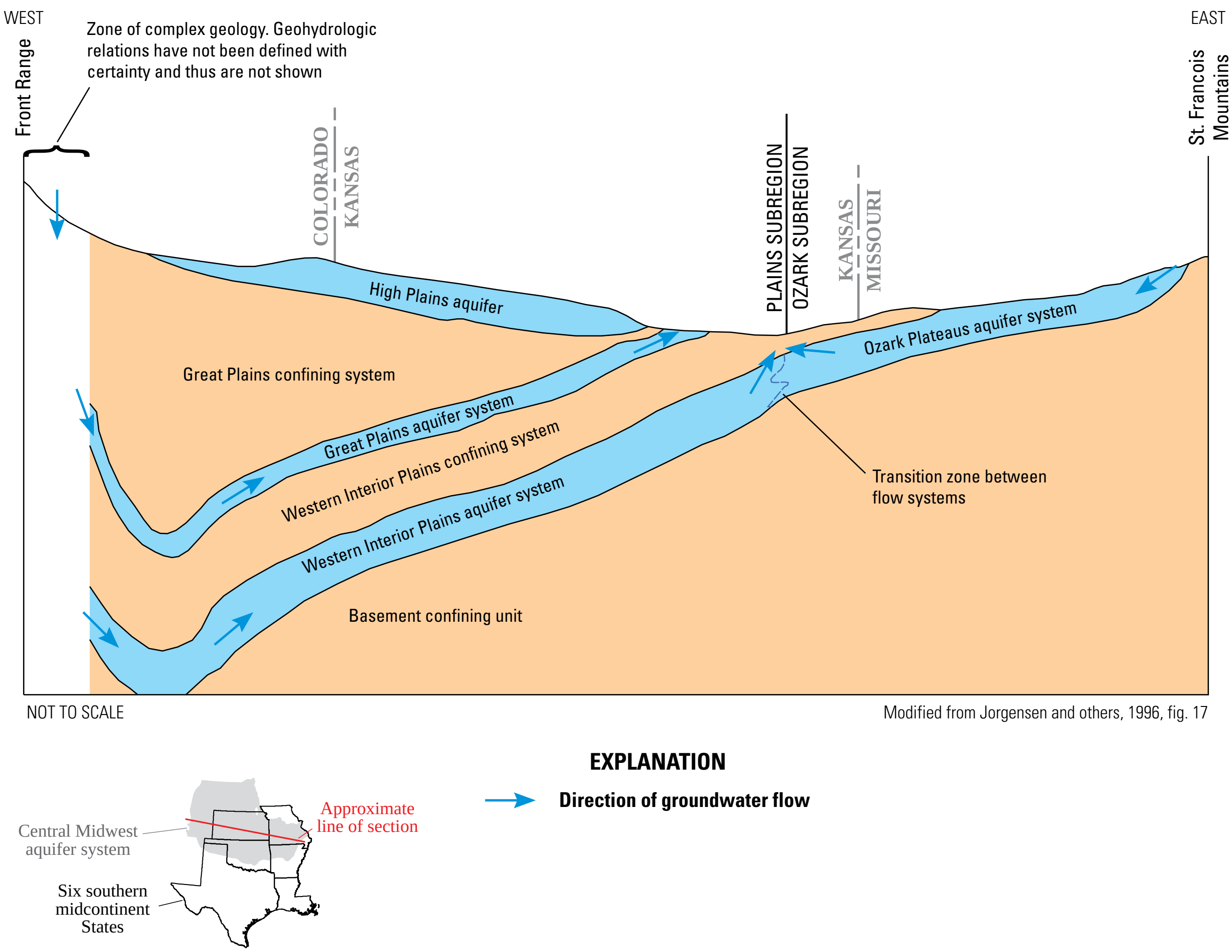

Figure 19. Generalized section from central Colorado to eastern Missouri showing hydrogeologic units and direction of groundwater flow in the Central Midwest regional aquifer system.

Table 10. Time-stratigraphic, rock-stratigraphic, and hydrogeologic units of the Plains subregion, Central Midwest regional aquifer system.

[Modified from Jorgensen and others, 1996, table 1; Fm, Formation; Sh, Shale; Ls, limestone; Ss, Sandstone; ss, sandstone; Dol, Dolomite; Gp, Group]

Time-stratigraphic unit	Rock- and time-stratigraphic units	Hydrogeologic unit	
Quaternary and Tertiary	Ogallala Fm and unconsolidated deposits	High Plains aquifer	
Upper Cretaceous	Pierre Sh, Niobrara Fm, Carlile Sh, Greenhorn Ls, Graneros Sh	Great Plains confining system	
Lower Cretaceous	Dakota Ss, "D" ss, "J" ss, and equivalent of Newcastle Ss	Maha aquifer	Great Plains aquifer system
	Kiowa Sh and equivalent of Skull Creek Sh	Apishapa confining unit	
	Cheyenne Ss and equivalent of Fall River Ss and Lakota Ss	Apishapa aquifer	
Jurassic through Upper Mississippian (Chesterian)	Morrison Fm, Sundance Fm, Entrada Ss, Dockum Fm, Elk City Ss, Doxey Sh, Big Basin Ss, Cloud Chief Fm, Day Creek Dol, Whitehorse Ss, Nippewalla Gp, Sumner Gp, Cedar Hills Ss, Garber Ss, Wellington Fm, Chase Gp, Council Grove Gp, Admire Gp, Wabaunsee Gp, Shawnee Gp, Douglas Gp, Lansing Gp, Kansas City Gp, Pleasanton Gp, Marmaton Gp, Cherokee Gp, Atokan rocks, Morrowan rocks, and Springer Gp	Western Interior Plains confining system	
Upper Mississippian through Upper Cambrian	Meramecian, Osagean, and Kinderhookian rocks	Upper aquifer unit	Western Interior Plains aquifer system
	Chattanooga Sh and Woodford Sh	Confining unit	
	Hunton Gp, Sylvan Sh, equivalent of Galena Dol, Viola Ls, Simpson Gp, Arbuckle Gp, and Reagan Ss	Lower aquifer units	
Cambrian and Precambrian	Mostly igneous and metamorphic rocks	Basement confining unit	

Table 11. Time-stratigraphic, rock-stratigraphic, and hydrogeologic units of the Ozark subregion, Central Midwest regional aquifer system.

[Modified from Jorgensen and others, 1996, table 3; Gp, Group; Sh, Shale; Fm, Formation; Ls, Limestone; Ss, Sandstone; Dol, Dolomite]

Time-stratigraphic unit	Rock- and time-stratigraphic units	Hydrogeologic unit	
Middle Pennsylvanian through Upper Mississippian (Chesterian)	Marmaton Gp, Cherokee Gp, Atokan rocks, Bloyd Sh, Hale Fm, Morrowan rocks, Pitkin Ls, Fayetteville Sh, and Batesville Ss	Western Interior Plains confining system	
Mississippian	Moorefield Fm, St. Louis Ls, Salem Ls, Warsaw Ls, Boone Fm, St. Joe Ls Member of Boone Fm, Keokuk Ls, Burlington Ls, and Fern Glen Ls	Springfield Plateau aquifer	Ozark Plateaus aquifer system
Lower Mississippian and Upper Devonian	Chouteau Gp, Chattanooga Sh, Northview Sh, and Hannibal Sh	Ozark confining unit	
Middle Devonian through Upper Cambrian	Clifty Ls, Penters Chert, Lafferty Ls, St. Clair Ls, Brassfield Ls, Cason Sh, Fernvale Ls, Kimmswick Ls, Plattin Ls, Joachim Dol, St. Peter Ss, Everton Fm, Smithville Fm, Powell Dol, Cotter Dol, Jefferson City Dol, Roubidoux Fm, Gasconade Dol, Gunter Ss Member of Gasconade Dol, Eminence Dol, and Potosi Fm	Ozark aquifer	
Upper Cambrian	Elvins Gp, Derby and Doe Run Dols, Davis Fm	St. Francois confining unit	
	Bonneterre Dol, Lamotte Ss, and Reagan Ss	St. Francois aquifer	
Precambrian	Mostly igneous and metamorphic rocks	Basement confining unit	

Great Plains Confining System

The Great Plains confining system overlies the Great Plains aquifer system in most places (fig. 19) and restricts flow to and from the Great Plains aquifer system and the overlying High Plains aquifer. The confining system consists mostly of very slightly permeable Cretaceous shale and is as thick as 8,000 ft in the Denver Basin (Jorgensen and others, 1993).

Great Plains Aquifer System

The Great Plains aquifer system encompasses an area of about 170,000 mi^2 in the northern part of the Plains subregion (fig. 18). The Great Plains aquifer system is divided into the Maha aquifer (consisting mostly of the Dakota Sandstone), the Apishapa confining unit (consisting mostly of the Kiowa Shale), and the Apishapa aquifer (consisting mostly of the Cheyenne Sandstone) of Early Cretaceous age (table 10) (Jorgensen and others, 1996). Both the Maha aquifer and Apishapa aquifer consist primarily of permeable, loosely cemented, medium- to fine-grained sandstones (Helgesen and others, 1993; Jorgensen and others, 1996). The Maha aquifer is the thickest and most areally extensive unit of the Great Plains aquifer system, ranging in thickness from less than 100 ft in eastern Colorado to more than 900 ft in central Nebraska (fig. 20); thickness of the Apishapa aquifer is generally less than 400 ft (fig. 21) (Helgesen and others, 1993). Porosity of both aquifers ranges from approximately 10 to 30 percent, generally being smallest in the deeper basins (Helgesen and others, 1993).

