GEOHYDROLOGY, WATER QUALITY, AND SIMULATION OF GROUND-WATER FLOW AT THE WELDON SPRING CHEMICAL PLANT AND VICINITY, ST. CHARLES COUNTY, MISSOURI, 1987-90

By Michael J. Kleeschulte and Jeffrey L. Imes

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	by	To obtain
	Length	
inch	25.4	millimeter
foot	0.3048	meter
mile	1.609	kilometer
foot per mile	0.1894	meter per kilometer
	Area	
acre	4,047	square meter
square foot	0.09294	square meter
square mile	2.590	square kilometer
	Volume	
acre-foot	1,233	cubic meter
gallons	0.2642	liters
million gallons per day	0.04381	cubic meter per second
	Flow	
foot per second	0.3048	meter per second
cubic foot per second	0.02832	cubic meter per second
cubic foot per second per square mile	0.01903	cubic meter per second per square kilometer
gallon per minute	0.06308	liter per second
mile per hour	1.609	kilometer per hour
	Temperature	
degree Fahrenheit	°C = 5/9 x (°F-32)	degree Celsius
	Specific capacity	
gallon per minute per foot	0.2070	liter per second per meter
	Hydraulic conductivity	
foot per day	0.3048	meter per day
	Transmissivity	
foot squared per day	0.09290	meter squared per day

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

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ABSTRACT

A study was begun during 1987 to better define the geohydrology and water quality as it relates to the low-level radioactive and associated wastes stored at the Weldon Spring chemical plant site, St. Charles County, Missouri. Because of possible contaminant movement, another objective of the study was to gain knowledge about ground-water movement between the shallow and the deeper aquifers underlying the chemical plant.

Analyses of water samples from wells adjacent to pits containing radioactive wastes from plant processing operations (raffinate pits) indicated that water from the pits has entered the ground-water system and is present in the underlying bedrock. The most probable migration route for surface water from the raffinate pit area is downward seepage through unconsolidated surficial materials. On its downward migration, this water reaches zones of greater permeability, such as the residuum layer and weathered top of bedrock, that are capable of more rapidly transporting water to the water table. Water-table gradients and analyses of water samples indicate that one direction of ground-water flow from the chemical plant site is toward the north. Troughs in the top of bedrock between the chemical plant site and Burgermeister spring have potential to channel contaminated ground water to the spring.

Analyses of water samples collected from 26 wells located on the chemical plant site, 2 wells on the U.S. Army property, and 4 wells on the August A. Busch Memorial Wildlife Area contained elevated concentrations of chemical constituents associated with the chemical plant site. Tributaries receiving part of their flow from the chemical plant site are the southeast drainage (tributary 5300), Schote Creek (tributary 6200), including both the west and east tributaries, and tributary 6300. The mainstem of Dardenne Creek has elevated concentrations of uranium (4 micrograms per liter) at County Road N during low-flow periods. These elevated concentrations are thought to be caused by the inflow of water from tributary 6300 into Dardenne Creek. Analysis of water samples from five springs located in tributaries 5300 and 6300 indicated they also receive recharge from the chemical plant site.

A regional three-dimensional ground-water flow model was developed to assess the ground-water flow in the shallow, middle, and deep aquifers. The results of the steady-state model simulation indicate 21 percent of the ground-water flow out of model layer 1 (shallow aquifer) in a small area of the model centered at the chemical plant site has the potential to enter model layer 2 (middle aquifer). Approximately 80 percent of the ground-water flow out of model layer 2 in this same area has the potential to infiltrate into model layer 3 (deep aquifer).

INTRODUCTION

In 1941, the U.S. Department of the Army acquired 17,232 acres surrounding what is currently (1992) the Weldon Spring chemical plant site and operated the site until 1945 as an explosives production facility known as the Weldon Spring ordnance works (hereafter referred to as the ordnance works). The ordnance works was declared surplus to U.S. Army needs in 1946 and ownership of all but about 1,655 acres was transferred. A more detailed description of the history of the original U.S. Army site is given in reports by the International Technology Corporation (1989) and Kleeschulte and Emmett (1986). During 1955, the U.S.

tion of the Weldon Spring uranium feed materials plant (now referred to as the Weldon Spring chemical plant).

The Weldon Spring uranium feed materials plant operated under contract for the U.S. Atomic Energy Commission from 1957 to 1966. The plant processed uranium-ore concentrates and recycled scrap to obtain uranium tetrafluoride, uranium trioxide, and pure uranium metal (Kleeschulte and Emmett, 1987). Some thorium residues also were processed. Radioactive wastes from the operation were pumped as a slurry to four large pits (hereafter called raffinate pits) excavated in glacial till near the plant between 1958 and 1964. The disposal of these wastes in an area where glacial till is underlain by carbonate rocks has created the potential for contamination of surface and ground water.

Data collected by the U.S. Geological Survey between 1984 and 1986 at the chemical plant site (the "phase I" study) confirmed that ground water near the pits is contaminated with products from the uranium processing operation (Kleeschulte and others, 1986). Nitrate as nitrogen concentrations ranging from 53 to 990 milligrams per liter were detected in five monitoring wells near the raffinate pits. Two wells are completed in the glacial till and three wells are completed in the underlying limestone bedrock. In most cases, water from these wells also had elevated concentrations of calcium, magnesium, sodium, sulfate, lithium, strontium, and uranium. The U.S. Department of Energy (MK-Ferguson Company, 1987) stated general low-level nitroaromatic contamination also was present over most of the chemical plant site and raffinate-pits area. The source of the nitroaromatic compounds was the ordnance works.

Because ground-water contamination is known to exist at the Weldon Spring chemical plant (MK-Ferguson Company, 1987), a better understanding of the geohydrology in the vicinity of the chemical plant site was needed to help access the fate of the contaminants. Also several municipalities, public-water-supply districts, mobile-home parks, and subdivisions located in St. Charles County use the bedrock aquifers, especially the deep aquifer, for public-water supply. Because of water use from the deep aquifer in the county, the U.S. Department of Energy was concerned about the potential for water to enter the deep aquifer from directly under the Weldon Spring chemical plant. The phase II study addresses these concerns and was conducted by the U.S. Geological Survey, in cooperation with the U.S. Department of Energy.

Purpose and Scope

This report presents the results of the phase II study at the Weldon Spring chemical plant site. The objectives of the study were to (1) improve the understanding of the geohydrology, (2) collect water-quality data to better define the extent, both areal and vertical, and magnitude of contamination of the water resources in the vicinity of the plant site, and (3) quantitatively assess the ground-water flow system in St. Charles County by using the results of simulations made with a three-dimensional flow model of the system.

This report presents a regional overview of the geologic setting of St. Charles County by describing the regional geologic history and bedrock stratigraphy of the Ozark Plateaus Province. Also included is a description of regional geologic structures in eastern Missouri that affect the regional hydrology of St. Charles County and a detailed description of the geology of the Weldon Spring chemical plant site.

The five geohydrologic units that are significant to the regional ground-water flow in St. Charles County are described. This is followed by a detailed discussion of the geohydrology of the study area, which includes the surface water. Because losing stream reaches and springs are important in understanding the hydrology of the study area, the surface- and ground-water interaction also is discussed.

The data used to define the local water quality were collected between 1985 and 1989 and consisted of more than 360 water-quality samples collected from 58 wells, 19 springs, and 27 surface-water sites between Dardenne Creek and the Missouri River (Kleeschulte and others, 1986; Kleeschulte and Cross, 1990). Expected background water-quality concentrations were calculated by statistical methods.

Water is pumped from the deep aquifer through several public-water-supply wells in St. Charles County. To address the concern about the potential for contaminated water to enter the deep aquifer from directly under the Weldon Spring chemical plant, a regional three-dimensional ground-water flow model (MOD-FLOW) was developed to describe the ground-water flow between the aquifers in St. Charles County.

Description of Study Area

St. Charles County in eastern Missouri (fig. 1) includes two distinctly different physiographic areas. The southern one-third of the county lies on the northern flank of the Salem Plateau, which is a part of the larger Ozark Plateaus physiographic province (Fenneman, 1938). This area is characterized by rugged topography, narrow, irregular drainage divides, and is drained by many short, steep-gradient streams that flow into the Missouri River. An apparent trend for the orientation of the streams in the southern part of the county is approximately N. 30° W. to N. 40° W. The largest stream in this area is Femme Osage Creek. Thin surficial material deposits (typically 0 to 4 feet thick) cover much of this southern part of the county, with the exception of the broader upland area in the southwestern part of the county where these deposits can be more than 16 feet thick (Allen and Ward, 1977).

The northern two-thirds of the county is in the Dissected Till Plains of the Central Lowland physiographic province, which is characterized by moderately to slightly undulating topography covered by glacial drift and loess deposits. Glacial deposits are more than 60 feet thick on broad upland areas in the western part of the county (Allen and Ward, 1977); elsewhere, the deposits typically are thin and dissected. Surface drainage throughout most of the Dissected Till Plains is into the Mississippi River. The Cuivre River, Peruque Creek, and Dardenne Creek are the three largest tributaries in the county to the Mississippi River (fig. 1). Several of the streams in the northern part of the county generally trend between N. 40° to 50° E., with the exception of Peruque Creek and Dardenne Creek.

The Weldon Spring chemical plant site is on a ridge that trends west to east with the land-surface altitude decreasing to the east in the south-central part of St. Charles County. This ridge is a major surface-water divide that separates the drainage basins in the Missouri and Mississippi Rivers and separates the Salem Plateau from the Dissected Till Plains in St. Charles County. Thus, the chemical plant is in a transitional area between the two physiographic provinces.

During the phase II study, 280 square miles that includes most of St. Charles County was investigated; however, the focus for the more intense examination (hereafter referred to as the study area) is the 43-square-mile area that extends south from Dardenne Creek to the Missouri River (fig. 2) and includes the 17,232 acres previously owned by the U.S. Department of the Army from 1941 to 1945. Current (1992) land owners in the study area include the U.S. Department of Energy, which owns the Weldon Spring chemical plant site (fig. 3) and another tract southwest of the chemical plant known as the Weldon Spring quarry, and the Missouri Department of Conservation, which owns two separate tracts known as the August A. Busch Memorial Wildlife Area and the Weldon Spring Wildlife Area. The remaining land is divided between the University of Missouri, the St. Charles County well field, the village of Weldon Spring Heights, St. Charles County Consolidated School District, and the Missouri Highway and Transportation Department.

Climate

The climate of St. Charles County can be summarized as moderate, with an average annual temperature of approximately 55 degrees Fahrenheit. The average monthly temperatures ranged from a low of 29 degrees Fahrenheit in January to a high of 78 degrees Fahrenheit in July. During 1988 the temperature ranged from -5 degrees Fahrenheit to 102 degrees Fahrenheit (National Oceanic and Atmospheric Administration, 1988).

The midcontinent location of St. Charles County is exposed to cold air from the north, dry air from the west, and warm, humid air from the Gulf of Mexico. Wind speeds and direction were recorded at the Weldon Spring chemical plant site during 1985 (Bechtel National, Inc., 1986a). Prevailing winds during the summer and fall were from the south and averaged about 9 miles per hour; during the winter, the winds were from the northwest and west-northwest and averaged about 11 miles per hour.

The mean annual precipitation in the study area is about 35 inches. About 15 inches of the total precip-

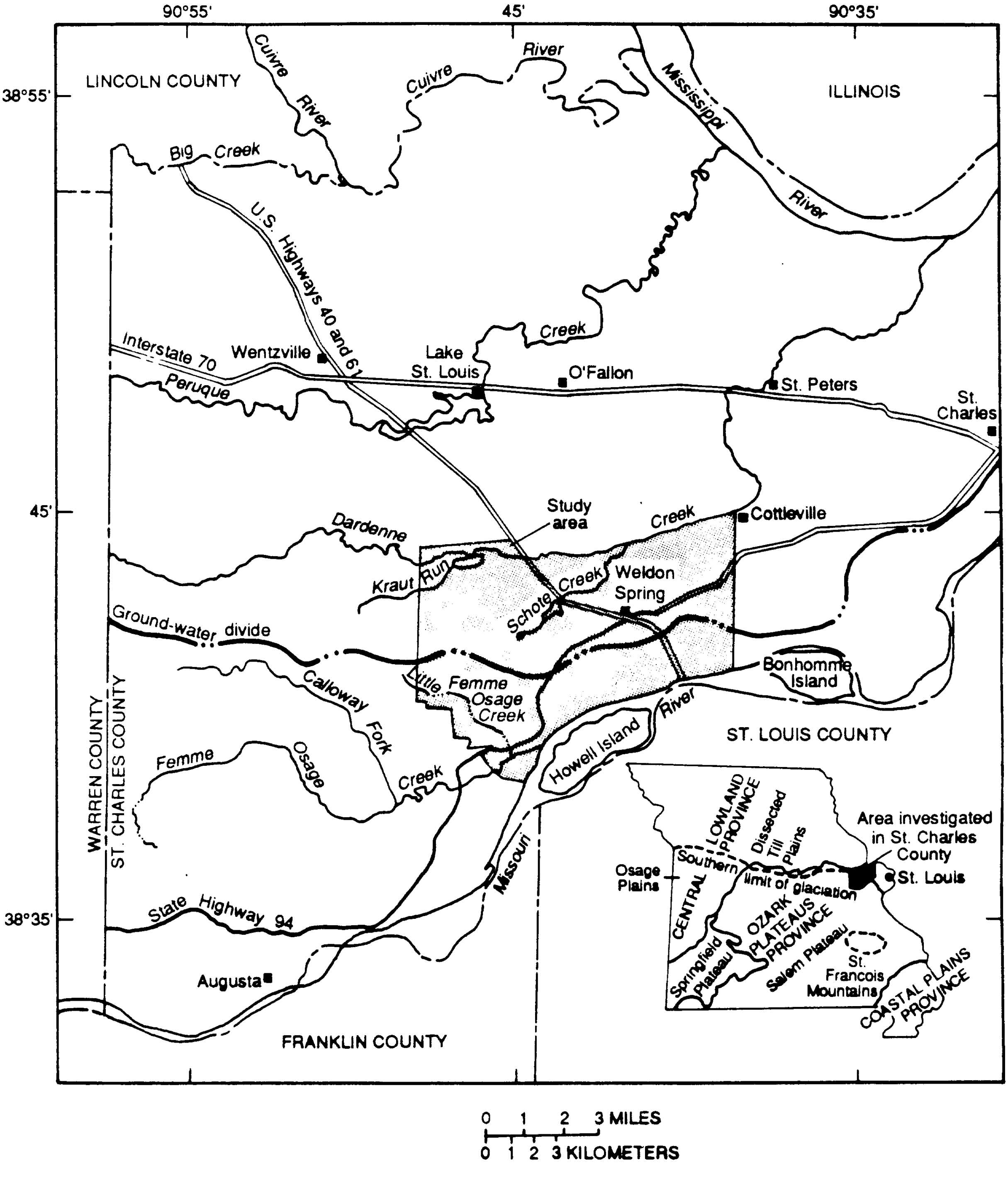


Figure 1. Study area and regional drainage network (physiography from Fenneman, 1938).

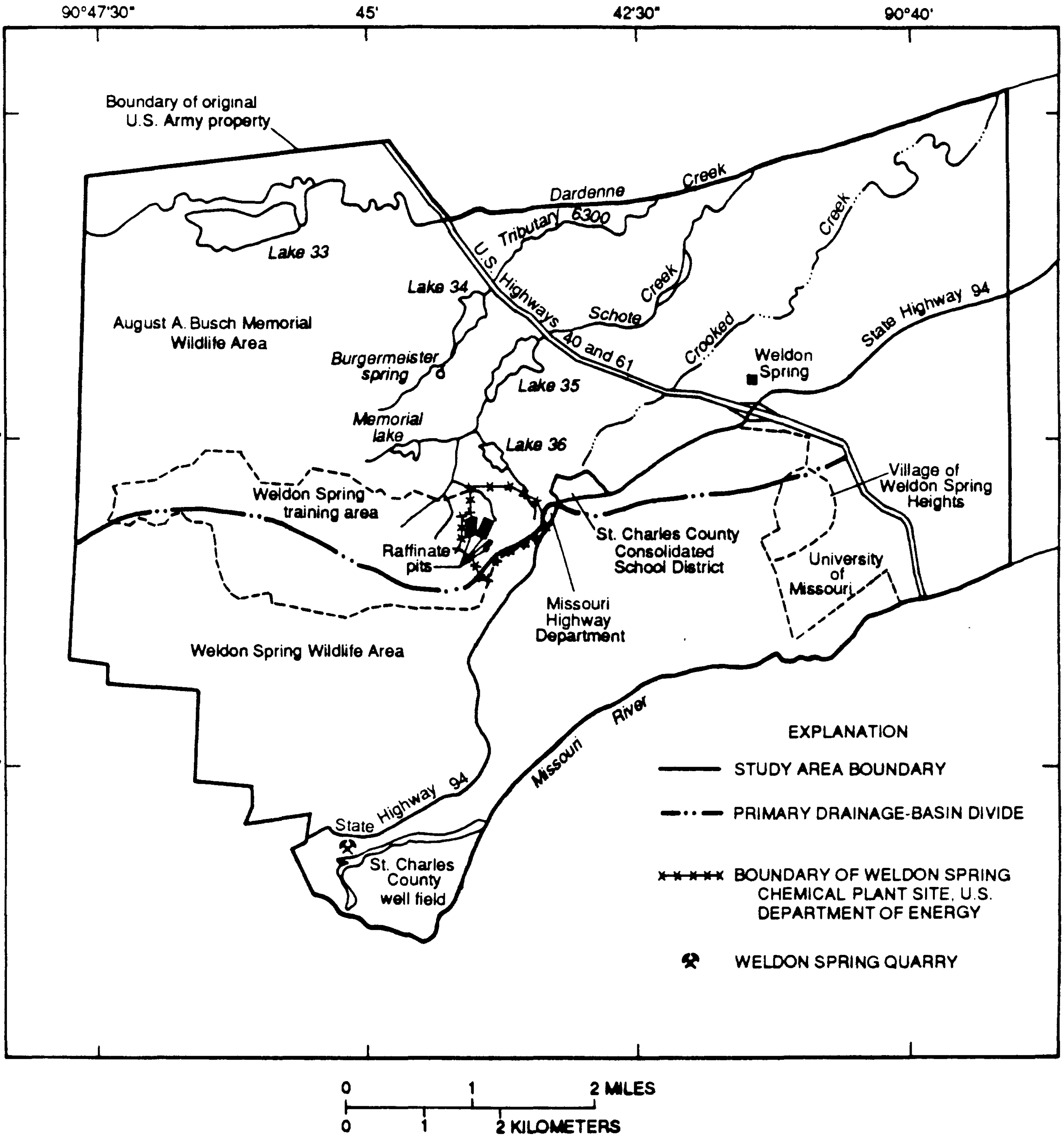


Figure 2. Study area.