Strata of the Great Plains aquifer system were deposited during Early Cretaceous time in an environment that fluctuated between marine shoreline and nonmarine (Jorgensen and others, 1996). The Laramide orogeny of Late Cretaceous and early Tertiary time uplifted the Rocky Mountains (Front Range uplift) and formed the adjacent Denver and Raton Basins (fig. 22). In late Tertiary time, broad uplift and regional tilting to the east led to development of the modern west-to-east hydraulic gradient in the Great Plains aquifer system (Jorgensen and others, 1996). Erosion has exposed the rocks of the Great Plains aquifer system along the eastern and southern margins of the aquifer system. In areas where the Great Plains confining system is absent, the High Plains aquifer directly overlies the Great Plains aquifer system along the southern and eastern margins of the aquifer system, and Quaternary-age deposits directly overlie the aquifer system (Jorgensen and others, 1993).

Recharge by direct infiltration in outcrop areas of the Great Plains aquifer system occurs in southeastern Colorado, northeastern New Mexico, and the Black Hills uplift in southwestern South Dakota (fig. 22) (Helgesen and others, 1993). Local recharge occurs near the southern and eastern extents of the aquifer system, where the aquifers are close to land surface. Most recharge to the system, however, is by downward leakage through overlying hydrogeologic units, such as the High Plains aquifer and the Missouri River alluvium (Helgesen and others, 1993; Jorgensen and others, 1996). Most discharge from the Great Plains aquifer system is by upward flow into overlying geologic units, but some discharge is to streams in aquifer outcrop areas along the Missouri River Valley and along the eastern edge of the aquifer system (Helgesen and others, 1993; Miller and Appel, 1997).

Flow of groundwater through the Great Plains aquifer system is primarily from southwest to east-northeast toward the eastern edge of the aquifer system in Kansas and eastern Nebraska (Helgesen and others, 1993). Deep burial by several thousand feet of younger sediments and faulting along the western margin of the Denver and Raton Basins have isolated much of the aquifer system hydraulically from freshwater at or near land surface (Helgesen and others, 1993). As a result, groundwater moves very slowly (calculated velocities from 0.01 to 10 feet per year) through most areas of the Great Plains aquifer system (Helgesen and others, 1993).

Concentrations of dissolved solids in water from the Great Plains aquifer system generally are less than 1,000 mg/L in areas where the aquifer system is at or near land surface, primarily near the southern and eastern margins of the aquifer system, and in a small area in northwest Nebraska (Helgesen and others, 1993) (figs. 20 and 21). Water in these areas is primarily a calcium-bicarbonate type, formed where meteoric water entering the aquifers resulted in dissolution of carbonate cement (Helgesen and others, 1993). Small areas of calcium-sulfate-type and sodium-chloride-type water are near the eastern boundary of the system, where regionally flowing water from the west becomes diluted by freshwater recharge (Helgesen and others, 1993).

In areas where the Great Plains aquifer system is overlain by the Great Plains confining system, dissolved-solids concentrations generally exceed 1,000 mg/L, and groundwater is mostly a sodium-bicarbonate or sodium-chloride type (Helgesen and others, 1993). Water containing 1,000–10,000 mg/L dissolved solids is characteristic of much of the Great Plains aquifer system (Helgesen and others, 1993). The near-shore depositional environment of sediments composing this aquifer system probably included original formation water that was fresh to moderately saline. Deep burial by several thousand feet of younger sediments and faulting along the western margin of the aquifer system restricted freshwater flow and prevented complete flushing of original formation water from much of the slow-moving groundwater in this aquifer system (Helgesen and others, 1993).

Dissolved-solids concentrations of 10,000–20,000 mg/L are common in the central and east-central parts of this aquifer system and probably are related to a combination of incomplete flushing of formation water and upward flow of saline water from adjacent salt-bearing strata (Helgesen and others, 1993). In central Kansas, saline water in this aquifer system is related to upward flow from the underlying Permian Cedar Hills Sandstone, which contains brine from underlying evaporite deposits (Helgesen and others, 1993). Groundwater containing more than 100,000 mg/L dissolved solids in the Nebraska Panhandle probably is caused by upward flow of brine along faults or fractures from underlying Permian evaporite deposits (Russell, 1961; Helgesen and others, 1993).

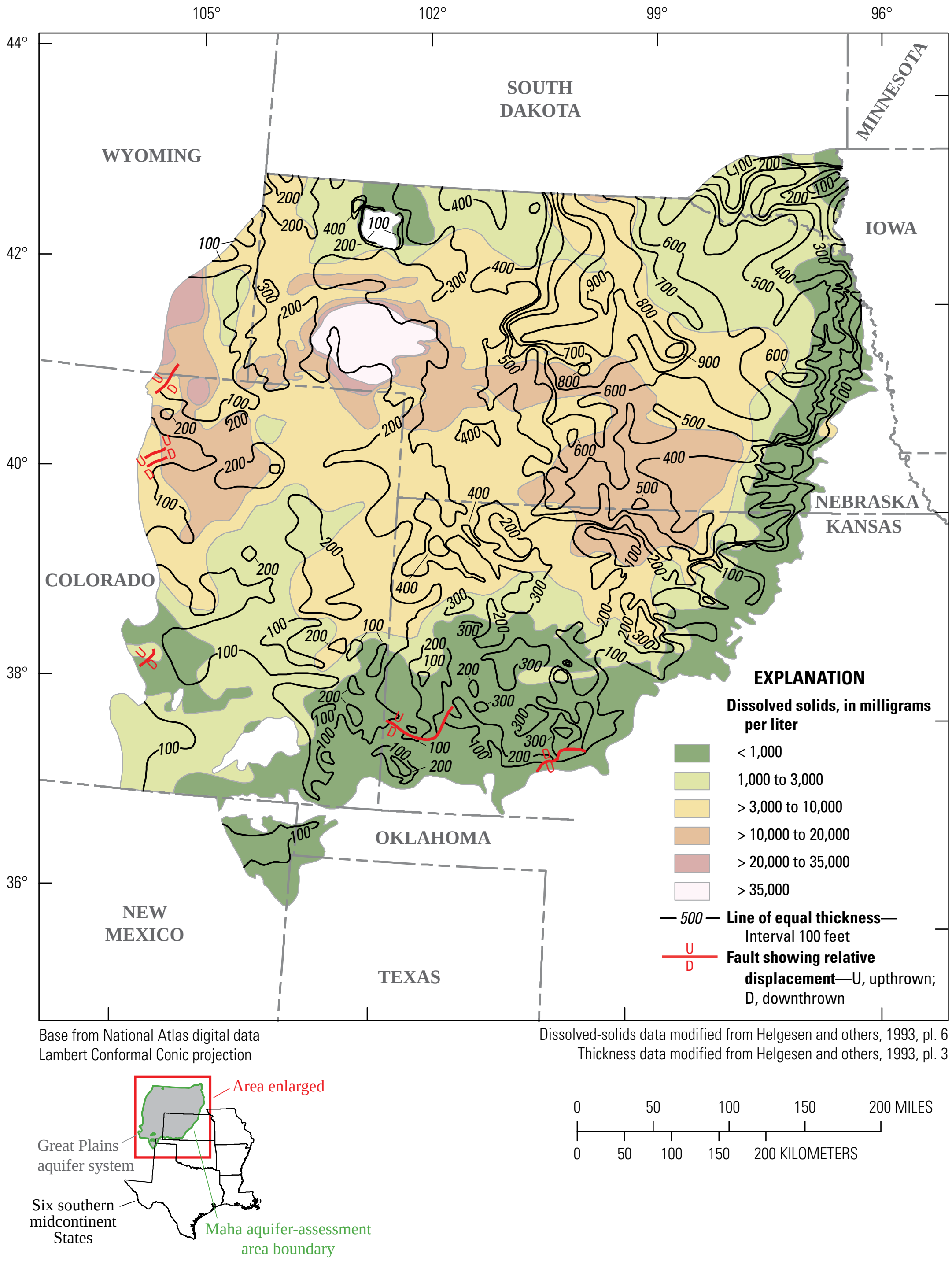

Figure 20. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the Maha aquifer in the Great Plains aquifer system, Central Midwest regional aquifer system.