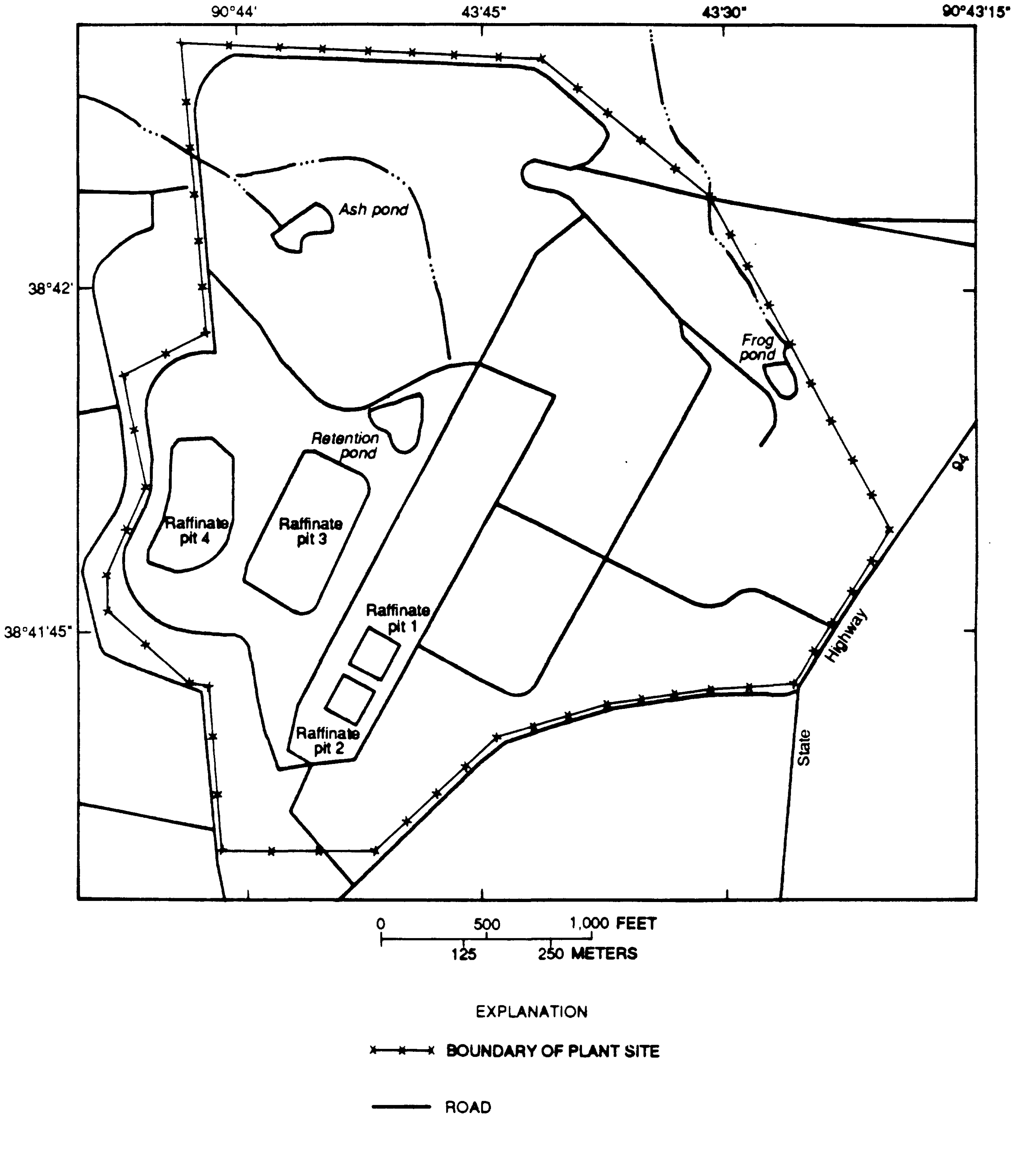


Figure 3. Weldon Spring chemical plant site.

itation normally falls from April through July (National Oceanic and Atmospheric Administration, 1988). December through February normally are the driest months with precipitation totaling about 6 inches. The study area is located in a humid region that has mean monthly relative humidity ranging from 60 to 70 percent (U.S. Department of Interior, 1970).

Site-Location Numbering System

The site-location numbering system used in this study was established by U.S. Department of Energy contractors and Missouri Department of Natural Resources. This system uses a two-letter prefix to identify the type of feature followed by four numbers that provide a unique location identifier. The prefixes are MW for monitoring wells, SP for springs, ST for streams, and SH for swallow holes. The first digit of the four-number unique location identifier, Xnnn, represents a general location and feature type. The 2000-4000 series are numbers reserved for monitoring wells. The 2000 series wells are located in the chemical plant area, the 3000 series wells are located in the raffinate-pits area, and the 4000 series wells are located on vicinity property. The 5000-6000 series are used to describe hydrologic features. The 5000 series indicates a location in the Missouri River basin to the south of the Weldon Spring chemical plant site and the 6000 series indicates a location in the Mississippi River basin to the north (fig. 4). The second digit of the four digit identifying number, nXnn, represents a drainage basin. The numbering begins with the drainage basin at the east end of the original U.S. Army property and increases to the west. The zero hundreds series, n0nn, represents drainage basins out of the area of interest. The last two digits, nnXX, of the identifier are a sequential number assigned to the feature. This provides a unique identification label for each feature (Missouri Department of Natural Resources, 1991).

Acknowledgments

Many individuals contributed to this project by providing assistance, data, or access to their property for sampling or water-level measurements. Although it is not possible to list every person whose contribution has helped this project, the authors especially thank personnel with the Missouri Department of Conservation at the August A. Busch Memorial Wildlife Area for their cooperation, in particular for allowing the installation of several wells and a stream-gaging station on their property, lending equipment, and providing access to their lands for frequent sampling trips. The authors also thank the Missouri Highway and Transportation Department for allowing the installation of a stream-gaging station along the right-of-way of U.S. Highways 40 and 61. Appreciation also is expressed to the U.S. Army for access to their land and data, the Missouri Department of Natural Resources, Division of Geology and Land Survey, and U.S. Department of Energy contractors for access to their data and for their cooperation. The authors particularly thank the managers of Twin Island Lake, Inc., who allowed us to install a stream-gaging station on their property and allowed us access to their wells for sampling. The St. Charles Countians Against Hazardous Waste Committee are thanked for their assistance and for access to their data during the last several years.

GEOHYDROLOGY

A detailed description of the geohydrology of the Weldon Spring chemical plant site is given, but such detail is not available for the entire study area and certainly not for all of St. Charles County. Certain hydrologic features described in detail at the chemical plant site were assumed to be present elsewhere in the study area. When this assumption is made, it is noted in the text.

Geology

The geologic history of the area, which was compiled during a regional study of the Ozarks Plateaus Province, is described by Imes and Emmett (in press). Only the southern part of St. Charles County is in the Ozark Plateaus Province, but this history is pertinent to the study area. The history describes which formations were deposited in a continuous sequence and where unconformities are located. This informa-

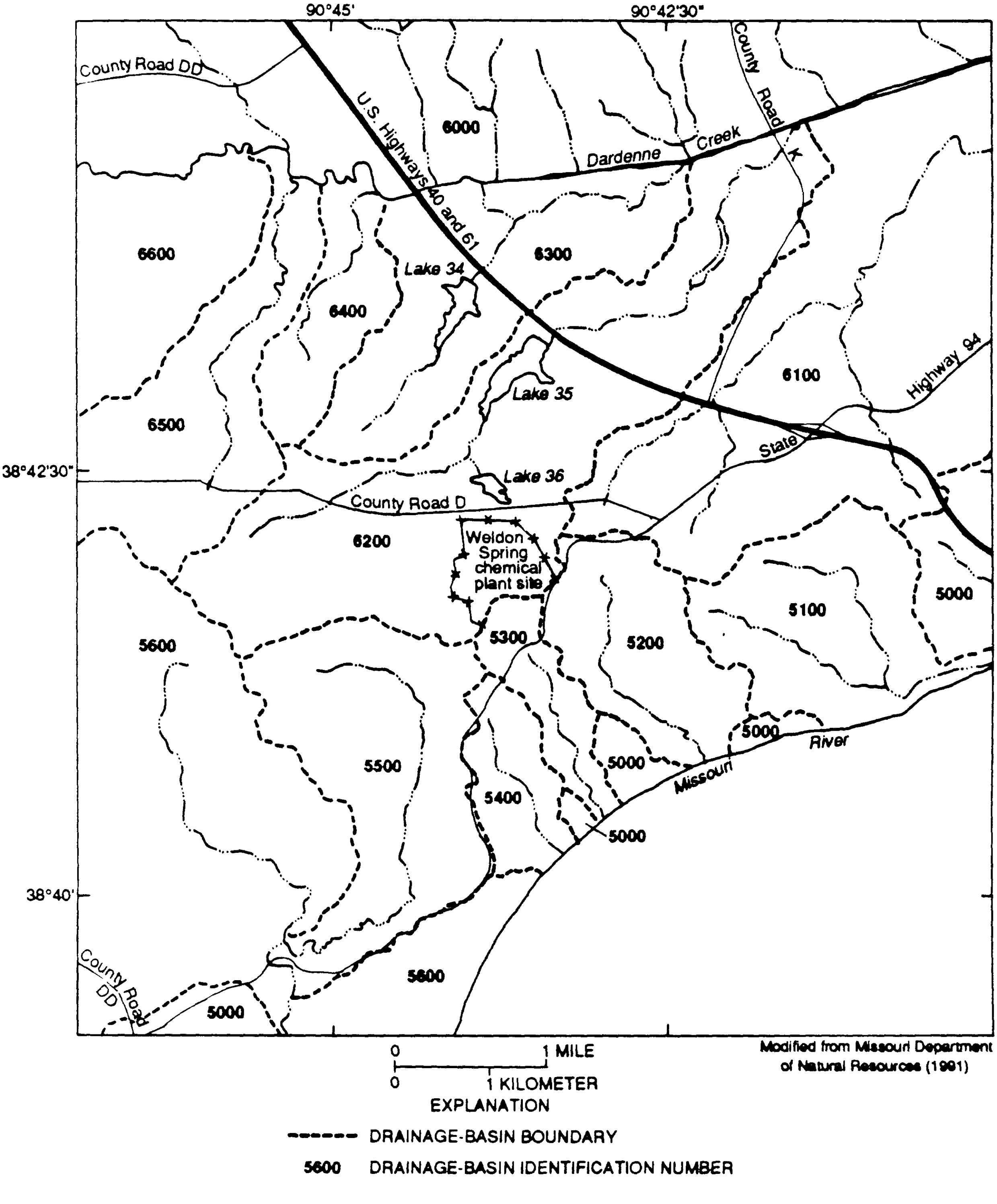


Figure 4. Drainage-basin numbering system.

tion is important because sediments that were deposited in similar environments typically have similar hydrologic properties. The depositional history of each formation was considered when combining formations into aquifers or confining units in the ground-water flow model. Imes and Emmett (in press) obtained much of the history from Gerdemann and Myers (1972) and Kurtz and others (1975). A more detailed discussion of the regional geologic structures of the area can be found in a report by McCracken (1971). Much of the description of the stratigraphy and lithology of eastern Missouri was obtained from Koenig (1961) and the description of the stratigraphy of the Weldon Spring chemical plant site was obtained from U.S. Department of Energy contractors.

Geologic History and Bedrock Stratigraphy of the Area

Geologic formations ranging in age from Holocene (alluvium) to Lower Ordovician (Cotter Dolomite) are exposed in St. Charles County. Consolidated formations primarily are dolostone and limestone, with smaller units of shale and sandstone. A generalized description of these formations, including lithology, is listed in figure 5.

Crystalline rocks of Precambrian age form the foundation on which younger sedimentary rocks were deposited during periods of submergence of the Ozark Plateaus Province (hereafter called the Ozarks). In the western part of the study area, available well data indicate this foundation to be basic igneous rock. To the east of the study area (St. Louis County), granitic rocks were encountered in the subsurface (Koenig, 1961).

During late Cambrian time, the Ozarks slowly subsided and a shallow Cambrian sea formed. The Lamotte Sandstone was the first sediments of Cambrian age to be deposited on the Precambrian basement. The thickness of the Lamotte Sandstone varies throughout the State; in areas where it laps against a Precambrian ridge or knob, the formation is absent, but in depressions between ridges it can be about 500 feet thick. In St. Charles County, the Lamotte Sandstone was logged as being 460 feet thick. This formation is a clean, permeable, well-sorted, quartzose sand. The deposition of the Lamotte Sandstone was followed by the deposition of a calcareous sediment of which the Bonneterre Formation is the oldest unit. Clay and silt were present during the later stages of deposition as evidenced by the increased siltstone and shale content of the Davis Formation and the Derby-Doe Run Dolomites. This increased siltstone and shale content separates the more clastic formations from the formations with a less clastic fraction. A later deposition now is represented by the Potosi and Eminence Dolomites, which ended the Cambrian deposition. At the end of late Cambrian time, the area was uplifted and the sediments were lithified.

The Ozark uplift and other major arches and basins of the midcontinent began to develop at the end of Cambrian and early Ordovician time (Imes and Emmett, in press). The structural features first resulted from subsidence of surrounding basins more than from the uplifting of the Ozark Dome. An unconformity between Cambrian and Ordovician rocks marks the emergence of the Ozark landmass. Submergence of the area in early Ordovician time allowed thick layers of calcareous sediments to be deposited. These sediments became the Gasconade Dolomite, Roubidoux Formation, Jefferson City Dolomite, Cotter Dolomite, and Powell Dolomite. Units where sand is a major component include the Gunter Sandstone member of the Gasconade Dolomite and in localized areas the Roubidoux Formation. A major unconformity marks the end of this depositional period.

The deposition of the St. Peter Sandstone marked the beginning of middle Ordovician time. The Everton Formation has occasionally been identified on well logs in St. Charles County (data on file at the Missouri Division of Geology and Land Survey, Rolla, Missouri); however, if it is present, it is discontinuous and generally thought to be absent north of St. Louis County. The remaining formations that were deposited during the middle Ordovician period are in ascending order: Joachim Dolomite, Plattin Formation, Decorah Formation, and Kimmswick Limestone. Significant quantities of sand, silt, and clay were deposited with the calcareous sediments.

The Maquoketa Shale is the only formation present in the study area representing the late Ordovician period and is present only in the eastern part of St.