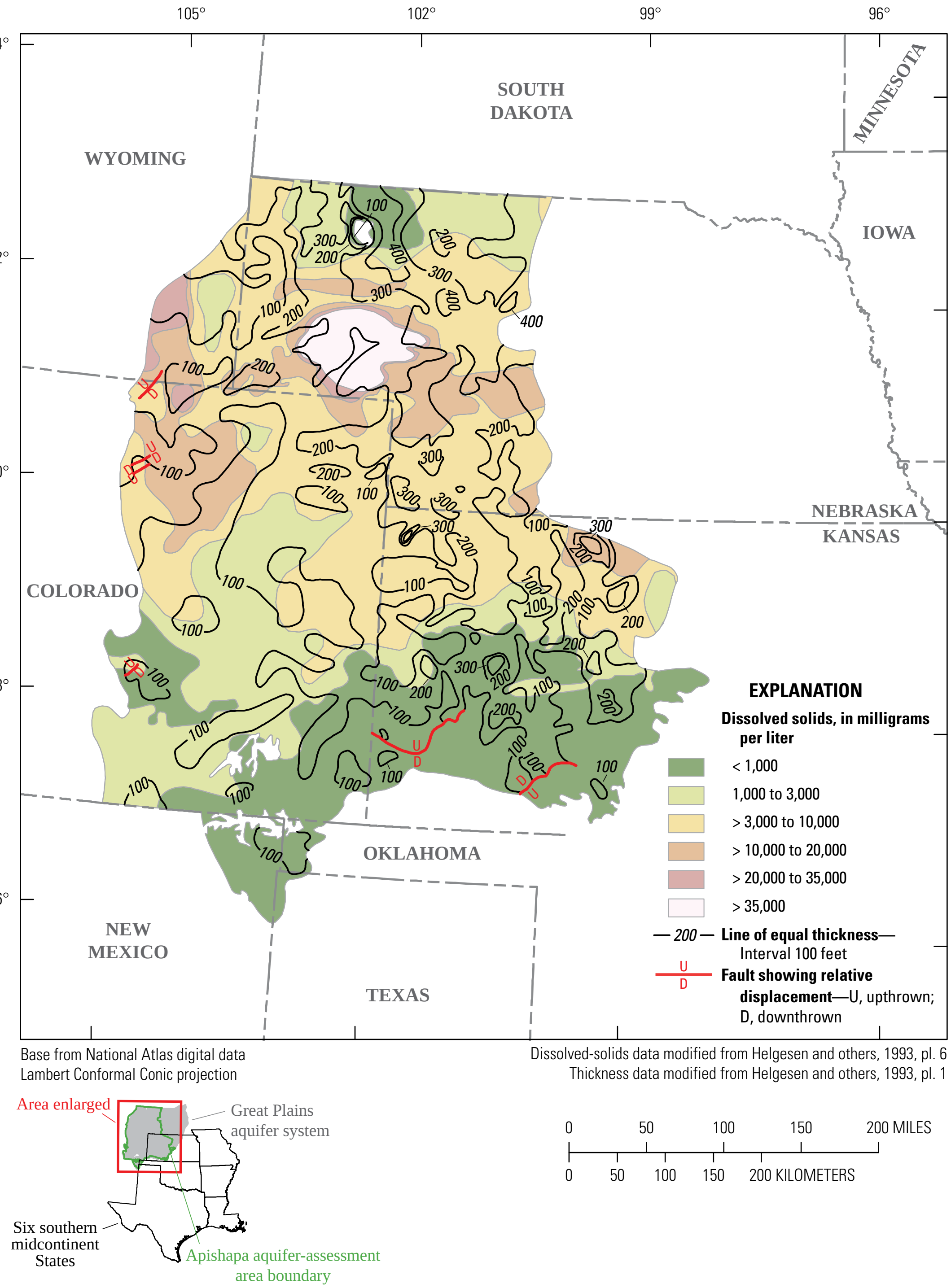

Figure 21. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the Apishapa aquifer in the Great Plains aquifer system, Central Midwest regional aquifer system.

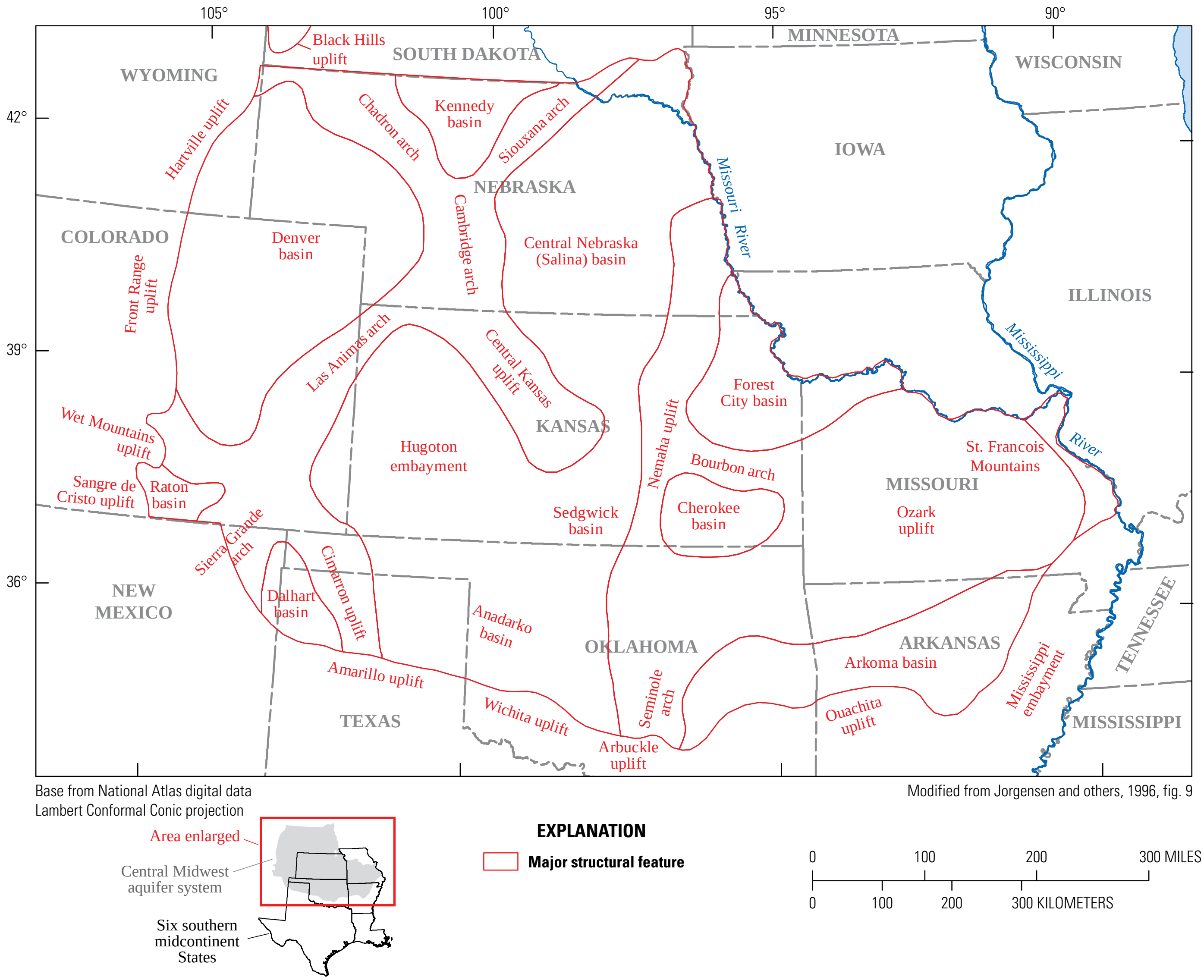

Figure 22. Major structural features of the Central Midwest regional aquifer system and adjacent areas.

Western Interior Plains Confining System

The Western Interior Plains confining system is present in both the Plains and Ozark subregions. The confining system, consisting of mostly shale, limestone, sandstone, and evaporite deposits of Pennsylvanian and Permian age, restricts flow between the High Plains and Great Plains aquifer systems and the underlying Western Interior Plains aquifer system (table 10). Thickness of the confining system ranges from 0 ft in northeastern Nebraska and in the Ozark subregion to more than 20,000 ft in the Anadarko Basin (Jorgensen and others, 1993).

Although the Western Interior Plains confining system functions as a regional confining unit, permeable limestone and sandstone formations in the system are locally water bearing (Baker and Leonard, 1995). Water from the system at depths of 500 ft or more below land surface generally contains large concentrations of dissolved solids, locally as large as 300,000 mg/L; however, the concentrations of dissolved solids in water from depths of less than 500 ft vary greatly (Baker and Leonard, 1995). In eastern Kansas and parts of Oklahoma, some of the permeable sandstone units are locally important aquifers that provide freshwater for municipal supply, agriculture, and other uses (Ryder, 1996). Little is known about saline waters in these aquifers, and those waters are not described in this report.

Western Interior Plains Aquifer System

The Western Interior Plains aquifer system in the Plains subregion (fig. 18) is divided into an upper aquifer unit, a confining unit, and lower aquifer units (table 10). The upper aquifer unit consists primarily of limestone of Mississippian age, and the lower aquifer units consist of dolostone, limestone, and sandstone of Cambrian to Devonian age. The upper aquifer unit and lower aquifer units are separated at most locations by a shale confining unit (Jorgensen and others, 1996).

All rock-stratigraphic units of the Western Interior Plains aquifer system dip away from the Missouri River and the Ozark uplift toward the Denver, Anadarko, and Arkoma Basins, except along the Front Range uplift (fig. 22). The upper aquifer unit was removed from large parts of the Western Interior Plains aquifer system by erosion in Mississippian time (Jorgensen and others, 1996), and as a result, the thickness of the upper aquifer unit is generally less than 1,000 ft (fig. 23). Thickness of the lower aquifer units exceeds 10,000 ft in the Anadarko Basin in south-central Oklahoma (fig. 24) (Signor and others, 1996).

Rocks of the Western Interior Plains aquifer system are deeply buried beneath the thick Western Interior Plains confining system in most of the Plains subregion. Deeply buried geologic units are less permeable and less porous than the same units in shallower areas that have been exposed to subaerial weathering (Baker and Leonard, 1995). Regional porosity of the upper and lower aquifer units is small (about 1 percent) in deep basins but increases to 10–15 percent near the Central Kansas, Nemaha, and Ozark uplifts (fig. 22) (Signor and others, 1996).