System	Series	Stratigraphic unit	Depth from ground level to top of formation	Range of thickness, in feet	Typical thickness, in feet	Lithologic and physical properties	Geohydro-logic unit	Hydrologic properties and remarks
QUATERNARY	HOLOCENE	Alluvium	0	0-65	10-30	Gravelly, silty loam over occasionally gravelly, silty clay loam	Alluvial aquifer	Deposits underlie tributaries to the Missouri and Mississippi Rivers
			0	65-120	100-110	Silty loam, clay, and sand over sand, gravelly sand		Deposits underlying the Missouri and Mississippi River flood plains generally yield large quantities of water to wells (600-2,600 gallons per minute)
	PLEISTOCENE	Loess and glacial drift. Includes the Ferrelview Formation (a)	0	0-150	5-30 30-60	Silty clay, silty loam, clay, or loam over residuum or bedrock, or both	Not considered in this report	Yields little water to wells (25 gallons per minute)
PENNSYLVANIAN	DESMOINESIAN	Undifferentiated	0-120	0-75	b	Partly silty, red shale with purplish-red to light gray clay		Yields small quantities of water to wells (less than 1-10 gallons per minute)
MISSISSIPPIAN	MERAMECIAN	St. Louis Limestone	0-120	0-105	70-75	Limestone; white to light gray, lithographic to crystalline, medium- to thickly bedded; contains some shale		Individually, the rock units yield small to moderate quantities of water to wells (5-10 gallons per minute). Collectively, these units yield sufficient water to supply most domestic and livestock needs
		Salem Formation	0-225	0-140	90-130	Limestone; light gray white, fine to coarsely crystalline, cross-bedded; some siltstone and shale in lower part		
		Warsaw Formation	0-345	0-90	70-90	Calcareous shale and interbedded shaly limestone, grades downward to shaly dolomitic limestone		
	OSAGEAN	Burlington and Keokuk Limestones (undifferentiated)	0-405	0-220	160-200	Limestone; white to bluish-gray, medium- to coarsely crystalline, thickly bedded, cherty	Shallow aquifer	
		Fern Glen Formation	0-500	0-85	50-70	Limestone; yellowish-brown, fine-grained, medium- to thickly bedded; contains appreciable chert		
	KINDERHOOKIAN	Chouteau Group (undifferentiated)	0-580	0-105	50-70	Dolomitic limestone; gray to yellowish-brown, fine-grained, thinly to medium bedded	Upper confining unit	

Figure 5. Generalized stratigraphic column with descriptions of the lithologic and hydrologic properties of the formations present in St. Charles County.

System	Series	Stratigraphic unit	Depth from ground level to top of formation	Range of thickness, in feet	Typical thickness, in feet	Lithologic and physical properties	Geohydro-logic unit	Hydrologic properties and remarks
MISSISSIPPIAN		Bushberg Sandstone	0-625	0-20	5-15	Quartz sandstone; reddish-brown, fine- to medium-grained, friable	Upper confining unit	Yields small to moderate quantities of water to wells (5-50 gallons per minute)
DEVONIAN	UPPER	Lower part of Sulphur Springs Group (undifferentiated)--also includes Glen Park[(a)] and Grassy Creek Formations [(a)]	0-625	0-60	35-40	Calcareous siltstone and sandstone with oolitic limestone with some dark, hard, carbonaceous shale	Upper confining unit	
ORDOVICIAN	UPPER	Maquoketa Shale	0-650	0-75	30-50	Calcareous or dolomitic shale; typically thinly laminated, silty with shaly limestone lenses	Upper confining unit	Yields small quantities of water to wells
ORDOVICIAN	MIDDLE	Kimmswick Limestone	0-710	0-150	90-100	Limestone; white to light gray, coarsely crystalline, medium- to thickly bedded, cherty near base	Middle aquifer	Yields small to moderate quantities of water to wells (10-50 gallons per minute)
ORDOVICIAN	MIDDLE	Decorah Formation	0-810	0-35	30	Interbedded green and yellow shale with thin beds of limestones	Lower confining unit	
ORDOVICIAN	MIDDLE	Plattin Formation	0-840	0-195	100-125	Limestone; light to dark gray, finely crystalline, thinly bedded, weathers to pitted surface	Lower confining unit	
ORDOVICIAN	MIDDLE	Joachim Dolomite	0-950	0-135	90-110	Dolostone; yellowish-brown, silty, thin- to thickly bedded, grades into silt-stone, shales common	Lower confining unit	
ORDOVICIAN	MIDDLE	St. Peter Sandstone Everton Formation (discontinuous)	0-1,070	0-250	120-150	Quartz sandstone; yellowish-white to white, fine- to medium-grained, massively bedded	Deep aquifer	Yields moderate quantities of water to wells (10-140 gallons per minute)
ORDOVICIAN	LOWER	Powell Dolomite	0-950	0-65	50-60	Dolostone; medium to finely crystalline; often sandy, occasionally cherty or shaly	Deep aquifer	Generally yields small quantities of water to wells (less than 10 gallons per minute)
ORDOVICIAN	LOWER	Cotter Dolomite	0-1,250	75-275	200-250	Dolostone; light gray to light brown, medium to finely crystalline, cherty, argillaceous, interbedded with green shale	Deep aquifer	
ORDOVICIAN	LOWER	Jefferson City Dolomite	100-1,500	145-225	160-180	Dolostone; light brown to brown, medium to finely crystalline	Deep aquifer	

Figure 5. Generalized stratigraphic column with descriptions of the lithologic and hydrologic properties of the formations present in St. Charles County--Continued.

System	Series	Stratigraphic unit	Depth from ground level to top of formation	Range of thickness, in feet	Typical thickness, in feet	Lithologic and physical properties	Geohydro-logic unit	Hydrologic properties and remarks
ORDOVICIAN	LOWER	Roubidoux Formation	350-1,700	150-170	150-170	Dolomitic sandstone	Deep aquifer	Yields moderate to large quantities of water to wells (10-300 gallons per minute)
		Gasconade Dolomite	500-1,850	[c] 250 (Gunter Sandstone Member is about 30 feet thick)	b	Cherty dolostone; Gunter Sandstone Member is arenaceous		
CAMBRIAN	UPPER	Eminence Dolomite	750-2,100	[c] 190	b	Dolostone; medium- to massively bedded, light gray, medium- to coarse-grained		Yields moderate to large quantities of water to wells (10-500 gallons per minute) Freshwater only in southwest part of St. Charles County and salinewater elsewhere in county
		Potosi Dolomite	950-2,250	[c] 100	b	Dolostone; massive, thickly bedded, medium- to fine-grained, abundant quartz druse		
		Derby-Doe Run Dolomites [d]	1,050-2,350	[c] 140	b	Dolostone; thinly to medium-bedded alternating with thinly bedded siltstone and shale	Lower (no flow) model boundary	Hydrologic characteristics unknown in St. Charles County. Is a confining unit elsewhere in State
		Davis Formation	1,200-2,500	[c] 170	b	Shale, siltstone, fine-grained sandstone, dolostone, and limestone conglomerate		
		Bonneterre Formation	1,350-2,650	[c] 430	b	Dolostone; typically light gray, medium- to fine-grained, medium-bedded		Yields unknown in St. Charles County; however, water probably is saline
		Lamotte Sandstone	1,800-3,100	[c] 460	b	Predominantly quartzose		
PRECAMBRIAN		Igneous rocks (undifferentiated)	2,200-3,500	b	b	Igneous rocks		Yields no water

[a] Usage of Missouri Division of Geology and Land Survey.
[b] Insufficient data to make estimates.
[c] No range given because of lack of data.
[d] Designated Derby-Doe Run Dolomite by the Missouri Division of Geology and Land Survey.

Figure 5. Generalized stratigraphic column with descriptions of the lithologic and hydrologic properties of the formations present in St. Charles County--Continued.

Charles County (Imes, 1985). This formation is bounded above and below by unconformities.

Devonian sediments were deposited during short periods of land submergence and are unconformable with overlying and underlying strata. The dominant sediments during this period were calcareous with a large clay and silt content. Uplift at the end of the Devonian time resulted in widespread erosion.

At the start of Mississippian time the area again was submerged and deposition of primarily carbonate sediments occurred. At the base of the Mississippian strata, however, a discontinuous sandstone formation, called the Bushberg Sandstone, is present. Whether this formation is Devonian or Mississippian is not clear because of the absence of fossils. Currently (1992), the Missouri Department of Natural Resources recognizes this formation as Mississippian.

Calcareous sediments and clay were later deposited, lithified, and dolomitized, and now form the rocks of the Chouteau Group, which is undifferentiated in this report. These deposits were buried by much thicker deposits of calcareous sediments that now represent the cherty, thickly bedded formations of the Osagean Series and the Meramecian Series. These formations include the Fern Glen Formation, Burlington and Keokuk Limestones, Warsaw Formation, Salem Formation, and the St. Louis Limestone. The unconformity at the top of the St. Louis Limestone marks a period of emergence of the area from the Mississippian sea.

During early Pennsylvanian time, another period of land submergence occurred and clay, silt, and calcareous sediments were deposited; renewed uplift in Middle Pennsylvanian time ended the deposition. Remnants of these deposits are represented by the Pennsylvanian shales and clays on the broad ridge tops in western St. Charles County and on isolated ridge tops in eastern St. Charles County. In southwestern St. Charles County, Pennsylvanian deposits directly overlie Ordovician rocks, in particular, the Kimmswick Limestone, and indicate the effectiveness of post-Mississippian erosion.

Unconsolidated formations in the county are represented by residuum, glacial drift, loess, and alluvial deposits, which are composed of varying particle sizes ranging from clay to boulder. The oldest surficial deposits are residuum. These deposits resulted from the in-situ weathering and decomposition of bedrock. During Pleistocene time, the northwestern part of St. Charles County was covered by glacial ice (Koenig, 1961). The glacial drift in the county is attributed to this event. The glacial drift primarily is a clay till with some sand at depth. Ice sheets from later glaciations are not thought to have entered St. Charles County; however, loess deposits are believed to have been deposited during these later periods. The youngest unconsolidated deposits in the county are the alluvial deposits. This material has been eroded from upland areas or transported into the county by the major rivers.

Geologic Structure

The uplift of the St. Francois Mountains in southeast Missouri and the formation of the Illinois Basin are the two dominant geologic processes affecting the attitude of formations and hydrology in St. Charles County (fig. 6). The consolidated rocks in the county are on the northeast flank of the Ozark uplift. The regional strike of the Ordovician formations in the southwestern part of the county is about N. 45° W. with a dip of about 50 feet per mile to the northeast; further east in the county the strike gradually changes to about N. 20° W. These measurements are based on a structural contour map of the base of the Roubidoux Formation (McCracken, 1971). The structural maps created for this study indicate the same general trend for the Burlington and Keokuk Limestones and older rocks throughout most of St. Charles County.

The asymmetrical Lincoln Fold is about 165 miles long in Missouri and plunges eastward toward the Illinois Basin (McCracken, 1971). The regional strike of the fold is N. 45° W. The extreme eastern end of the fold north of St. Charles County in Lincoln County (fig. 1) trends nearly east-west. The dip of the northeast flank of the Lincoln Fold is gentle, but the dip of the southwest flank is steep. The southwest flank in Lincoln County corresponds to the Cap au Gres Monocline. The steep dips [typically 20 to 70 degrees, but may be vertical (Collinson and Swann, 1958)] along the monocline are caused by horizontal compression or a deep-seated reverse fault that did not reach the surface. However, there is some debate as to whether the

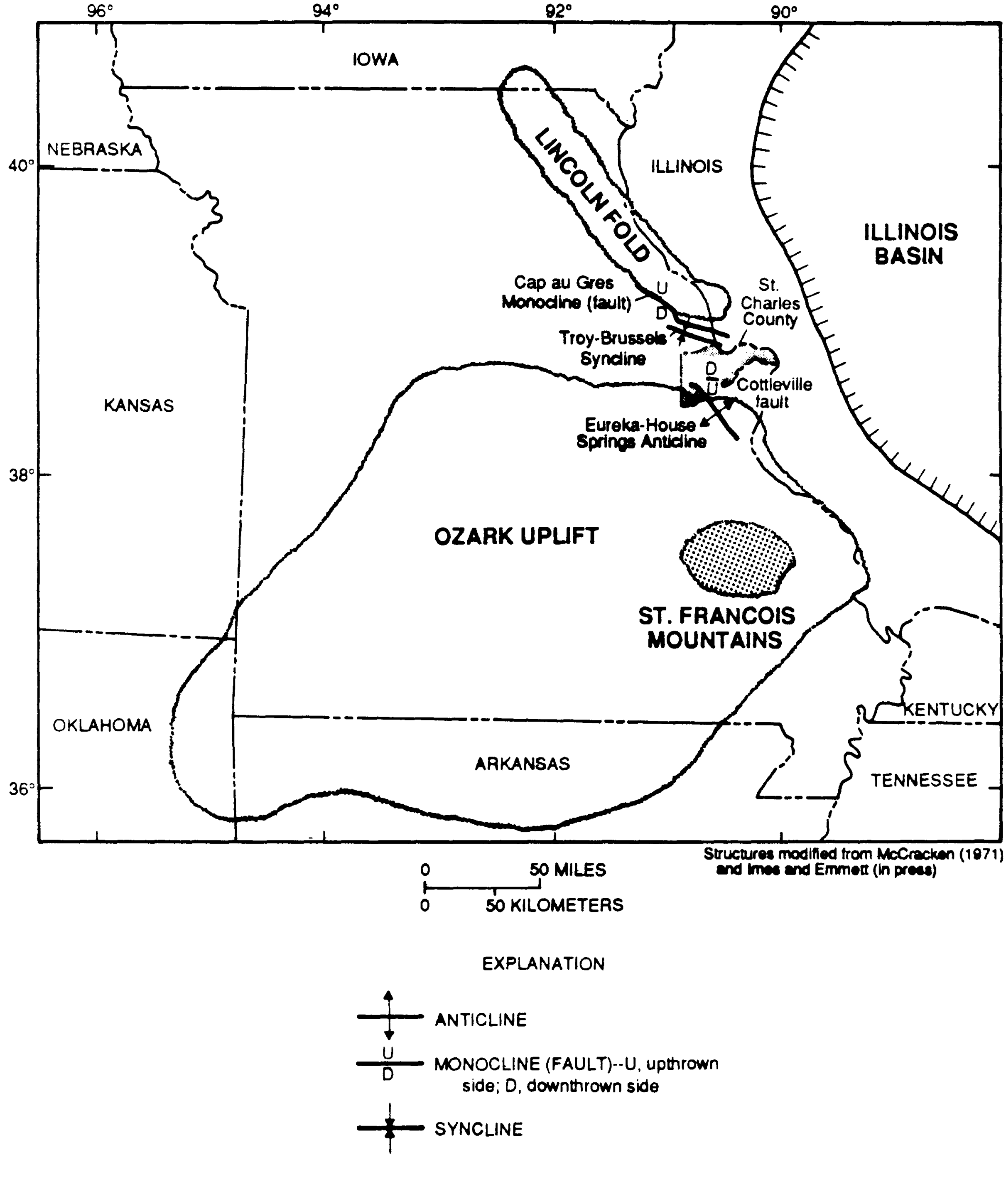


Figure 6. Geologic structures in Missouri and the study area.

structure is a monocline, left lateral fault, or a nearly vertical fault (McCracken, 1971). Where Ordovician rocks are exposed along the crest of the Lincoln Fold and the Cap au Gres Monocline, these structures provide a source of recharge of fresh water into the Cambrian and Ordovician formations.

The Troy-Brussels Syncline is located south of the Cap au Gres Monocline and separates the monocline from the Ozark Uplift. The deepest part of the syncline is adjacent to the Cap au Gres Monocline and the syncline gradually plunges to the east (Collinson and Swann, 1958).

The Eureka-House Springs Anticline [referred to by the Missouri Department of Natural Resources as the Eureka-House Springs structure (Missouri Department of Natural Resources, written commun., 1991)] extends from south of St. Louis County (fig. 1) into St. Charles County (fig. 5). Evidence of the structure can be seen as an outcrop of Ordovician rocks 8 miles west of the Weldon Spring chemical plant site (fig. 2) on Dardenne Creek. This structure, while not especially large, is parallel to the predominant northwest-southeast trend of many other structures within the State (McCracken, 1971).

The Missouri Department of Natural Resources (J.W. Whitfield, oral commun., 1992) mapped an east-west trending fault, referred to as the Cottleville Fault, located about 1 mile north of the chemical plant site. The fault has a maximum vertical displacement of 40 to 60 feet and is described as a normal fault with the north side downthrown. The fault is estimated to have occurred between post-Pennsylvanian and pre-Quaternary time.

Removal of sediments during the post-Mississippian emergence released stress from underlying Mississippian and Ordovician strata throughout the Ozarks, resulting in large fractures and faults aligned approximately N. 55° W. and N. 35° E (Kisvarsanyi and Martin, 1977). Joints in the limestone provide channels for the downward movement of water, which can dissolve the rock and enlarge the channels. Jointing in rocks is common in St. Charles County. The Burlington and Keokuk Limestones, the Chouteau Group, and the Kimmswick Limestone have two distinct sets of joints that generally are vertical: one set ranges from N. 30° to 72° E., the other ranges from N. 30° to 65° W. (Roberts, 1951). Several tributaries of Dardenne Creek trend from N. 40° to 50° E. and seem to have developed along fracture lines or solution channels (V.C. Fishel and C.C. Williams, U.S. Geological Survey, written commun., 1944).

Geology of the Weldon Spring Chemical Plant Site

As part of the site characterization, numerous investigations at the Weldon Spring chemical plant site (hereafter referred to as the site) were conducted to describe the site geology. The following discussion is based on the findings of these investigations. Only the unconsolidated surficial materials and the undifferentiated Burlington and Keokuk Limestones (hereafter referred to as the Burlington and Keokuk Limestones) are described because most of the shallow ground-water flow of interest on the site is restricted to these units.