Groundwater flow in the Western Interior Plains aquifer system is regionally southeastward from north-central Nebraska and otherwise eastward toward a broad topographic and potentiometric low area in eastern Kansas and northeastern Oklahoma. Discharge in the broad, topographically low area is vertically upward to streams or to the near-surface water-table aquifers (fig. 19) (Jorgensen and others, 1996). Minimal recharge to the aquifer system occurs from vertical leakage through the overlying confining system (Signor and others, 1996). Groundwater in the Western Interior Plains aquifer system moves very slowly, with modeled velocities as slow as 40 ft per million years in deeply buried rock-stratigraphic units, because in most of the area both intrinsic permeability and hydraulic gradient are small (Signor and others, 1996).

Most water in the Western Interior Plains aquifer system is saline or brine and is a sodium-chloride type (Jorgensen and others, 1996). Dissolved-solids concentrations of water in the upper aquifer unit range from less than 10,000 mg/L in the transition zone to the freshwater-flow system of the Ozark Plateaus aquifer system and in southeastern Nebraska (fig. 23) to more than 250,000 mg/L in small areas of north-central Oklahoma and south-central Kansas (Jorgensen and others, 1996). The dissolved-solids concentrations of water in the lower aquifer units range from less than 3,000 mg/L in the transition zone to the freshwater-flow system of the Ozark Plateaus aquifer system and in areas of northern and eastern Nebraska (fig. 24) to more than 300,000 mg/L in southwestern Oklahoma. Dissolved-solids concentrations range from 10,000 to 35,000 mg/L in parts of eastern Nebraska, along the Las Animas arch in eastern Colorado, along the Nemaha uplift in northeastern Kansas, and along the Arbuckle uplift in south-central Oklahoma (fig. 24), where the lower aquifer units are close to land surface and receive some recharge (Baker and Leonard, 1995). The large dissolved-solids concentrations in the Western Interior Plains aquifer system are attributed to a paleomarine evaporative brine, slow-moving groundwater and long residence time, and minimal recharge through the overlying confining system (Jorgensen and others, 1996).

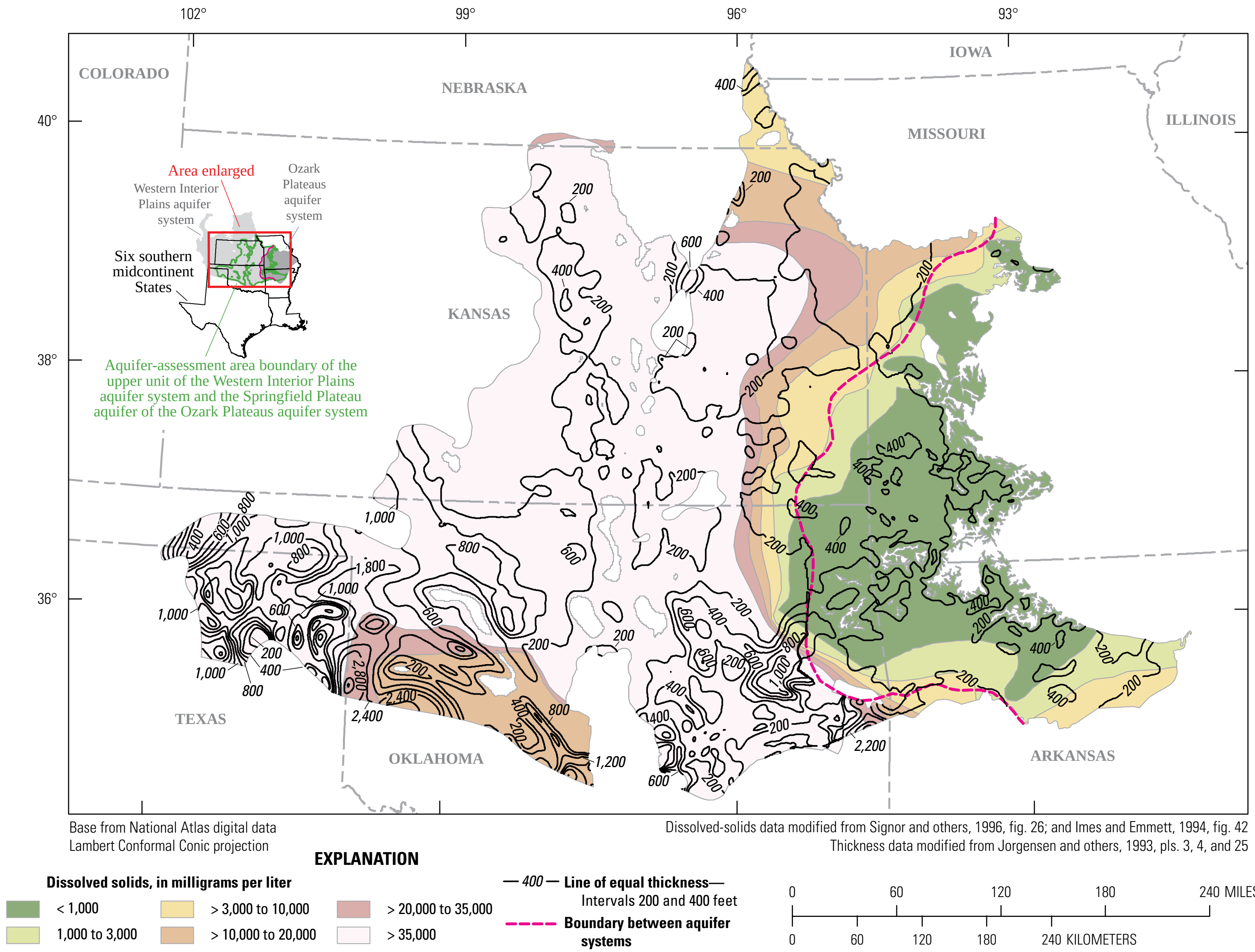

Figure 23. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the upper aquifer unit in the Western Interior Plains aquifer system and the Springfield Plateau aquifer in the Ozark Plateaus aquifer system, Central Midwest regional aquifer system.

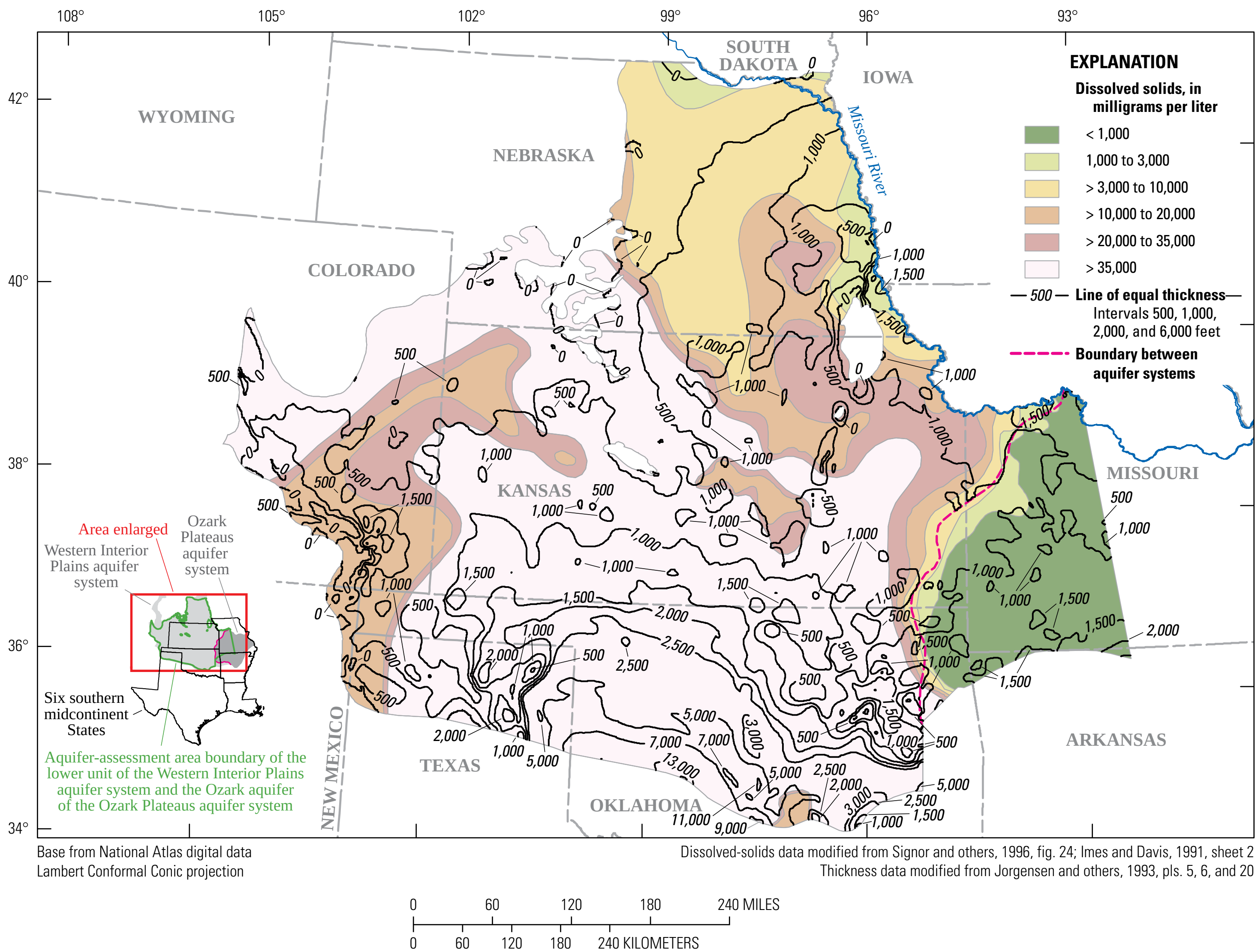

Figure 24. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the lower aquifer units in the Western Interior Plains aquifer system and the Ozark aquifer in the Ozark Plateaus aquifer system, Central Midwest regional aquifer system.

Ozark Plateaus Aquifer System

The Ozark Plateaus aquifer system in the Ozark subregion (fig. 18) is divided into the Springfield Plateau aquifer, Ozark confining unit, Ozark aquifer, St. Francois confining unit, and St. Francois aquifer (table 11) (Signor and others, 1996). The Springfield Plateau aquifer consists of fractured, permeable Mississippian limestone (Jorgensen and others, 1993). The Ozark confining unit underlies the Springfield Plateau aquifer, where it restricts flow between the Springfield Plateau aquifer and the Ozark aquifer (Imes and Emmett, 1994). The Ozark aquifer consists of highly fractured and moderately faulted rocks of Late Cambrian to Middle Devonian age. Lithologies of this aquifer include dolostone, limestone, sandstone, chert, and shale, with dolostone being the dominant rock type. Thickness of the Ozark aquifer generally ranges from about 800 to 1,500 ft (Signor and others, 1996). Underlying the Ozark aquifer is the St. Francois confining unit, which restricts flow between the Ozark aquifer and the St. Francois aquifer at most locations (Jorgensen and others, 1993). The confining unit consists of very slightly permeable shale, siltstone, dolostone, and limestone and ranges in thickness from 0 to 730 ft (Jorgensen and others, 1993). The St. Francois aquifer consists of Upper Cambrian sandstone and dolostone and is generally 200 to 500 ft thick (Jorgensen and others, 1993).

The Springfield Plateau aquifer crops out at the land surface over part of the Ozark subregion and dips into the subsurface along the western and southern boundaries of the subregion, where the aquifer is overlain by the Western Interior Plains confining system (Jorgensen and others, 1993). Recharge to the Ozark Plateaus aquifer system is primarily by infiltration of precipitation that falls on the topographically high aquifer-outcrop areas near the center of the Ozark subregion. Regional groundwater flow is radially outward from the recharge area (Baker and Leonard, 1995).

Concentrations of dissolved solids in the Ozark Plateaus aquifer system generally are less than 500 mg/L but exceed 1,000 mg/L in the transition zone to the saline-water-flow system of the Western Interior Plains aquifer system (figs. 23 and 24) (Baker and Leonard, 1995). Water from the Ozark and St. Francois aquifers is generally a calcium-magnesium-bicarbonate type, caused by dissolution of the predominately dolostone rocks of the Ozark and St. Francois aquifers, and water from the Springfield Plateau aquifer is generally a calcium-bicarbonate type, similar to the composition of the predominately limestone rocks of the Springfield Plateau aquifer (Baker and Leonard, 1995).

Saline-Water Volume of the Central Midwest Regional Aquifer System

Estimated water volume of salinity zones in aquifer-assessment areas of the Great Plains aquifer system is about 8,170 million acre-ft of saline water, of which 6,280 million acre-ft is in the assessment area of the Maha aquifer, and 1,890 million acre-ft is in the assessment area of the Apishapa aquifer (table 12). Estimated water volume of salinity zones in the combined aquifer-assessment areas of the Western Interior Plains and Ozark Plateaus aquifer systems is about 2,660 million acre-ft of saline water, of which 497 million acre-ft is in the assessment area of the upper aquifer unit and the Springfield Plateau aquifer, and 2,160 acre-ft is in the assessment area of the lower aquifer units and the Ozark aquifer (table 13).

Table 12. Estimated water volume of salinity zones in the aquifer-assessment areas of the Maha and Apishapa aquifers in the Great Plains aquifer system, Central Midwest regional aquifer system.

[mg/L, milligrams per liter; values may not sum to totals because of independent rounding]

Salinity zone, dissolved-solids concentration (mg/L)[1]	Area (million acres)	Mean thickness (feet)[2]	Mean porosity fraction[3]	Water volume (million acre-feet)
		Maha aquifer		
1,000–3,000	27	278	0.26	1,950
3,000–10,000	37.6	351	0.24	3,200
10,000–20,000	14.3	329	0.24	1,110
20,000–35,000	1.02	137	0.15	21
TOTAL				6,280
		Apishapa aquifer		
1,000–3,000	17.1	143	0.21	514
3,000–10,000	27.8	175	0.22	1,070
10,000–20,000	8.29	180	0.19	284
20,000–35,000	1.04	149	0.15	23.2
TOTAL				1,890
TOTAL		Great Plains aquifer system		8,170

[1]Determined from dissolved-solids-concentration map (modified from Helgesen and others, 1993, pl. 6).

[2]Computed from thickness maps (modified from Helgesen and others, 1993, pls. 1 and 3).

[3]Computed from porosity map (modified from Signor and others, 1996, fig. 35).

Table 13. Estimated water volume of salinity zones in aquifer-assessment areas of the Western Interior Plains and Ozark Plateaus aquifer systems, Central Midwest regional aquifer system.

[mg/L, milligrams per liter; values may not sum to totals because of independent rounding]

Salinity zone, dissolved-solids concentration (mg/L)[1]	Area (million acres)	Mean thickness (feet)[2]	Mean porosity fraction[3]	Water volume (million acre-feet)
		Upper aquifer unit and Springfield Plateau aquifer		
1,000–3,000	4.77	238	0.08	90.9
3,000–10,000	5.10	190	0.09	87.2
10,000–20,000	6.56	403	0.05	132
20,000–35,000	3.68	725	0.07	187
TOTAL				497
		Lower aquifer units and Ozark aquifer		
1,000–3,000	4.44	753	0.07	234
3,000–10,000	17.5	630	0.06	662
10,000–20,000	18.9	768	0.05	726
20,000–35,000	15.2	702	0.05	534
TOTAL				2,160
TOTAL		Western Interior Plains and Ozark Plateaus aquifer systems		2,660

[1]Determined from dissolved-solids-concentration maps (modified from Imes and Davis, 1991; Imes and Emmett, 1994; Signor and others, 1996).

[2]Thickness of the upper and lower aquifer units were computed by taking the difference between the elevation maps of the aquifers' surfaces (modified from Jorgensen and others, 1993); thickness of the Springfield Plateau and Ozark aquifers were computed from thickness maps (modified from Jorgensen and others, 1996).

[3]Computed from porosity maps (modified from Signor and others, 1996, figs. 23 and 25).

Northern Midwest Regional Aquifer System in Northern Missouri

The Northern Midwest regional aquifer system underlies about 161,000 mi^2 in parts of Illinois, Indiana, Iowa, Minnesota, Missouri, and Wisconsin (Sun and others, 1997), but only the part in northern Missouri was evaluated for this study (fig. 1). The Mississippian aquifer and the Cambrian-Ordovician aquifer, the two major aquifers in the northern Missouri part of the Northern Midwest regional aquifer system, are bounded to the south by the Missouri River and to the east by the Mississippi River (figs. 25–26).

Mississippian Aquifer

The Mississippian aquifer in northern Missouri consists of carbonate rocks of Mississippian age that are approximately age equivalent to those of the Springfield Plateau aquifer in the Ozark Plateaus aquifer system (tables 11 and 14); however, these aquifers are hydraulically separated by the Missouri River (Miller and Appel, 1997). The Keokuk and Burlington Limestones are the primary water-yielding rocks in the Mississippian aquifer (table 14). Both of these rock-stratigraphic units consist of crystalline limestone containing chert nodules (Imes, 1985). Miller and Vandike (1997) estimate the specific yield of the Mississippian aquifer to be 5 percent.

The Mississippian aquifer is unconfined in the eastern and southeastern parts of the aquifer, where the aquifer is exposed at the surface or is overlain by glacial-drift aquifers. The aquifer becomes confined to the northwest, where it is overlain by Pennsylvanian shale and sandstone (Imes, 1985). Recharge to the aquifer is mostly from infiltration of precipitation on the unconfined part of the aquifer. Some recharge is from downward leakage from overlying Pennsylvanian and Mississippian strata and from upward flow from the underlying Cambrian-Ordovician aquifer (Imes, 1985). Regionally, groundwater from the northwest flows either eastward toward the Mississippi River or southwestward toward the Missouri River (Imes, 1985). In the south and southeast, groundwater flows from topographically high recharge areas and discharges to the Mississippi and Missouri Rivers.

Dissolved-solids concentrations are smallest (less than 1,000 mg/L) where the Mississippian aquifer is unconfined in the eastern and southeastern parts of the aquifer (fig. 25) (Imes, 1985). Dissolved-solids concentrations are largest (10,000–20,000 mg/L) in the south-central part of the aquifer (fig. 25) because of upward flow of saline water from the Cambrian-Ordovician aquifer (Imes, 1985).

Cambrian-Ordovician Aquifer

The Cambrian-Ordovician aquifer in northern Missouri consists of several water-yielding sandstones and dolostones (table 14). Some of the rock-stratigraphic units in the aquifer are equivalent to parts of the Ozark aquifer in the Ozark Plateaus aquifer system, but the Missouri River hydraulically separates the aquifers in some places (Miller and Appel, 1997). The Cambrian-Ordovician aquifer extends across northern Missouri, but only the saline waters in the eastern part of the aquifer were evaluated for this report (fig. 26) because the mapped thickness of the aquifer (Miller and Appel, 1997) was available for only the eastern part.