Unconsolidated surficial materials at the site consist of six units and primarily are clays, silty clays, and clayey silts, with the exception of the residuum. The combined thickness of these units ranges from about 15 to 60 feet. The unconsolidated deposits that include the loess, Ferrelview Formation, clay till, and basal till were a result of Pleistocene glaciation (fig. 5). The uppermost, topsoil-fill unit ranges in thickness from 0 to 30 feet. The topsoil is an organically rich, silty clay, or clayey silt, and has a maximum thickness of 3.5 feet. The fill is thought to be onsite materials that have been moved and recompacted to maintain grade and drainage control and to form dikes. Although not commonly present, loess underlies the fill in places. The loess is a clayey silt to silty clay with a maximum thickness of 11 feet, depending on predepositional topography and post-depositional erosion. The Ferrelview Formation has a maximum thickness of 20 feet and underlies the loess, where present, or the fill material where the loess is absent, and varies from a clay to silty clay. The underlying clay till is similar to the Ferrelview Formation, except that the clay till is a sandy, silty clay and contains pebble-size igneous and metamorphic rocks. It is present throughout most of the site and has a maximum thickness of 30 feet. Beneath the clay till is the basal till unit, which is a sandy, silty clay with angular chert gravel and cobbles. The thickness of the basal till is controlled by the topographic surface on which it was deposited and has a maximum thickness of 11 feet. Generally, it occurs in the western and north-central areas of the site. It is thickest in low areas and absent in topographically high areas (MK-Ferguson Company and Jacobs Engineering Group, 1991).

The residuum is the oldest surficial material on the site and was formed by the in-situ weathering of the Burlington and Keokuk Limestones. The residuum layer is 0 to 26 feet thick (MK-Ferguson Company and Jacobs Engineering Group, 1990b) and generally is thicker in bedrock lows than in other areas (Bechtel National, Inc., 1987). It consists of cobbles and boulders of chert and limestone in a silty, sandy, clay matrix and generally is orange red.

At the site the silty, argillaceous Burlington and Keokuk Limestones are the uppermost bedrock formations. These formations are not differentiated because their contact is difficult to distinguish. Together they are about 100 to 120 feet thick and can be divided into two different hydrologic units based on lithologic and hydrologic properties. The weathered or uppermost unit is extremely to moderately weathered and often has an irregular surface sometimes referred to as pinnacled. This unit also is extremely to moderately fractured, contains solution features ranging from vugs to small cavities as much as 5 feet in diameter, and contains abundant chert. The cavities generally are filled with silt, clay, chert, and gravel mixtures. The dissolutional features and predominant fractures in the weathered unit of the Burlington and Keokuk Limestones seem to be oriented parallel to bedding in the limestone (Bechtel National, Inc., 1987). The weathered unit ranges from 10 to more than 50 feet thick (MK-Ferguson Company and Jacobs Engineering Group, 1990b) and typically is unsaturated onsite. The unweathered or underlying unit is slightly weathered to fresh, thinly to massively bedded, and slightly fractured. Solution features are limited to occasional vugs in the upper part of the unit (Bechtel National, Inc., 1987). There is not a distinct contact separating the weathered unit from the unweathered unit, but instead the contact appears to be gradational.

The top of the weathered unit of the Burlington and Keokuk Limestones onsite has been mapped by U.S. Department of Energy contractors (MK-Ferguson Company and Jacobs Engineering Group, 1990a; fig. 7), but whether the structure was determined by geophysical methods or strictly from borehole core logs is not stated. The altitude of the top of the weathered unit ranges from about 578 to 635 feet above sea level at the site, and the general slope is toward the north. There are several small structures onsite. Contour highs are located north of raffinate pits 3 and 4, just south of raffinate pit 2, and in the eastern part of the site. Two trends of linear depressions or troughs also are apparent on the map; both trend northward. A part of a third depression can be seen near pit 4, which trends to the northwest. These channels have been attributed to differential weathering along joints (MK-Ferguson Company and Jacobs Engineering Group, 1989).

The top of the Burlington and Keokuk Limestones was mapped in most of the study area by Kleeschulte and Emmett (1987). Data for this map came primarily from auger holes. The map was updated on the basis of results of recent drilling in the study area and was redrawn using these new data. The top of bedrock within the site on figure 8 is from figure 7. Two troughs extending northward from the site have formed on the top of bedrock (fig. 8). The head of one trough is on the west side of the site near raffinate pit 4; the other trough is to the north and east of the raffinate pits. The troughs converge north of County Road D, then continue as one trough toward Burgermeister spring. The top of bedrock map also shows a low structure or saddle at the western end of the map.

Hydrology

Two large alluvial aquifers border St. Charles County. The Missouri River alluvium is in the southern part of the county and the Mississippi River alluvium is in the northern part. Although both aquifers are important sources of public-drinking water, neither is discussed in detail in this report because of their minimal effect on the hydrology of the Weldon Spring chemical plant site. Instead, the following section concentrates on five bedrock geohydrologic units.

Regional Geohydrologic Units

For the purposes of this report, geologic formations have been grouped into six separate units based

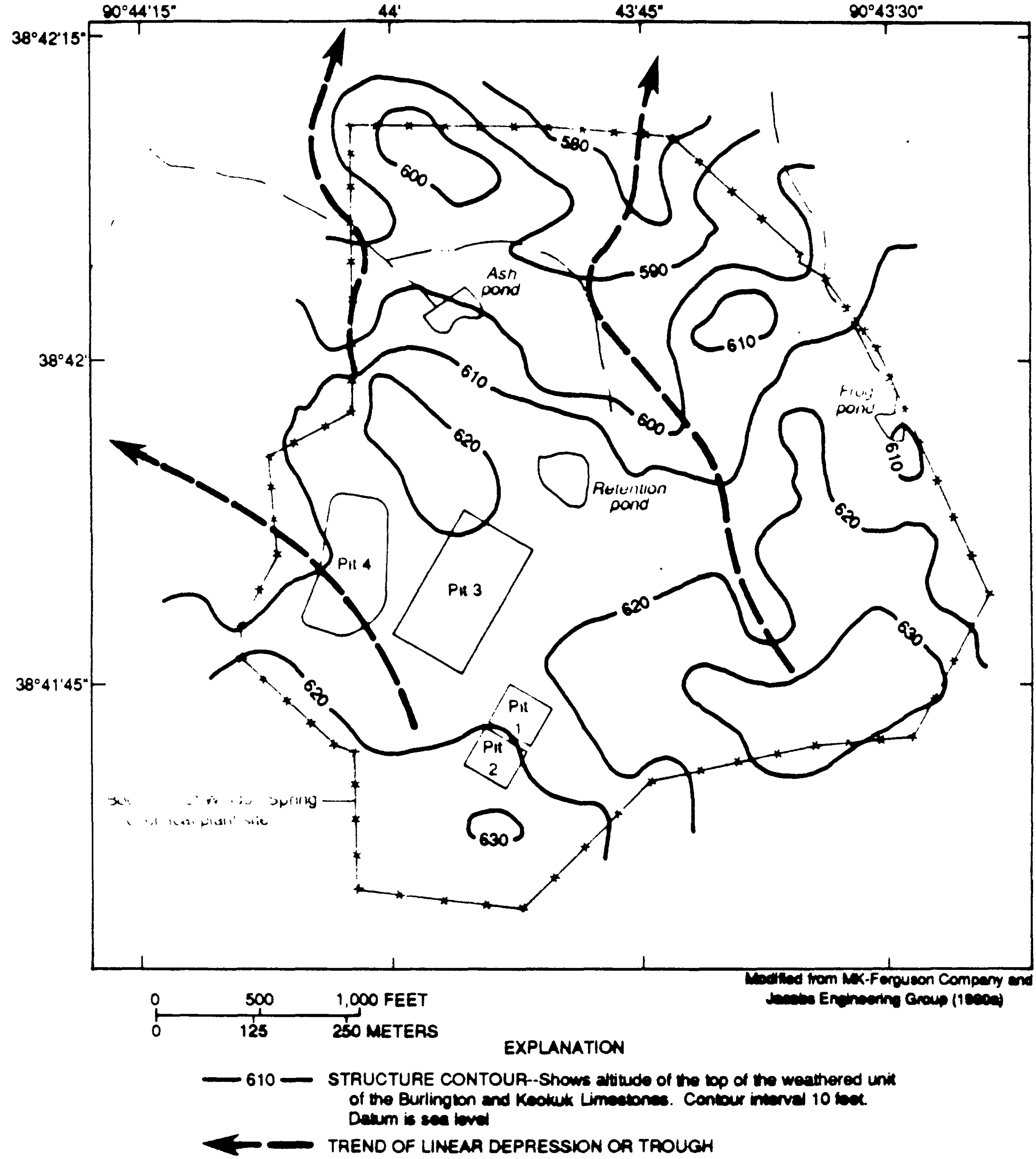
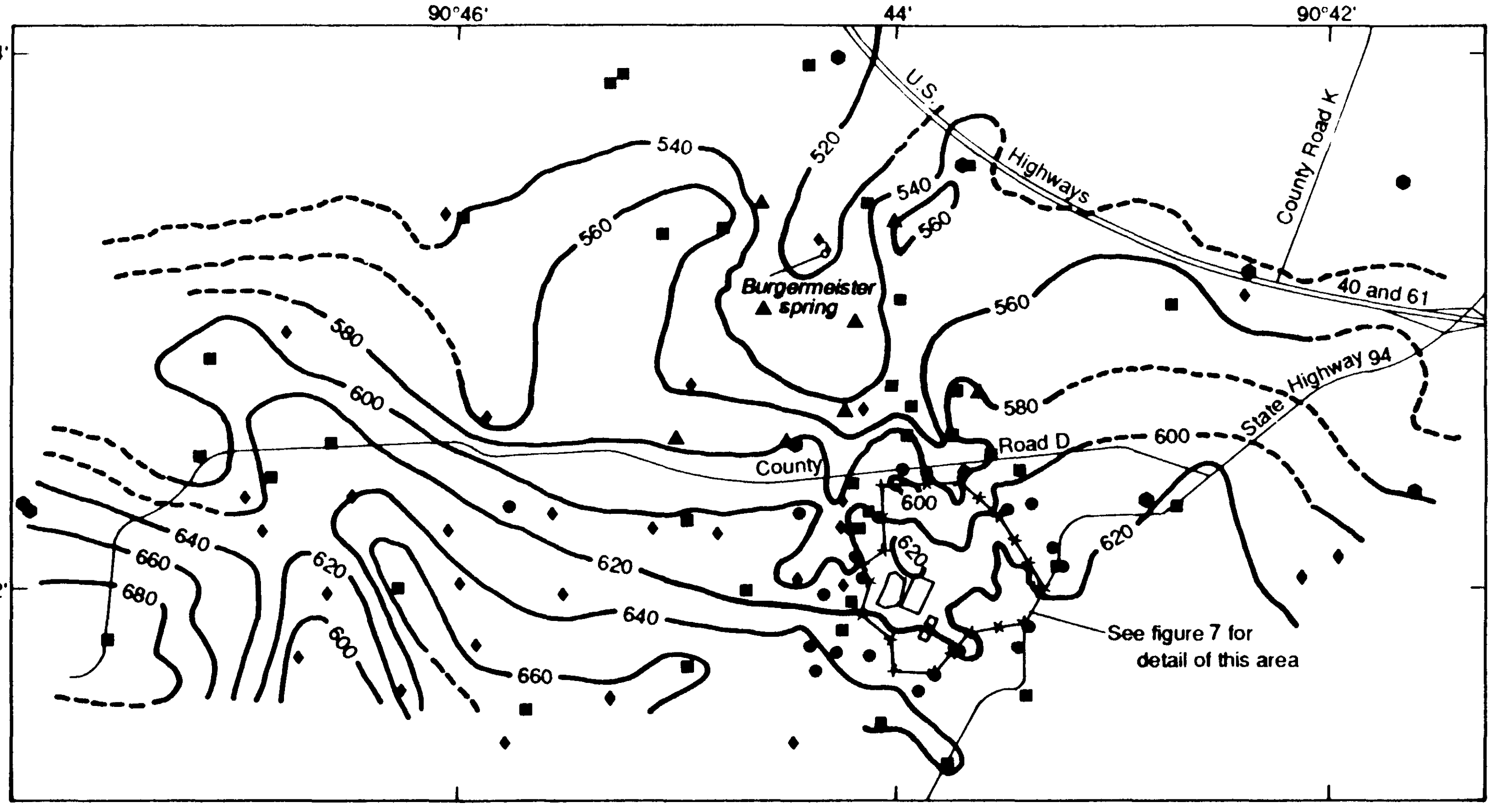


Figure 7. Structure of the top of the weathered unit of the Burlington and Keokuk Limestones at the Weldon Spring chemical plant site.



EXPLANATION

600 — STRUCTURE CONTOUR--Shows altitude of the top of the weathered unit of the Burlington and Keokuk Limestones. Dashed where approximately located. Contour interval 20 feet. Datum is sea level

BOUNDARY OF WELDON SPRING CHEMICAL PLANT SITE

SOURCE OF WELL OR TEST-HOLE DATA

- ▲ U.S. Geological Survey
- ● U.S. Department of Energy
- ⬣ Missouri Department of Natural Resources
- ■ Oak Ridge Associated Universities
- ◆ U.S. Army Corps of Engineers

Figure 8. Structure of the top of the weathered unit of the Burlington and Keokuk Limestones in the vicinity of the Weldon Spring chemical plant site.

on their ability to transmit water. The outcrop area of each unit is shown in figure 9, and a generalized geohydrologic cross section for the area is shown in figure 10. The uppermost unit includes the bedrock formations younger than the Osagean Series of the Mississippian System. This unit is not discussed in detail because the Pennsylvanian formations have limited extent and do not yield water in large quantities. The Mississippian formations younger than the Osagean Series that are thick enough to provide usable quantities of water are present primarily in the eastern part of St. Charles County, where they generally lie beneath the thick alluvial deposits of the Missouri and Mississippi Rivers. The five remaining geohydrologic units are of principal concern and include three aquifers and two confining units.

Shallow aquifer

The rocks that compose the Osagean Series of the Mississippian System form the shallow aquifer in the study area. The Burlington and Keokuk Limestones, the primary formation of the aquifer, is medium to coarsely crystalline and thickly bedded, and contains varying quantities of chert. The Fern Glen Formation, where present, is a cherty fine-grained limestone and also is included in the shallow aquifer. Well-developed solution channels are common in the aquifer. Linebach (1977) reports that the karst topography of eastern Missouri was developed before the Pennsylvanian formations were deposited based on the numerous approximately circular depressions that contain basal Pennsylvanian sediment. The weathered unit in the upper Burlington and Keokuk Limestones described for the site probably is present throughout much of the county because of the presence of numerous springs and caves (Missouri Department of Natural Resources, 1986).

In the southwestern part of the county the shallow aquifer has been eroded completely; where the aquifer is present, its thickness ranges from less than 100 feet in the southern part of the county to more than 300 feet in eastern St. Charles County (fig. 11), where the aquifer lies beneath alluvium. In the eastern two-thirds of St. Charles County, the aquifer typically is more than 200 feet thick. The top of the shallow aquifer dips to the northeast, and the altitude of the top ranges from more than 700 feet in the southern part of the county to approximately 20 feet in eastern St. Charles County (fig. 12).

Water recharges the shallow aquifer by inflow into the county from the west and by direct recharge from precipitation in areas where the aquifer is exposed or the surficial deposits overlying the aquifer are thin. In most of St. Charles County, however, the aquifer is covered by surficial materials that are deposits of glacial origin (fig. 13); in places, these deposits are more than 60 feet thick (Allen and Ward, 1977). In the western part of the county, rocks of the shallow aquifer are overlain by Pennsylvanian formations. In the northern part of the county, Mississippian formations younger than those of the shallow aquifer crop out. In these areas the recharge that enters the shallow aquifer depends on the permeability of the overlying formations or surficial materials. Typically, the permeability of the surficial materials and Pennsylvanian formations is much less than the shallow aquifer.

Water-level measurements made in the study area indicate the potentiometric surface of the shallow aquifer is controlled by topographic highs and the larger streams in the county (fig. 14). The most prominent ground-water divide is on the ridge that also is a surface-water divide for the Missouri and Mississippi River Basins. From the divide, part of the water flows to the north and is intercepted by Dardenne Creek; water that flows to the south ultimately discharges into the Missouri River. Another ground-water divide occurs between Dardenne Creek and Peruque Creek. The regional ground-water flow direction across the county is toward the east (Imes, 1985); however, this trend is masked by the local effects caused by topography and the presence of large streams. The aquifer may be dewatered in the extreme southwestern part of its extent (fig. 12) where it occurs in upland areas and directly overlies Ordovician rocks.

The Missouri Division of Geology and Land Survey reports that water from the shallow aquifer in St. Charles County ranged from a calcium magnesium bicarbonate type to a sodium sulfate, sodium bicarbonate, or a sodium chloride type. Water with large sulfate concentrations is limited to the area underlain by Penn-

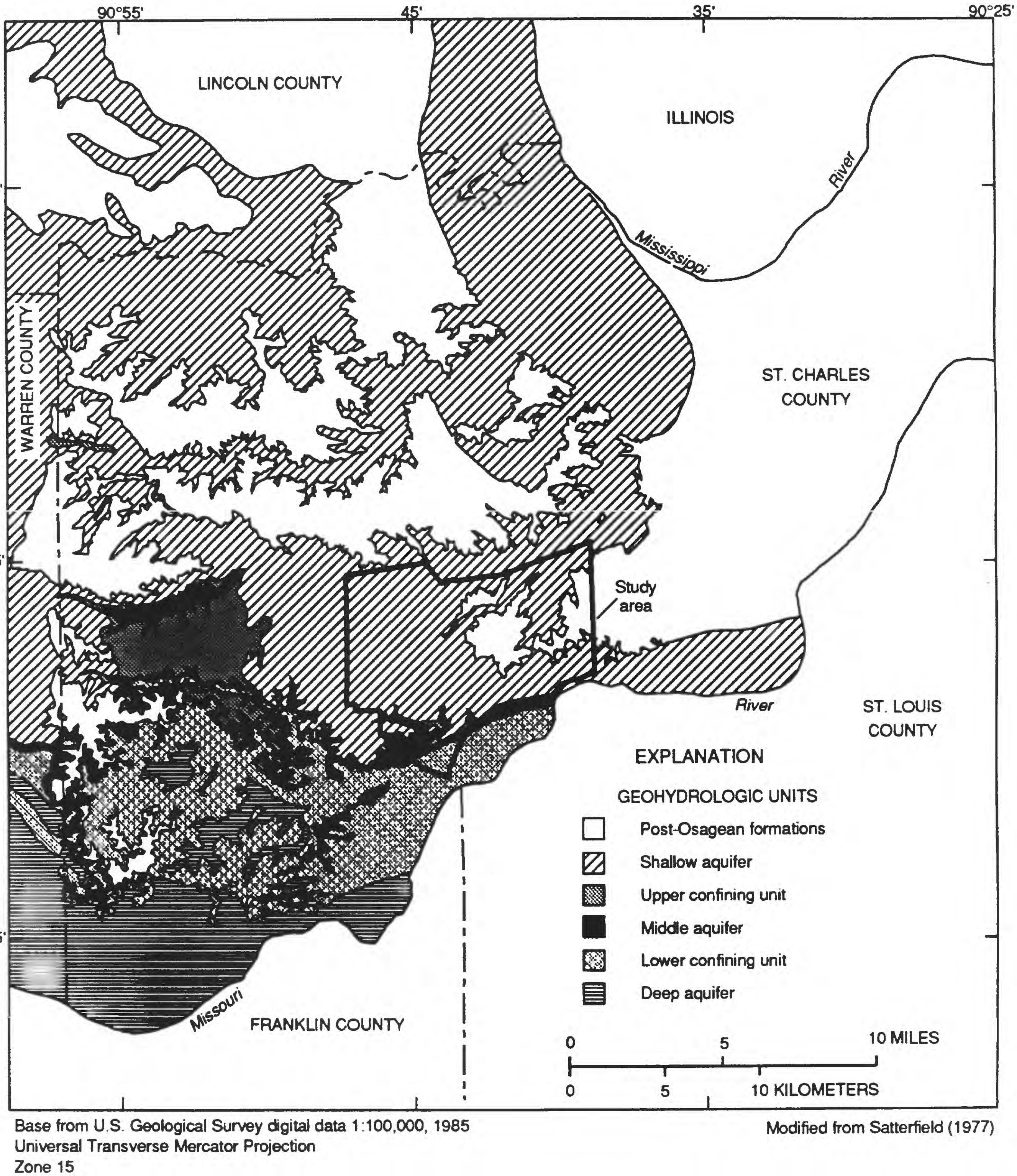


Figure 9. Geohydrologic units in the study area.

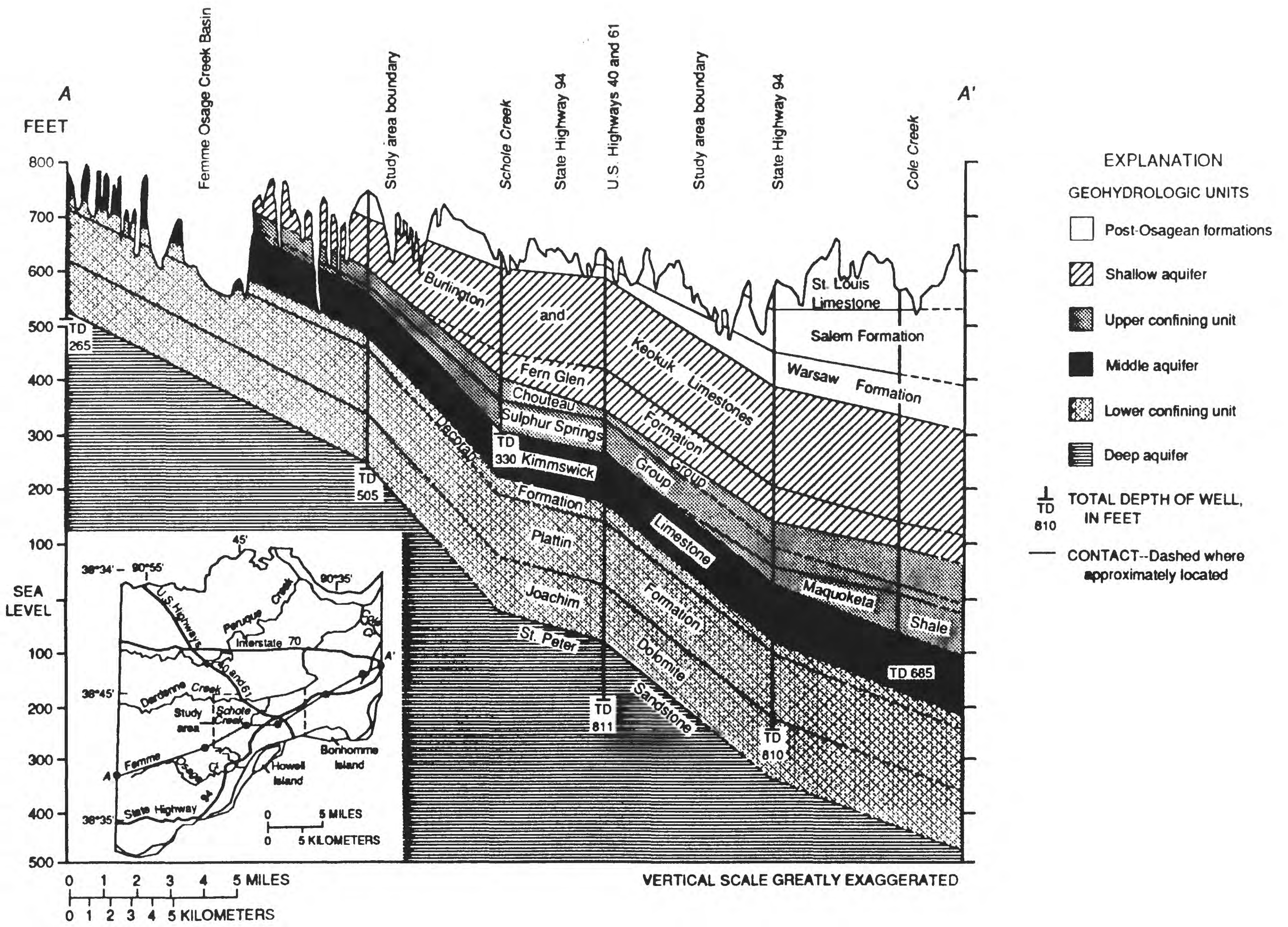
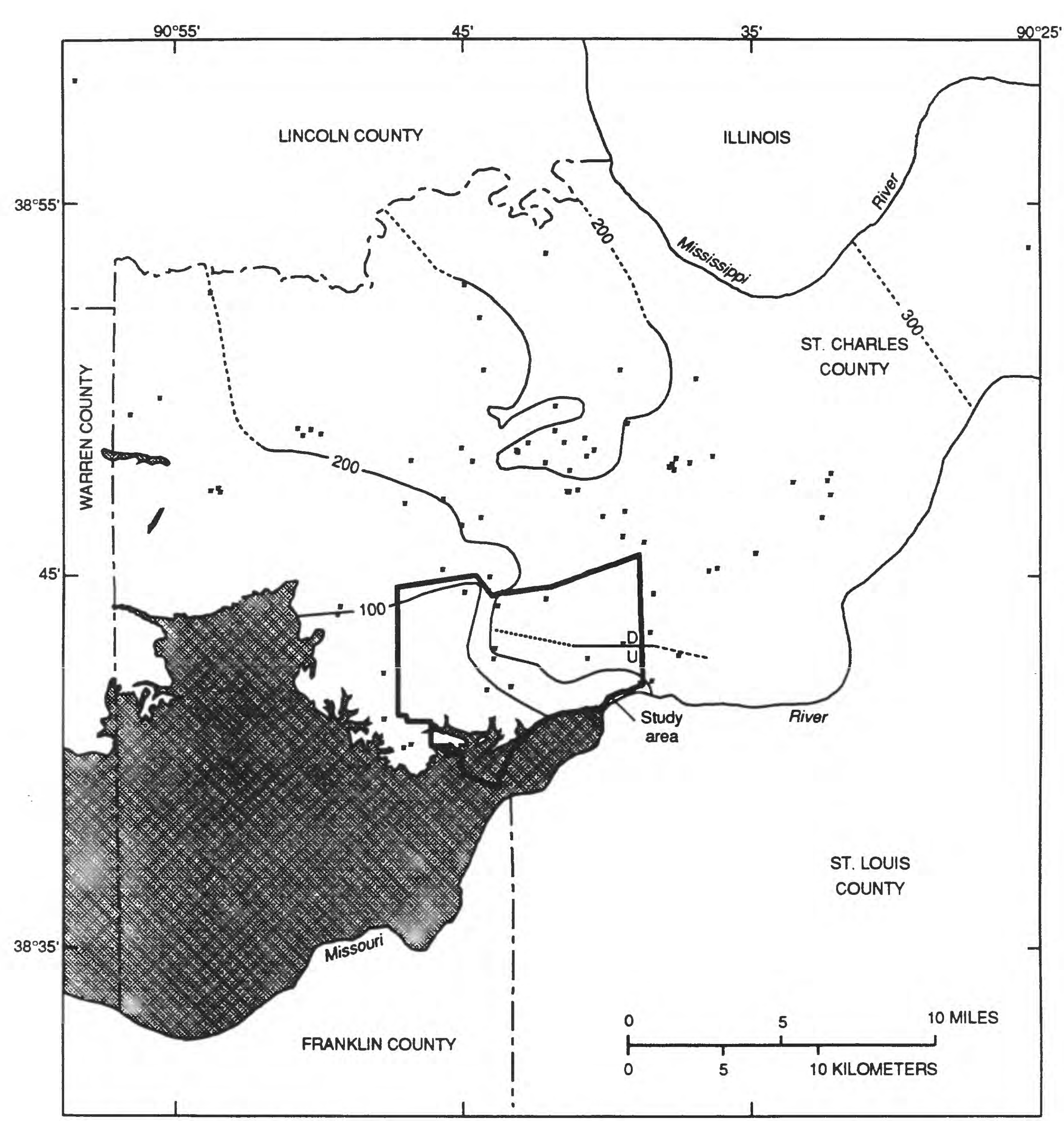


Figure 10. Geohydrologic section of the southern part of the study area.



Base from U.S. Geological Survey digital data
1:100,000, 1985
Universal Transverse Mercator Projection
Zone 15

EXPLANATION

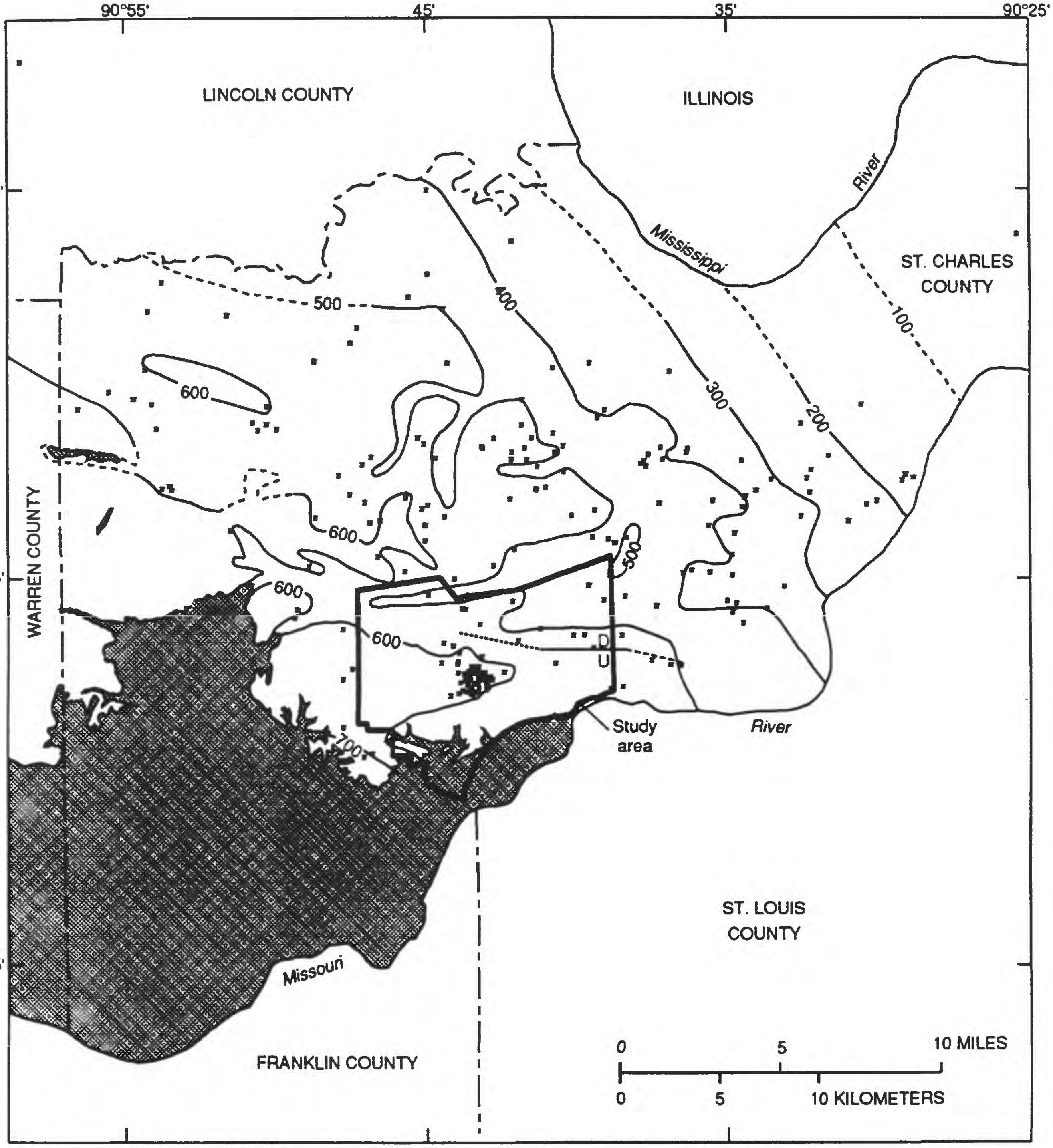
AREA WHERE SHALLOW AQUIFER IS ABSENT

— 200 - - LINE OF EQUAL THICKNESS OF SHALLOW AQUIFER--
Dashed where approximately located. Interval 100 feet

D/U COTTLEVILLE FAULT--D, downthrown side; U, upthrown side; dashed where inferred; dotted where postulated

▪ CONTROL POINT

Figure 11. Thickness of the shallow aquifer.