Primary water-bearing rock-stratigraphic units in the Cambrian-Ordovician aquifer are the Roubidoux Formation and the Gasconade, Eminence, and Potosi Dolomites (table 14). Both the Roubidoux Formation and Gasconade Dolomite contain permeable dolostones and sandstones (Imes, 1985). The Eminence and Potosi Dolomites consist of porous and permeable coarse-grained dolostone with solution channels (Imes, 1985). The Cambrian-Ordovician aquifer crops out near the Missouri and Mississippi Rivers in northeastern Missouri (Imes, 1985). The aquifer dips away from the Ozark uplift, to the north and west, where the aquifer becomes confined by younger rocks (Imes, 1985; Young, 1992).

Two groundwater-flow systems are in the Cambrian-Ordovician aquifer: a regional saline-water- flow system and a local freshwater-flow system (Imes, 1985). Groundwater flow in the regional saline-water-flow system is from Iowa into Missouri (Imes, 1985). Some of the saline water flows eastward and passes under the Mississippi River into Illinois, and some of the saline water flows southward to discharge into the Missouri River (Imes, 1985). A local freshwater-flow system in the southeastern part of the aquifer is recharged by infiltration of precipitation where the aquifer crops out along its southern margin and by downward flow of groundwater from overlying Mississippian strata (Imes, 1985).

Dissolved-solids concentrations in the Cambrian-Ordovician aquifer range from about 350 to 750 mg/L in the freshwater-flow system, and the water is a calcium-magnesium-bicarbonate type (Siegel, 1989). Dissolved-solids concentrations exceed 10,000 mg/L in the saline-water-flow system in areas along the Mississippi and Missouri Rivers because of discharge of regional slow-moving groundwater (Young and Siegel, 1992). In most of the saline-water-flow system in northern Missouri, dissolved-solids concentrations are between 1,000 and 10,000 mg/L, and the water is a sodium-mixed anion (no dominant anion) type (Young, 1992). This slightly to moderately saline water is isotopically depleted in oxygen-18 and deuterium isotopes with respect to modern precipitation, an indication that the source of the groundwater was precipitation in a colder climate. The primary source of recharge to this aquifer is thought to have been subglacial meltwater from Pleistocene-age glaciation in north-central Iowa (Siegel, 1989; Young and Siegel, 1992).

The Mississippian and Cambrian-Ordovician aquifers in the Northern Midwest regional aquifer system in northern Missouri contain an estimated 656 million acre-ft of saline water with dissolved-solids concentrations less than 20,000 mg/L (table 15). The assessment area of the Mississippian aquifer contains about 101 million acre-ft of saline groundwater, and the assessment area of the Cambrian-Ordovician aquifer contains about 555 million acre-ft (table 15).

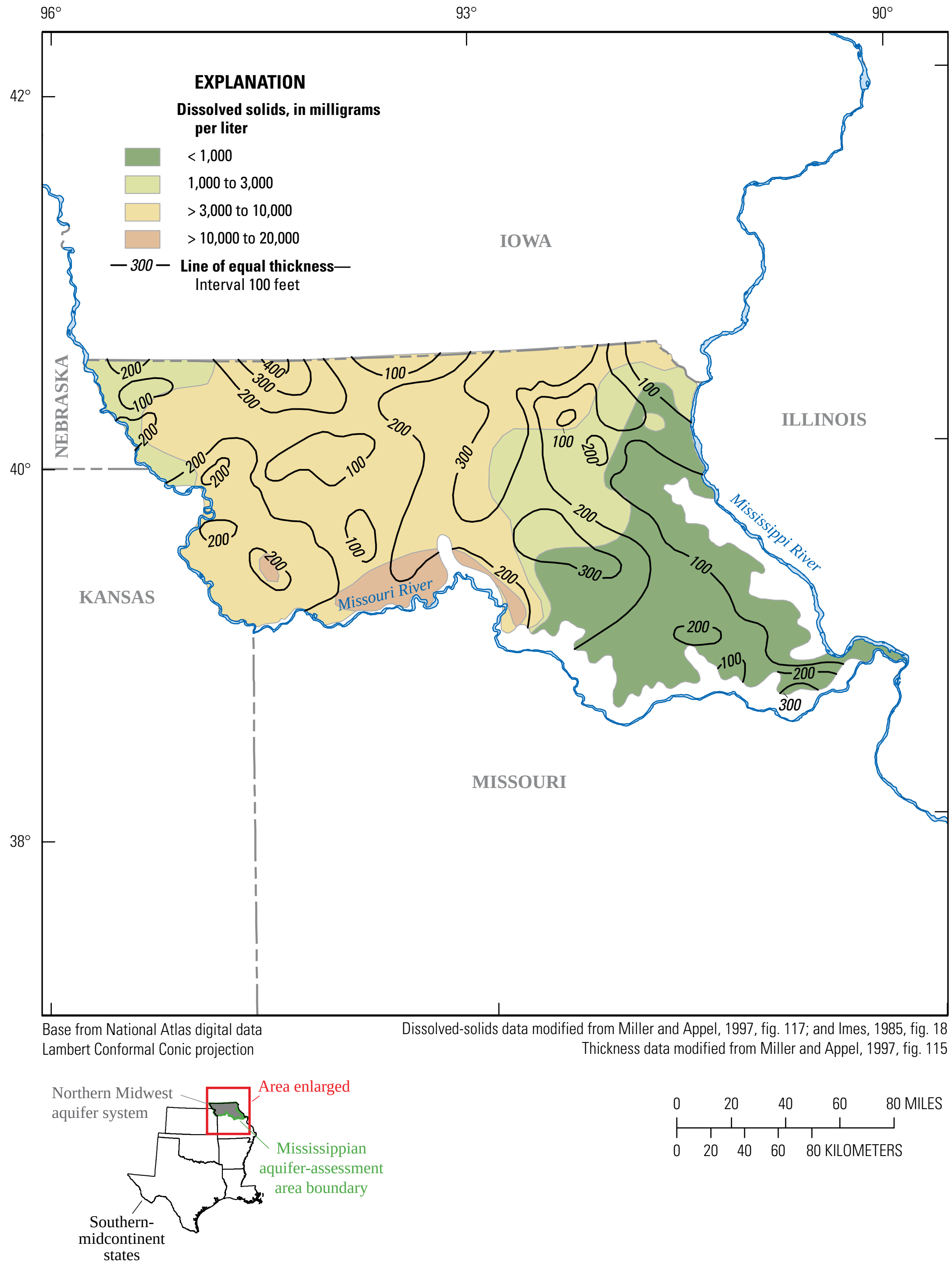

Figure 25. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the Mississippian aquifer in northern Missouri, Northern Midwest regional aquifer system.

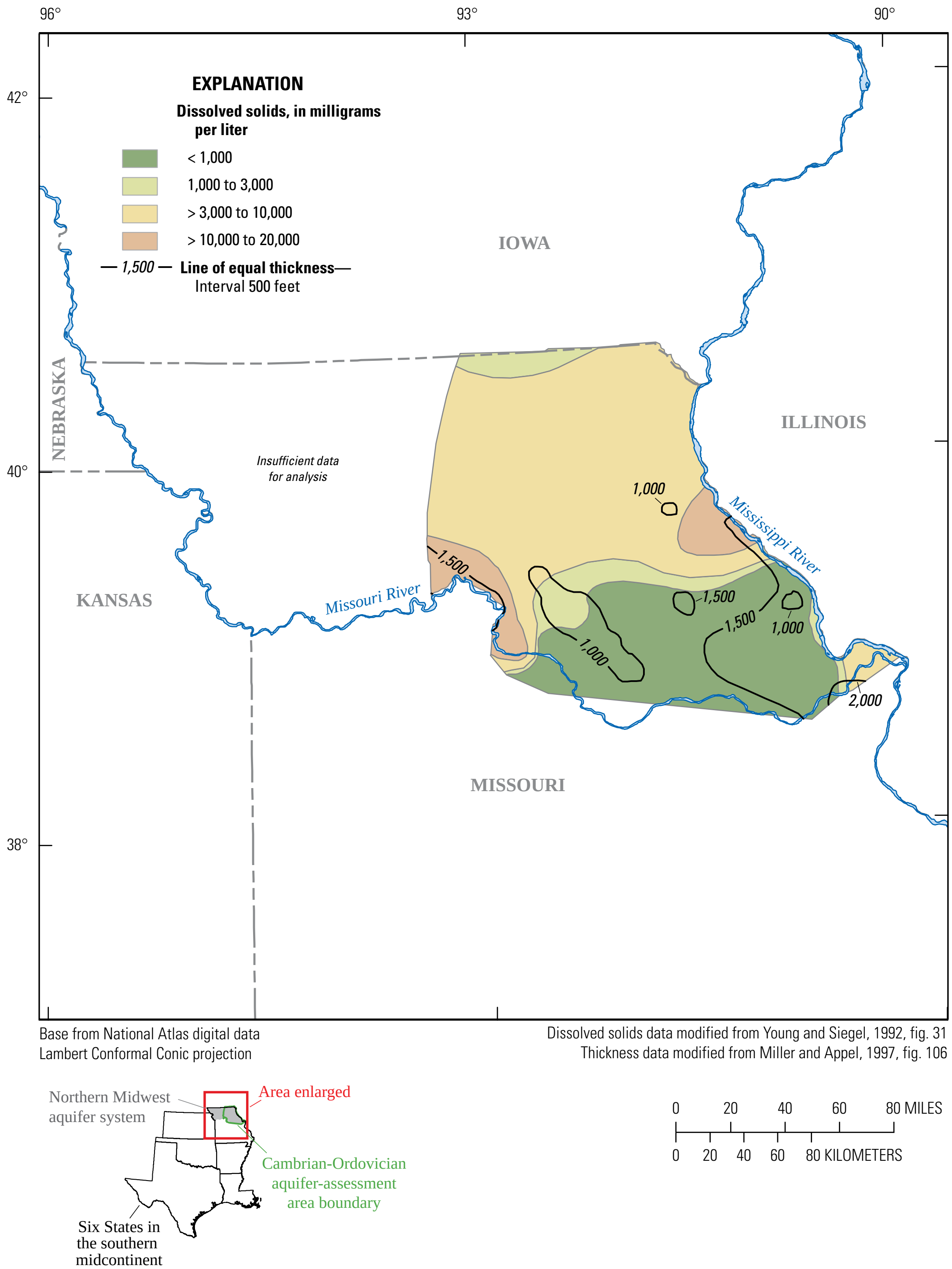

Figure 26. Dissolved-solids concentrations and thickness in the aquifer-assessment area of the Cambrian-Ordovician aquifer in northern Missouri, Northern Midwest regional aquifer system.