Base from U.S. Geological Survey digital data
1:100,000, 1985
Universal Transverse Mercator Projection
Zone 15

EXPLANATION

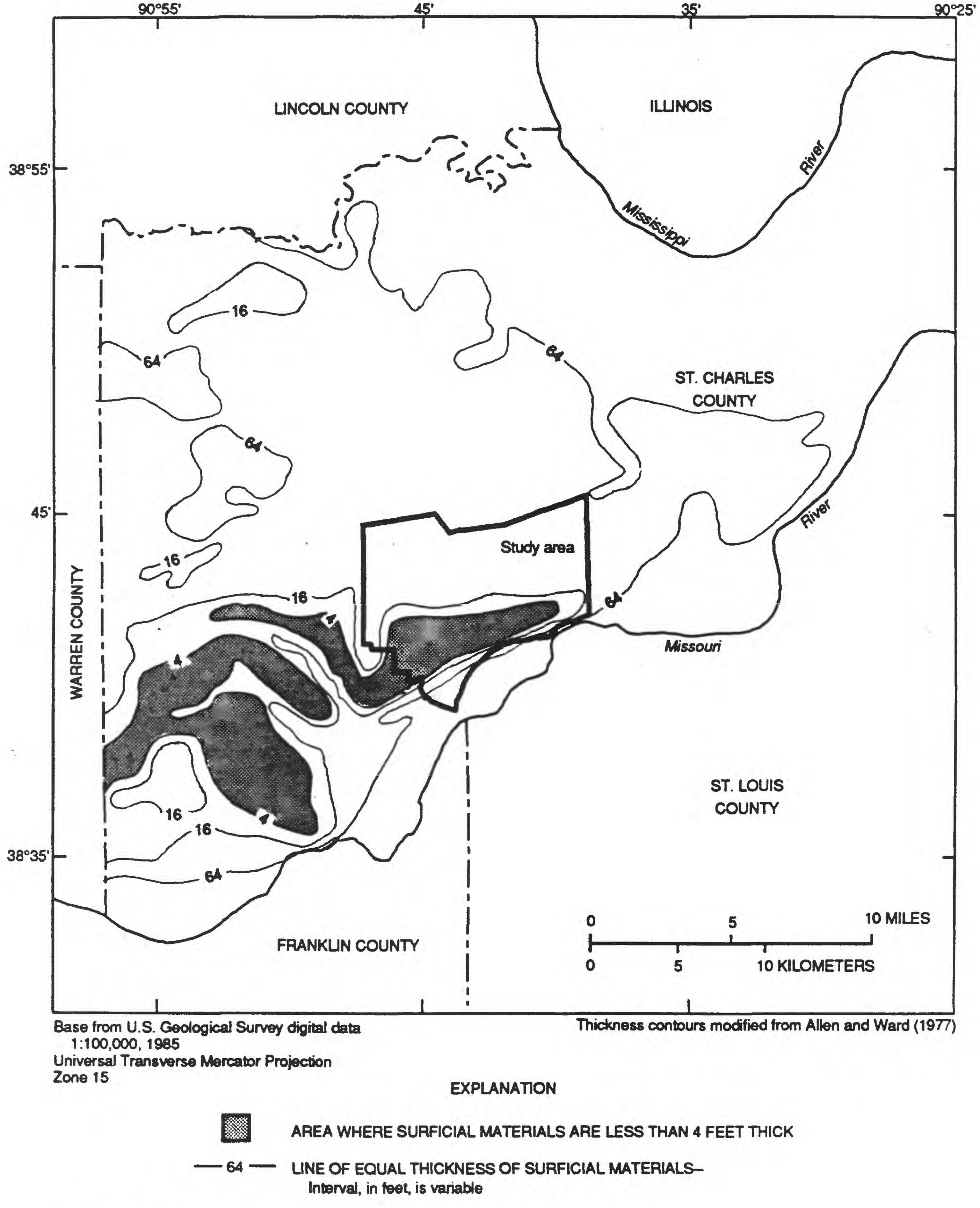
AREA WHERE SHALLOW AQUIFER IS ABSENT

— 100 - - STRUCTURE CONTOUR--Shows altitude of the top of the shallow aquifer. Dashed where approximately located. Interval 100 feet. Datum is sea level

D/U COTTLEVILE FAULT--D, downthrown side; U, upthrown side; dashed where inferred; dotted where postulated

▪ CONTROL POINT

Figure 12. Structure of the top of the shallow aquifer.



Base from U.S. Geological Survey digital data
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Universal Transverse Mercator Projection
Zone 15

Thickness contours modified from Allen and Ward (1977)

EXPLANATION

AREA WHERE SURFICIAL MATERIALS ARE LESS THAN 4 FEET THICK

—64— LINE OF EQUAL THICKNESS OF SURFICIAL MATERIALS–
Interval, in feet, is variable

Figure 13. Thickness of the surficial materials.

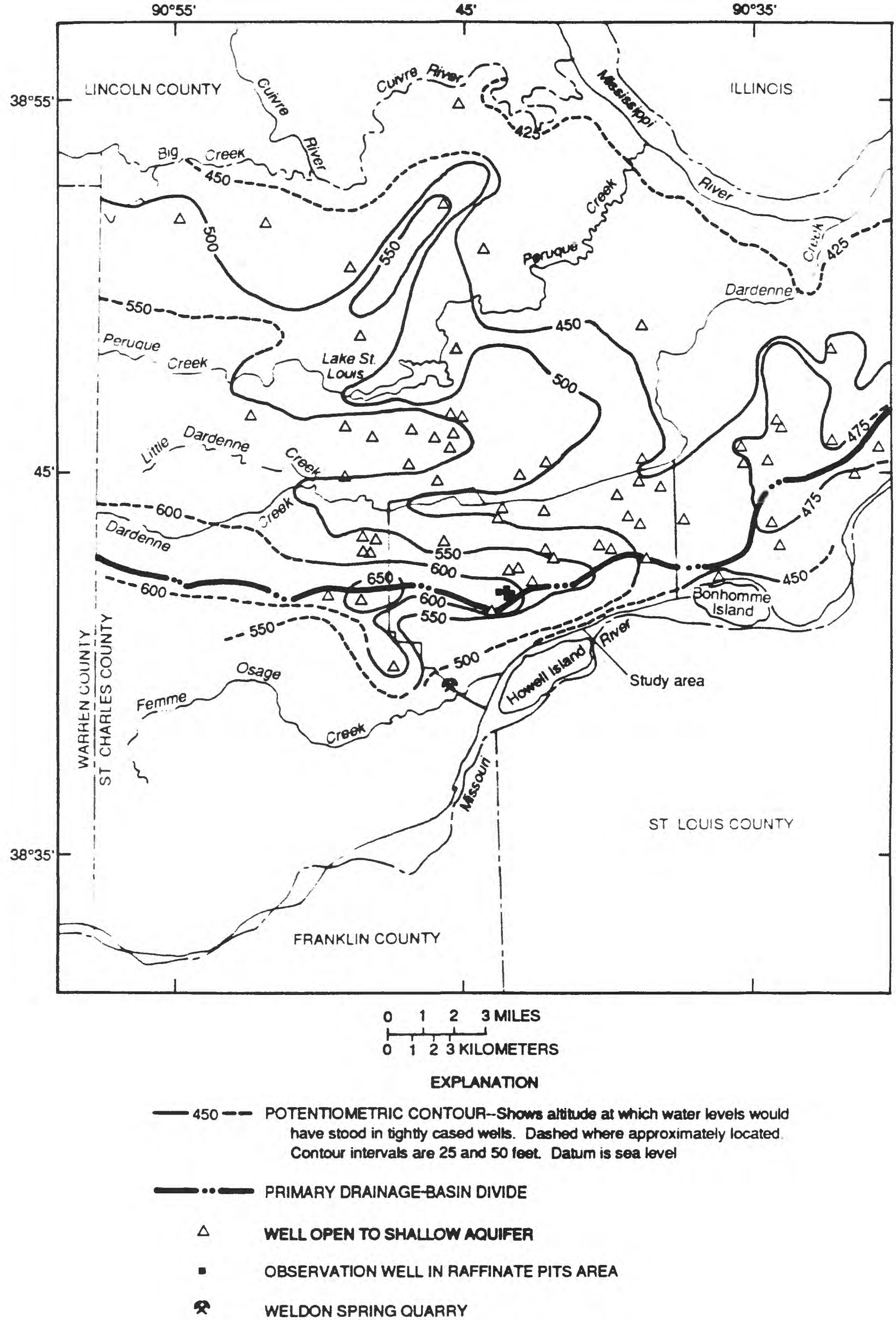


Figure 14. Potentiometric surface of the shallow aquifer, summer 1984 (from Kleeschulte and Emmett, 1986).

sylvanian shale, sandstone, and siltstone (Miller, 1977).

Dissolved solids concentration ranged from 122 to 17,500 milligrams per liter, and the concentration increased from west to east. The water with the larger dissolved solids concentrations is a sodium chloride type. The U.S. Geological Survey considers water that has a dissolved solids concentration of more than 1,000 milligrams per liter to be saline. The elevated dissolved solids concentration in the ground water in the shallow aquifer in the eastern part of the county is thought to be caused by salinewater from the deep aquifer moving upward into the shallow aquifer (Imes, 1985). In eastern St. Charles County, water in the deep aquifer has a higher potentiometric head than water in the shallow aquifer; therefore, the water from the deep aquifer has the potential to penetrate upward through the leaky confining units separating the shallow and deep aquifers.

Upper confining unit

The upper confining unit is composed of rocks ranging from the Kinderhookian Series of the Mississippian System to upper Ordovician. The geologic units include the undifferentiated Chouteau Group, the Bushberg Sandstone, the Sulphur Springs Group, and the Maquoketa Shale. Some zones of this unit yield water to wells; however, this entire sequence of rocks is considered together because on a regional scale they are a confining unit separating the shallow aquifer from the underlying more-permeable Kimmswick Limestone, the middle aquifer in this report. Dominant lithologies of the upper confining unit primarily are limestones and shales, with the notable exception of the Bushberg Sandstone (fig. 5). The Bushberg Sandstone is included with the confining unit because it typically is thin where present and is "sandwiched" between two thicker rock units that have much smaller permeabilities. The Maquoketa Shale is the least permeable formation of this confining unit; however, there are no aquifer-test data available for the study area to obtain hydraulic conductivity values for the unit.

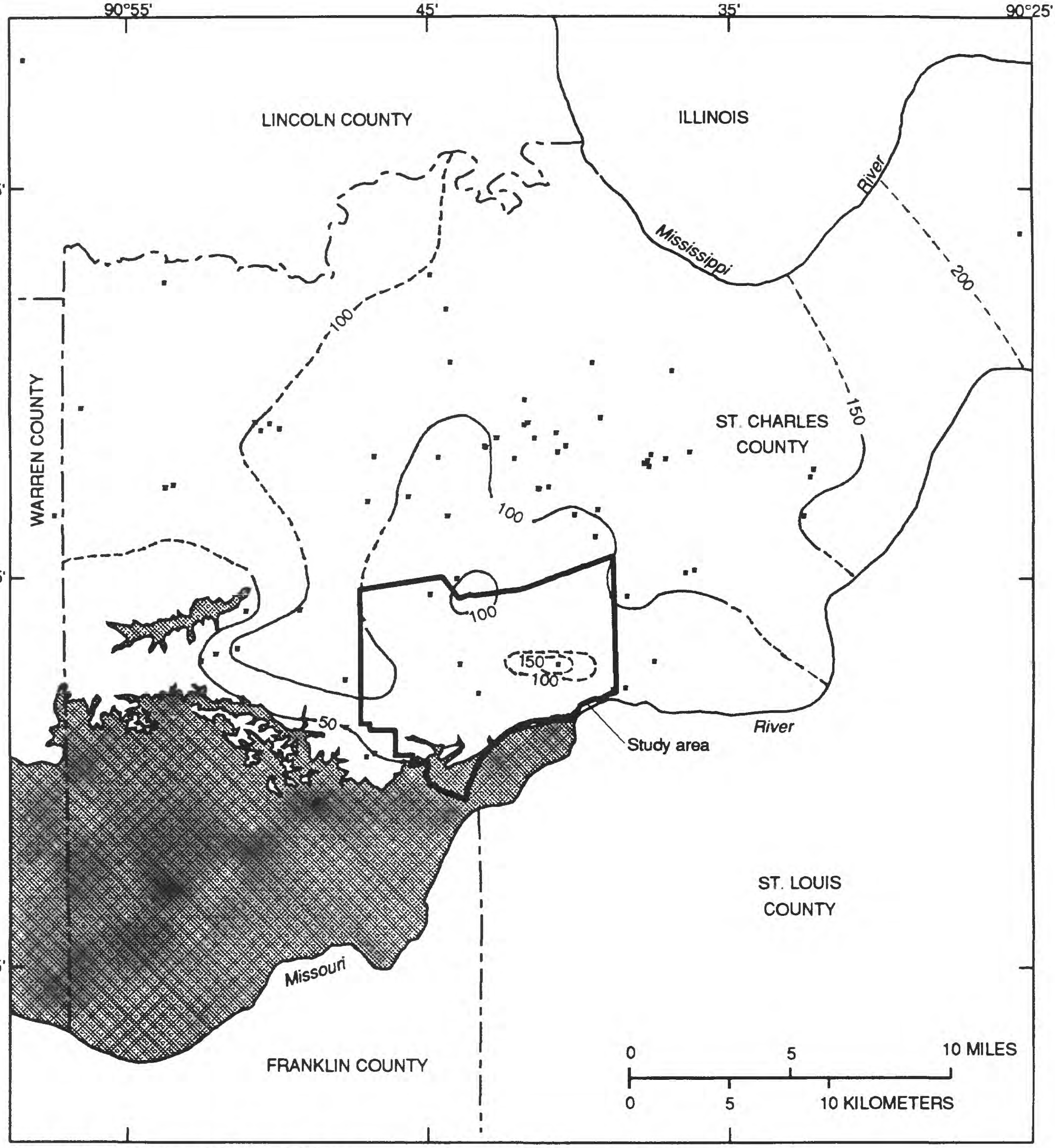
The upper confining unit has been removed in the southwestern part of St. Charles County. Maximum thickness of the confining unit is more than 200 feet in the extreme eastern part of the county (fig. 15). Throughout much of the area the unit is from 100 to 150 feet thick. The altitude of the top of the unit is highest at its southern limit in the county, where it has an altitude of about 720 feet. The unit dips almost uniformly to the northeast (fig. 16), but the dip decreases in the central part of the county.

Middle aquifer

The middle aquifer only consists of the Kimmswick Limestone. This formation typically is white to light gray, coarsely crystalline, medium to thickly bedded, and cherty near the base. In the southwestern part of St. Charles County, the middle aquifer is absent; however, well logs indicate that the unit ranges from 40 feet thick in the western part of the county to about 150 feet thick in the north-central part of the county (fig. 17). Near the southern limit of the middle aquifer in St. Charles County, it is 80 to 100 feet thick. The altitude of the top of the aquifer decreases to the northeast (fig. 18). The dip is greatest in the western part of the county, probably indicative of a subsurface expression of the Eureka-House Springs Anticline, and the dip decreases in the central part of the county.

The thickness of the middle aquifer typically is less than the shallow aquifer or the deep aquifer, and the middle aquifer yields small to moderate quantities of water to wells. The Kimmswick Limestone is treated as an aquifer in this report because the hydraulic conductivity of this formation is orders of magnitude larger than the conductivity of the formations above and below it. Aquifer tests in St. Charles County by drillers after completion of wells show that the specific capacities for wells penetrating formations from the Kimmswick Limestone through the St. Peter Sandstone ranged from 0.07 to 0.25 gallon per minute per foot of drawdown. If these tests had been made in wells that penetrated only the middle aquifer, the specific capacity values probably would be less.

The middle aquifer can receive recharge from precipitation where the unit crops out or where the overlying materials are thin, as in west-central St. Charles County. However, because the aquifer is in the subsurface in most of the county, a primary source of recharge is leakage through the overlying confining



Base from U.S. Geological Survey digital data
1:100,000, 1985
Universal Transverse Mercator Projection
Zone 15

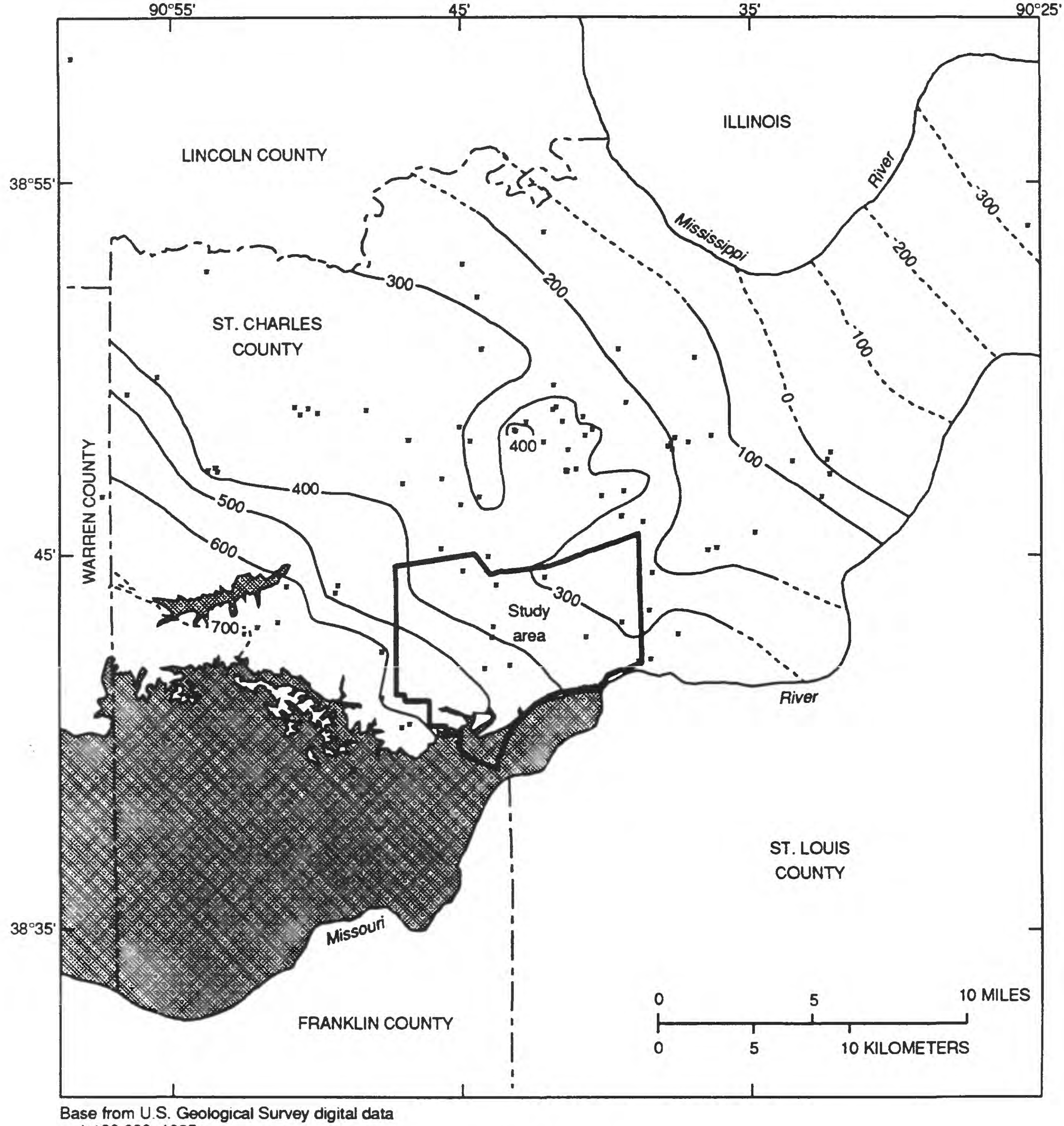
EXPLANATION

AREA WHERE THE UPPER CONFINING UNIT IS ABSENT

—100- - LINE OF EQUAL THICKNESS OF UPPER CONFINING UNIT--
Dashed where approximately located. Interval 50 feet

▪ CONTROL POINT

Figure 15. Thickness of the upper confining unit.



Base from U.S. Geological Survey digital data
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Zone 15

EXPLANATION

AREA WHERE THE UPPER CONFINING UNIT IS ABSENT

— 100 - - STRUCTURE CONTOUR--Shows altitude of the top of the upper confining unit. Dashed where approximately located. Interval 100 feet. Datum is sea level

CONTROL POINT

Figure 16. Structure of the top of the upper confining unit.

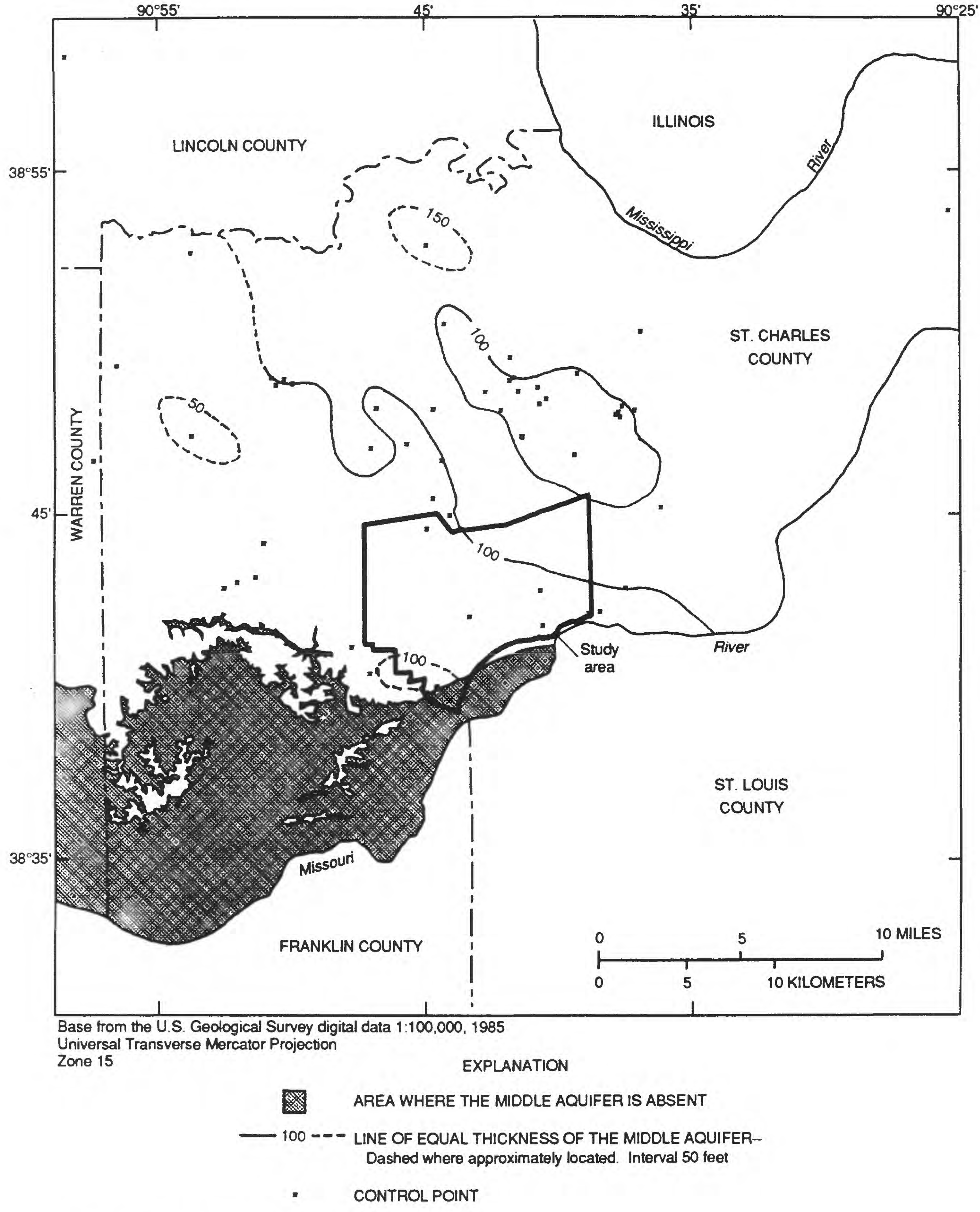
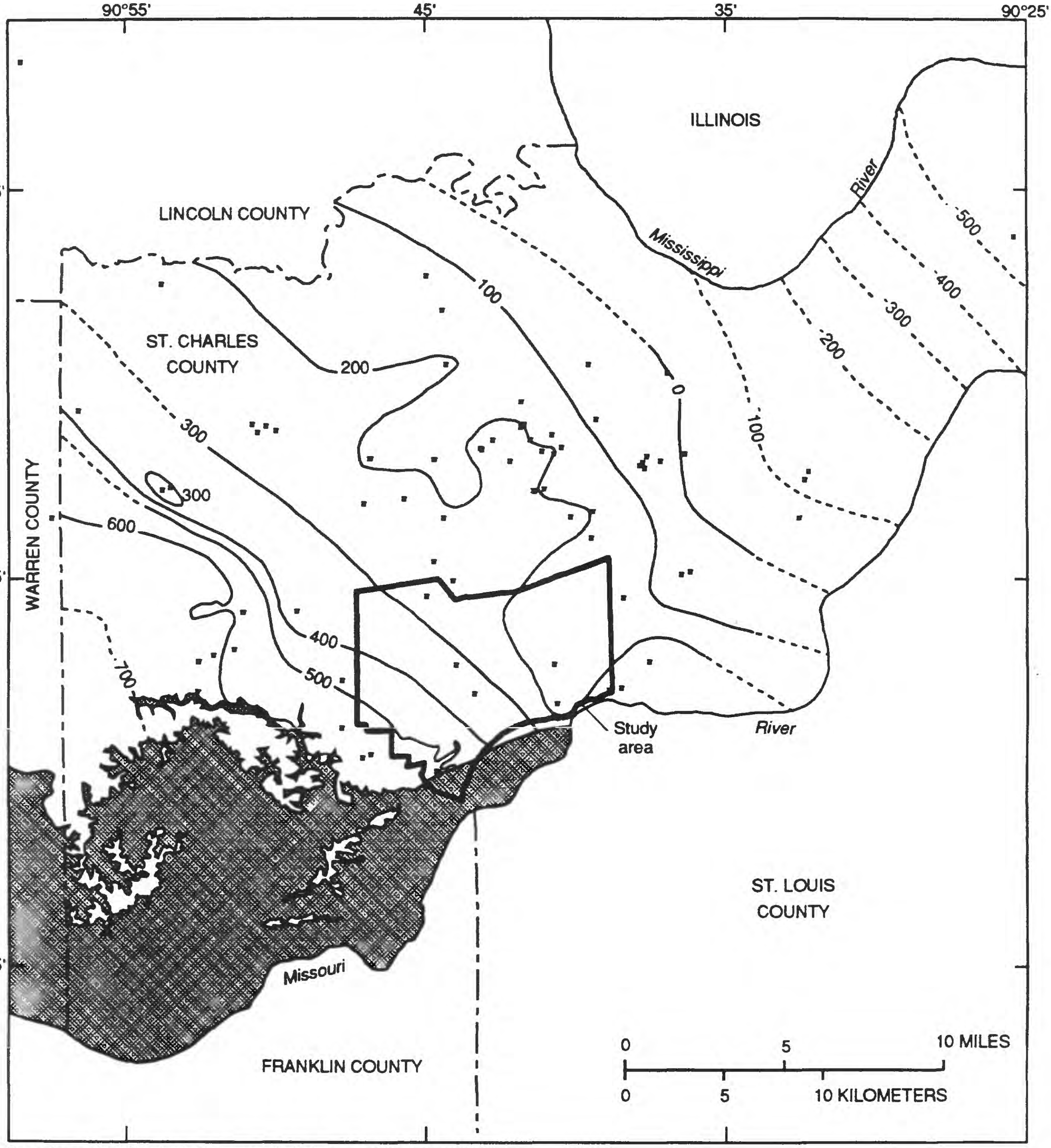


Figure 17. Thickness of the middle aquifer.



Base from U.S. Geological Survey digital data 1:100,000, 1985
Universal Transverse Mercator Projection
Zone 15

EXPLANATION

AREA WHERE THE MIDDLE AQUIFER IS ABSENT

— 100 - - STRUCTURE CONTOUR--Shows altitude of the top of the middle aquifer. Dashed where approximately located. Interval 100 feet. Datum is sea level

▪ CONTROL POINT

Figure 18. Structure of the top of the middle aquifer.

unit. In the southwestern part of the county, Pennsylvanian formations overlie the middle aquifer. In these areas, the recharge rate to the aquifer depends on the leakage through the Pennsylvanian formations. Because water-level measurements made in wells open only in the middle aquifer are sparse, there is no potentiometric surface map for this aquifer. Most of the wells that receive water from the middle aquifer also receive water from the shallow or the deep aquifer. Because these wells are open to more than one aquifer, it is difficult to determine which aquifer the measured water level represents.

Water from the middle aquifer generally is a calcium magnesium bicarbonate type and has a dissolved solids concentration ranging from about 300 to more than 4,700 milligrams per liter. The larger dissolved solids concentrations occur in northern and eastern St. Charles County, where this aquifer yields a sodium chloride type water (Miller, 1977). This increased salinity is thought to be caused by the upward leakage of ground water from the deep aquifer.

Lower confining unit

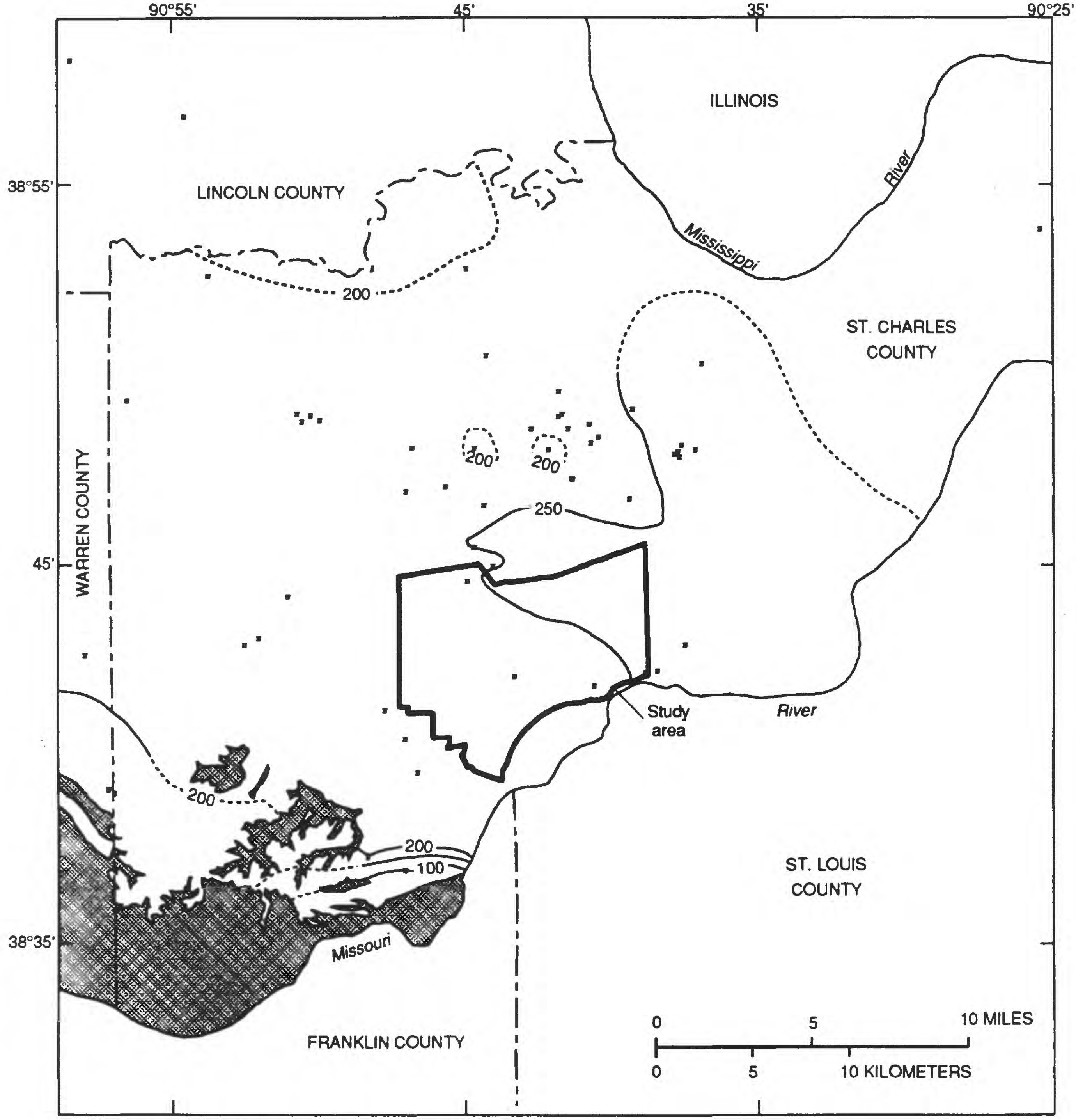
The Decorah Formation, Plattin Formation, and Joachim Dolomite are grouped together into a leaky, lower confining unit that separates the middle aquifer from the deep aquifer. The Decorah Formation is composed of shale interbedded with thin limestone; the Plattin Formation is a finely crystalline, thinly bedded limestone, which weathers to a characteristic pitted surface; and the Joachim Dolomite is a silty, thin to thick bedded dolostone grading to siltstone and commonly contains shale. All of these formations crop out in the southern part of the county. The lower confining unit has been eroded in parts of extreme southwestern St. Charles County, but in well logs where the unit is present, the thickness ranges from 70 to about 280 feet. The unit typically is 200 to 250 feet thick throughout most of St. Charles County (fig. 19). Where the unit does not crop out, the structure (fig. 20) is similar to that of the middle aquifer (fig. 18). The dip of the unit is to the northeast. The dip is greatest in the southern part of the county, decreases in the central part of the county, and is uniform in the eastern part of the county.

Imes (1985) included this lower confining unit in his description of the Cambrian-Ordovician aquifer, but qualified that designation by stating the formations that compose this unit yield limited quantities of water and may locally be considered a confining unit. Miller (1977) grouped the formations from the top of the Kimmswick Limestone to the base of the Joachim Dolomite as an aquifer in St. Charles County. However, he also reported the Joachim Dolomite is not considered a "good" aquifer because it generally does not yield water to wells in usable quantities. Water-level measurements made in well clusters that contain wells open only to the Kimmswick Limestone and St. Peter Sandstone show a hydraulic head difference ranging from 70 to 90 feet between the two formations. These measurements also indicate the confining ability of the rock sequence between the Decorah Formation and Joachim Dolomite.

Deep aquifer

The deep aquifer in this study includes the formations from the top of the St. Peter Sandstone to the base of the Potosi Dolomite (fig. 5). It is much thicker than the shallow or the middle aquifer. Many municipalities and public-water supplies in St. Charles County use this aquifer as a source of water because it can yield about 300 to 500 gallons per minute (fig. 5; Miller, 1977).