Table 14. Time-stratigraphic, rock-stratigraphic, and hydrogeologic units of the Northern Midwest regional aquifer system in northern Missouri.

[Modified from Young, 1992, table 1; Ls, Limestone; Fm, Formation; Ss, Sandstone; Dol, Dolomite]

Time-stratigraphic unit		Rock-stratigraphic unit	Hydrogeologic unit
System	Series		
Quaternary	Holocene	Alluvium	Alluvial aquifer
	Pleistocene	Glacial drift	Drift aquifer
Pennsylvanian	Virgilian Missourian Desmoinesian Atokan Morrowan	Undifferentiated	Confining unit
Mississippian	Chesterian	Undifferentiated	
	Meramecian	Ste. Genevieve Ls, St. Louis Ls, Salem Ls, Warsaw Ls	
	Osagean	Keokuk Ls, Burlington Ls	Mississippian aquifer
	Kinderhookian	Undifferentiated	Confining unit
Devonian	Upper Middle Lower	Undifferentiated	
Silurian	Cayugan Niagaran Alexandrian	Undifferentiated	
Ordovician	Cincinnatian	Maquoketa Shale	
	Mohawkian	Kimmswick Fm, Decorah Fm, Plattin Fm, Joachim Dol	Cambrian-Ordovician aquifer
	Chazyan	St. Peter Ss, Everton Dol	
	Canadian	Roubidoux Fm, Gasconade Dol	
Cambrian	Croixan	Eminence Dol, Potosi Dol, Derby-Doe Run Dol	
		Davis Fm	Confining unit
		Bonneterre Fm	(little information)
		Lamotte Ss	(probable aquifer)
Precambrian		Undifferentiated	Confining unit

Table 15. Estimated water volume of salinity zones in the aquifer-assessment areas of the Mississippian and Cambrian-Ordovician aquifers in northern Missouri, Northern Midwest regional aquifer system.

[mg/L, milligrams per liter; values may not sum to totals because of independent rounding]

Salinity zone, dissolved-solids concentration (mg/L)[1]	Area (million acres)	Mean thickness (feet)[2]	Mean porosity fraction[3]	Water volume (million acre-feet)
Mississippian aquifer				
1,000–3,000	2.28	201	0.05	22.9
3,000–10,000	7.30	202	0.05	73.7
10,000–20,000	0.486	192	0.05	4.67
TOTAL				101
Cambrian-Ordovician aquifer				
1,000–3,000	0.815	1,360	0.07	77.6
3,000–10,000	4.9	1,460	0.06	429
10,000–20,000	0.688	1,420	0.05	48.8
TOTAL				555
TOTAL	Northern Midwest regional aquifer system in northern Missouri			656

[1]Salinity zones for the Mississippian aquifer were determined from dissolved-solids-concentration maps (modified from Imes, 1985; Miller and Appel, 1997); salinity zones for the Cambrian-Ordovician aquifer were determined from dissolved-solids-concentration maps (modified from Young and Siegel, 1992).

[2]Mean thickness of the Mississippian aquifer was computed from thickness maps (modified from Imes, 1985); mean thickness of the Cambrian-Ordovician aquifer was computed from thickness maps (modified from Miller and Appel, 1997).

[3]Mean porosity of the Mississippian aquifer was based on estimated specific yield (Miller and Vandike, 1997); mean porosity of the Cambrian-Ordovician aquifer was estimated from mapped porosities in the lower aquifer units of the Western Interior Plains aquifer system (Signor and others, 1996).

Summary of Saline Groundwater in the Southern Midcontinent

Many of the aquifers in the southern midcontinent are underlain by one or more aquifers, resulting in vertically stacked aquifers. For example, in parts of Kansas and Nebraska, the High Plains regional aquifer system overlies the Great Plains aquifer system, which in turn overlies the Western Interior Plains aquifer system (fig. 19). Another example of stacked aquifers is in parts of Texas, Louisiana, and Mississippi, where permeable zones of the coastal lowlands aquifer system are vertically stacked (fig. 4). Thus, it follows that, in areas with vertically stacked aquifers, groundwaters of varying salinity are also stacked atop each other. The combined extents of slightly to moderately saline waters (dissolved-solids concentrations of 1,000–10,000 mg/L), very saline waters (dissolved-solids concentrations of 10,000–35,000 mg/L), and all saline waters (dissolved-solids concentrations of 1,000–35,000 mg/L) of the aquifers evaluated in this report are shown in figures 27, 28, and 29, respectively. These two-dimensional maps provide a visual representation of the three-dimensional (areal and vertical) distribution of saline groundwater in the southern midcontinent.

The aquifers evaluated in this study contain an estimated 39,900 million acre-ft of saline water, of which about 21,600 million acre-ft is slightly to moderately saline (1,000–10,000 mg/L dissolved solids) and about 18,300 million acre-ft is very saline (10,000–35,000 mg/L dissolved solids) (table 16). The aquifer systems containing the largest volumes of saline water are the coastal lowlands (about 16,300 million acre-ft), Mississippi embayment and Texas coastal uplands (about 12,000 million acre-ft), and Great Plains (about 8,170 million acre-ft) aquifer systems (fig. 30, table 16). Of the 22 aquifers evaluated in this study, the Maha aquifer in the Great Plains aquifer system contains both the largest estimated volume of saline water (about 6,280 million acre-ft) and the largest estimated volume of slightly to moderately saline water (about 5,150 million acre-ft) (fig. 30, table 16).

Figure 27. Extent of slightly to moderately saline groundwater (dissolved-solids concentrations of 1,000–10,000 milligrams per liter) in aquifer-assessment areas of the High Plains, Gulf Coast, Edwards-Trinity, Central Midwest, and Northern Midwest regional aquifer systems.

Figure 28. Extent of very saline groundwater (dissolved-solids concentrations of 10,000–35,000 milligrams per liter) in aquifer-assessment areas of the High Plains, Gulf Coast, Edwards-Trinity, Central Midwest, and Northern Midwest regional aquifer systems.

Figure 29. Extent of saline groundwater (dissolved-solids concentrations of 1,000–35,000 milligrams per liter) in aquifer-assessment areas of the High Plains, Gulf Coast, Edwards-Trinity, Central Midwest, and Northern Midwest regional aquifer systems.

Table 16. Summary of estimated water volume of salinity zones in aquifer-assessment areas of aquifer systems and aquifers in the southern midcontinent and adjacent areas.

[mg/L, milligrams per liter; values may not sum to totals because of independent rounding]

Aquifer system	Aquifer	Water volume (million acre-feet) by salinity zone, dissolved-solids concentration (mg/L)				Total saline water volume (million acre-feet)	
		1,000–3,000	3,000–10,000	10,000–20,000	20,000–35,000	Aquifer	Aquifer system
High Plains	High Plains	34.5	0	0	0	34.5	34.5
Coastal lowlands	Permeable zone A	1,000	1,040	1,070	630	3,740	16,300
	Permeable zone B	833	640	828	2,740	5,040	
	Permeable zone C	565	535	560	902	2,560	
	Permeable zone D	604	1,120	524	769	3,020	
	Permeable zone E	267	559	461	675	1,960	
Mississippi embayment and Texas coastal uplands	Mississippi River Valley alluvial	12.9	0	0	0	12.9	12,000
	Upper Claiborne	345	767	794	578	2,480	
	Middle Claiborne	860	728	870	283	2,740	
	Lower Claiborne-Upper Wilcox	451	344	86.1	65.1	946	
	Middle Wilcox	934	1,040	868	1,860	4,700	
	Lower Wilcox	198	194	334	313	1,040	
	McNairy-Nacatoch	60	14.8	0	0	74.8	
Edwards-Trinity	Edwards	17.1	32.0	0	0	49.1	49.1
Great Plains	Maha	1,950	3,200	1,110	21	6,280	8,170
	Apishapa	514	1,070	284	23.2	1,890	
Western Interior Plains and Ozark Plateaus	Upper aquifer unit and Springfield Plateau	90.9	87.2	132	187	497	2,660
	Lower aquifer units and Ozark	234	662	726	534	2,160	
Mississippian and Cambrian-Ordovician	Mississippian	22.9	73.7	4.67	0	101	656
	Cambrian-Ordovician	77.6	429	48.8	0	555	
TOTAL SALINE WATER VOLUME		9,070	12,500	8,700	9,610	39,900	39,900
TOTAL SALINE WATER VOLUME BY SALINE CLASSIFICATION		21,600 Slightly to moderately saline		18,300 Very saline		39,900 Saline	

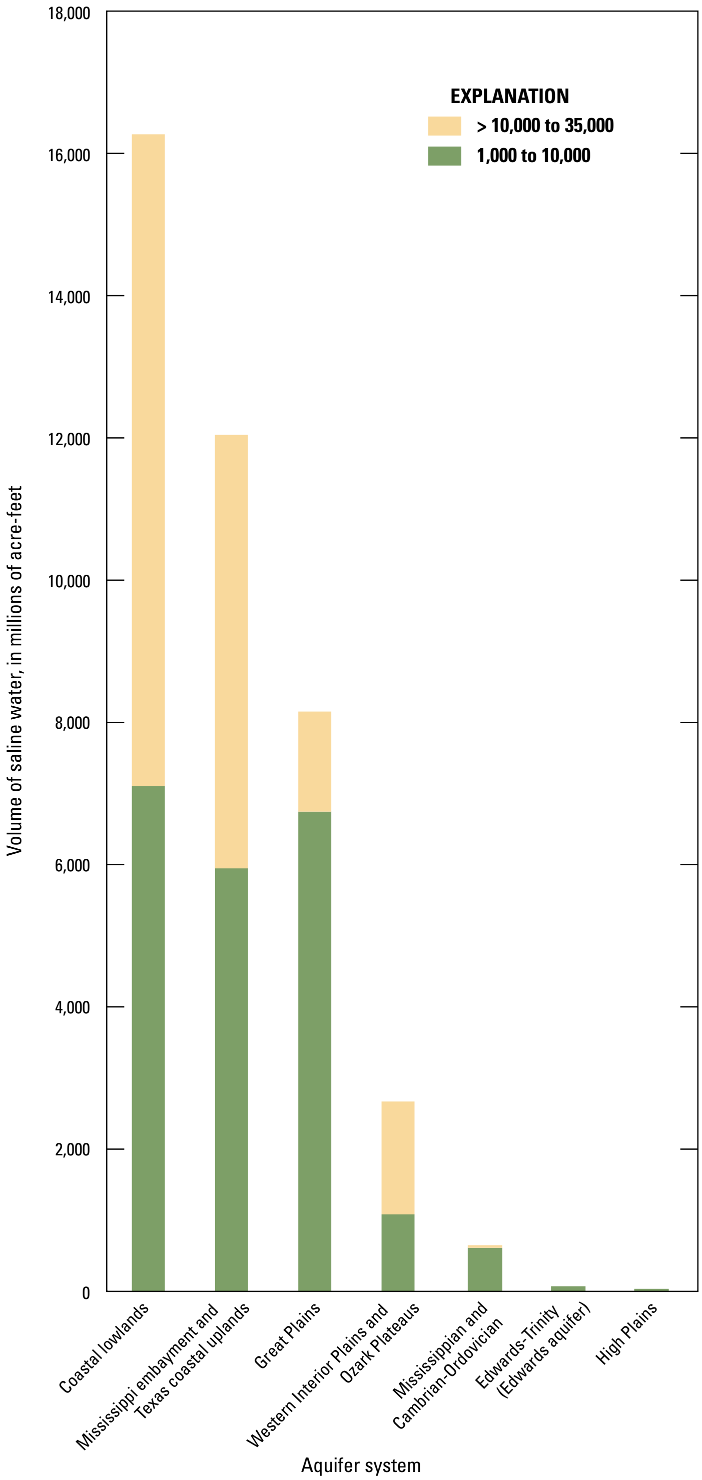

Figure 30. Volume of saline water in aquifer-assessment areas of aquifer systems in the southern midcontinent and adjacent areas.

Summary

Because of increasing demand for freshwater supplies and decreasing costs of desalination, saline groundwater is being considered a source of water that could reduce dependency on freshwater resources. Saline groundwater is known to be present in the southern midcontinent of the United States, but more information about the distribution and volume of saline aquifers is necessary to evaluate and develop saline groundwater resources. The U.S. Geological Survey (USGS) evaluated 22 aquifers in the southern midcontinent to map the distribution of saline groundwater and to compute the volume of saline water in storage.

Saline waters of the 22 aquifers were evaluated by defining salinity zones; digitizing data, primarily from the Regional Aquifer-System Analysis (RASA) Program of the USGS; and computing the volume of saline water in storage. Maps and information from five regional aquifer systems defined by the RASA Program (the High Plains, Gulf Coast, Edwards-Trinity, Central Midwest, and Northern Midwest regional aquifer systems) were used in this report. Twenty-two aquifers containing saline water had sufficient data to be included in this study. These aquifers underlie six States in the southern midcontinent—Arkansas, Kansas, Louisiana, Missouri, Oklahoma, and Texas—and adjacent areas including all or parts of Alabama, Colorado, Florida, Illinois, Kentucky, Mississippi, Nebraska, New Mexico, South Dakota, Tennessee, and Wyoming and some offshore areas of the Gulf of Mexico.

The distribution of saline groundwater in the southern midcontinent is substantially affected by the hydrogeology and groundwater-flow systems of the aquifers. Many of the aquifers in the southern midcontinent are underlain by one or more aquifers, resulting in vertically stacked aquifers containing waters of varying salinity. Saline groundwater is affected by past and present hydrogeologic conditions. Spatial variation of groundwater salinity in the southern midcontinent primarily is controlled by locations of recharge and discharge areas, groundwater-flow paths and residence time, mixing of freshwater and saline water, and interactions with aquifer rock and sediments.

The High Plains aquifer of the High Plains regional aquifer system and the Mississippi River Valley alluvial aquifer of the Gulf Coast regional aquifer system crop out at land surface throughout the extents of these aquifers and thus consist primarily of freshwater. In both of these aquifers, small areas of slightly saline water (1,000–3,000 milligrams per liter [mg/L] dissolved-solids concentrations) are caused by natural upward flow of saline groundwater from underlying geologic units and by pumping of high-capacity wells, which can induce or enhance upward flow of saline water from underlying geologic units.

In aquifers of the Gulf Coast regional aquifer system, dissolved-solids concentrations generally increase from recharge areas along the aquifer outcrops downdip toward the Gulf of Mexico and principal discharge areas. The major processes that affect saline-water chemistry of the Gulf Coast aquifers are water-rock interactions (leaching of soluble salts from the unsaturated zone, alteration of albite and other silicate minerals, cation exchange, and dissolution of evaporites) and mixing of freshwater by the upward flow of saline water from underlying units. Dissolution of halite occurs in areas where salt domes penetrate a permeable zone or aquifer at depths greater than approximately 4,000 feet (ft). Dissolution of halite is minimal at depths less than approximately 4,000 ft because salt domes commonly are sealed by relatively impervious cap rocks.

Water chemistry of the Edwards aquifer is primarily controlled by geologic processes that occurred in late Tertiary time, when the deeply buried aquifer, saturated with brine, was uplifted and faulted. Large volumes of freshwater began to infiltrate the aquifer in the fault zone that previously had been isolated from meteoric conditions, allowing freshwater to mix with older brine and saline water.

Slightly to moderately saline water content of much of the Great Plains aquifer system results from incomplete flushing of original formation water by slow-moving groundwater of this aquifer system. Very saline water in the central and east-central parts of the aquifer system results from upward flow of saline water from underlying salt-bearing strata. Groundwater containing more than 100,000 mg/L dissolved solids in the Nebraska panhandle probably is related to upward flow of brine along faults or fractures from underlying Permian evaporite deposits.

Most water in the Western Interior Plains aquifer system is saline or brine. Large dissolved-solids concentrations, which exceed 300,000 mg/L in southwestern Oklahoma, are attributed to a paleomarine evaporative brine, slow-moving groundwater and long residence time, and minimal recharge through the overlying confining system. Eastward flowing brine in the Western Interior Plains aquifer system converges with westward flowing freshwater in the Ozark Plateaus aquifer system in a broad, topographically low area that extends from northeastern Oklahoma into central Missouri and flows vertically upward to streams or to overlying rock units. Saline water occurs in the shared boundary between the two flow systems of these aquifer systems.

Water in the Mississippian aquifer in northern Missouri ranges from fresh in the eastern and southeastern parts of the aquifer, where the aquifer is unconfined, to very saline in the south-central part of the aquifer because of upward flow of saline water from the underlying Cambrian-Ordovician aquifer. Water in the Cambrian-Ordovician aquifer in northern Missouri is fresh along the southeastern margin of the aquifer, where the aquifer is unconfined. Dissolved-solids concentrations exceed 10,000 mg/L in areas along the Mississippi and Missouri Rivers because of discharge of regional slow-moving groundwater. Most water in the Cambrian-Ordovician aquifer in northern Missouri has dissolved-solids concentrations of 1,000–10,000 mg/L. The source of this slightly to moderately saline water is thought to be subglacial meltwater from Pleistocene glaciation in north-central Iowa.

The volume calculations made for the aquifer-assessment areas in the southern midcontinent indicate that about 39,900 million acre-feet (acre-ft) of saline water is in storage. About 21,600 million acre-ft of the water in storage is slightly to moderately saline (1,000–10,000 mg/L dissolved solids), and about 18,300 million acre-ft is very saline (10,000–35,000 mg/L dissolved solids). The largest volumes of saline water are in the coastal lowlands (about 16,300 million acre-ft), Mississippi embayment and Texas coastal uplands (about 12,000 million acre-ft), and Great Plains (about 8,170 million acre-ft) aquifer systems. Of the 22 aquifers evaluated in this report, the Maha aquifer in the Great Plains aquifer system contains both the largest volume of saline water (about 6,280 million acre-ft) and the largest volume of slightly to moderately saline water (about 5,150 million acre-ft).

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