The formations that are included in the deep aquifer have differing hydrologic properties and characteristics. The permeability of the St. Peter Sandstone, a quartz sandstone, varies with the degree of cementation of the sand grains, but generally the St. Peter Sandstone yields moderate quantities of water to wells (10 to 140 gallons per minute; Miller, 1977). The Everton Formation is a non-continuous, sandy dolostone that is not hydrologically significant. The Powell, Cotter, and Jefferson City Dolomites are argillaceous, cherty, and generally yield small quantities of water to wells (less than 10 gallons per minute). The Roubidoux Formation, a dolomitic sandstone, and the Gasconade Dolomite have permeable interbedded sandstones and yield moderate to large quantities of



Base from the U.S. Geological Survey digital data 1:100,000, 1985
Universal Transverse Mercator Projection
Zone 15

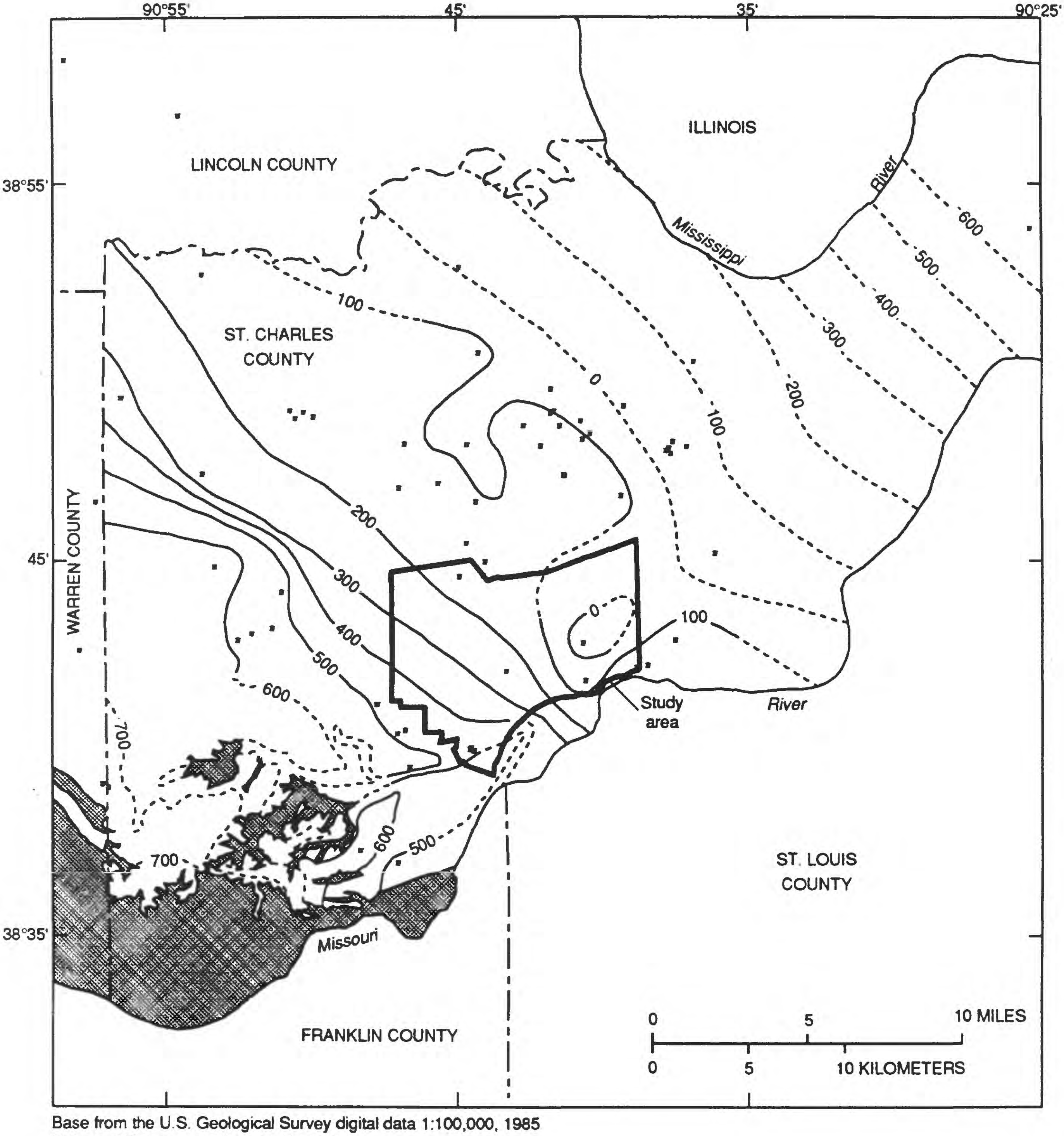
EXPLANATION

AREA WHERE THE LOWER CONFINING UNIT IS ABSENT

—250---- LINE OF EQUAL THICKNESS OF THE LOWER CONFINING UNIT--Dashed where approximately located. Interval 50 feet

▪ CONTROL POINT

Figure 19. Thickness of the lower confining unit.



Base from the U.S. Geological Survey digital data 1:100,000, 1985
Universal Transverse Mercator Projection
Zone 15

EXPLANATION

AREA WHERE THE LOWER CONFINING UNIT IS ABSENT

— 100 - - STRUCTURE CONTOUR--Shows altitude of the top of the lower confining unit. Dashed where approximately located. Interval 100 feet. Datum is sea level

▪ CONTROL POINT

Figure 20. Structure of the top of the lower confining unit.

water to wells (10 to 300 gallons per minute). The Gunter Sandstone Member of the Gasconade Dolomite can store and yield substantial quantities of water. The Eminence and Potosi Dolomites are coarse-grained, vuggy, and drusy dolostones that can yield large quantities of water. In southeast Missouri, where these formations are near land surface, these formations have well-developed solution channels. Wells penetrating these formations can produce about 500 gallons per minute. Although the Eminence and Potosi Dolomites are considered part of the deep aquifer in this report, the deepest public-supply wells in the county are completed in the Gasconade Dolomite and any potable water from the Eminence and Potosi Dolomites would be limited to the southwestern part of St. Charles County (Miller, 1977). To the north and east these two formations are deeply buried and contain salinewater. In southern Missouri, these formations have similar hydrologic characteristics as the overlying formations and are included with the Ozark aquifer of Missouri, Arkansas, Oklahoma, and Kansas (Imes and Emmett, in press). This same continuity is expected to exist in St. Charles County.

The deep aquifer crops out in the extreme southwestern part of the county and also where the larger streams have eroded the overlying formations (fig. 21). The outcrops of the aquifer include the St. Peter Sandstone and the Cotter Dolomite. The altitude of the top of the aquifer is based on the top of the St. Peter Sandstone. Where the St. Peter Sandstone is missing, the top of the Cotter Dolomite (fig. 21) was used. The aquifer dips uniformly to the northeast, except in the central part of the county, where the dip decreases. According to well logs on file at the Missouri Department of Natural Resources (Rolla, Missouri), the altitude of the top of the deep aquifer ranges from about 700 feet above sea level where the aquifer crops out to 900 feet below sea level in the eastern part of the county.

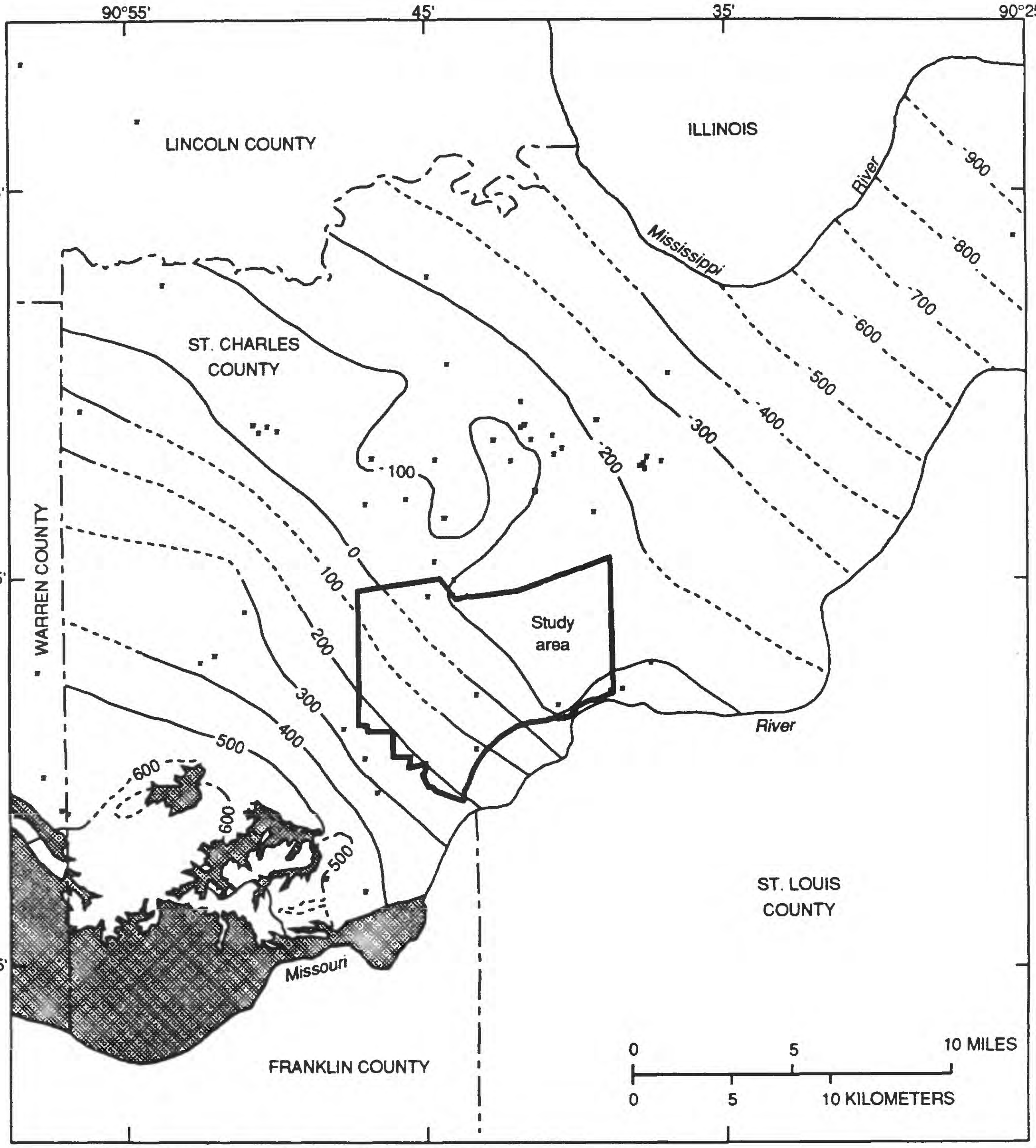
There were insufficient data to draw a thickness map of the deep aquifer for the study area. However, there are two wells in St. Charles County that have completely penetrated the deep aquifer. One of the wells, located in the northwest part of the county, penetrates a total aquifer thickness of 1,425 feet; the other well, located in the north-central part of the county, penetrates a total aquifer thickness of 1,522 feet. In areas where the St. Peter Sandstone crops out, the thickness of the aquifer is slightly less. Therefore, based on these two data points in the county and data from nearby areas, the deep aquifer is thought to range from 1,300 to 1,600 feet thick.

Imes (1985) used a hydraulic conductivity of 1.5×10^{-6} foot per second for the Cambrian-Ordovician aquifer in St. Charles County for his ground-water simulations. However, this value was used for the entire sequence of rocks from the Kimmswick Limestone to the top of the Davis Formation. Wells penetrating formations of the deep aquifer had specific capacities ranging from 0.53 to 2.64 gallons per minute per foot of drawdown (Miller and others, 1974) in St. Charles County.

St. Charles County contains part of a local freshwater-flow system that is nearly independent of the regional salinewater-flow system in northern Missouri (Imes, 1985). As the salinewater flows eastward from northern Missouri into Illinois, it flows around the northern edge of the Lincoln Fold, which serves as a ground-water barrier. One source of freshwater recharge to St. Charles County enters the deep aquifer atop the southern end of the Lincoln Fold where the deep aquifer is exposed. The deep aquifer also receives recharge from precipitation in the southern part of St. Charles County where the upper part of the aquifer is exposed. Leakage from overlying formations and regional flow entering the county primarily from the west also provide water for the area.

A predevelopment potentiometric map was drawn for the deep aquifer in St. Charles County (fig. 22). Most of the data are from water-level measurements collected from 1930 to 1960 at the time of well installation. Because water from the deep aquifer is saline in the eastern one-half of the county, there are few measurements available in that area. The potentiometric map shows a ground-water divide parallel to the surface-water divide in the southern part of the county. The map also indicates the aquifer discharges water to the Missouri River and has the potential to discharge water upward through the overlying formations to the Mississippi River. The Femme Osage Creek seems to be a drain for the deep aquifer.

A potentiometric map of the deep aquifer during summer 1984 also was drawn (fig. 23). The 1984 water



Base from U.S. Geological Survey digital data 1:100,000, 1985
Universal Transverse Mercator Projection
Zone 15

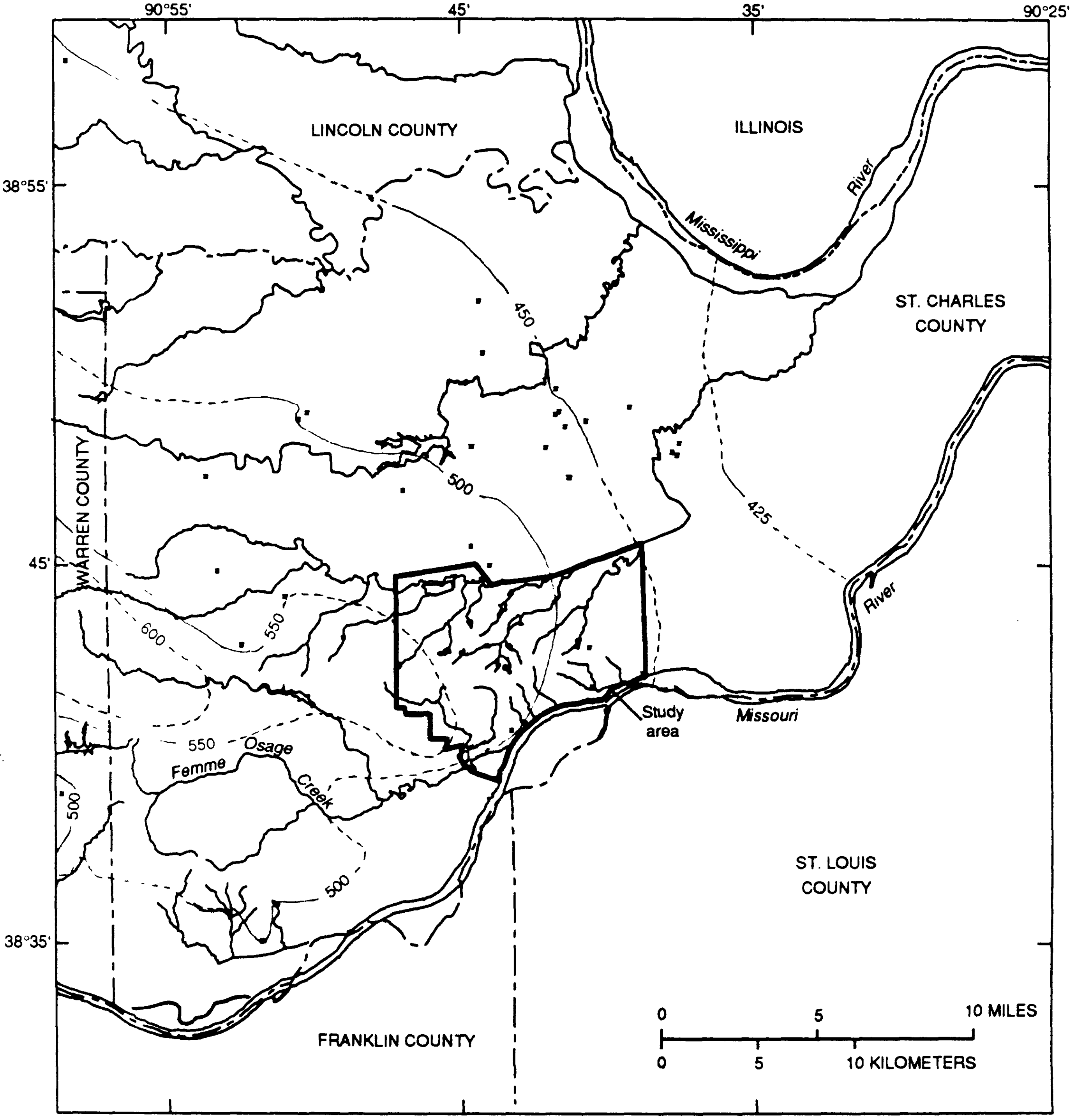
EXPLANATION

OUTCROP AREA OF THE DEEP AQUIFER

— 100 - - STRUCTURE CONTOUR--Shows altitude of the top of the deep aquifer. Dashed where approximately located. Interval 100 feet. Datum is sea level

▪ CONTROL POINT

Figure 21. Structure of the top of the deep aquifer.



Base from the U.S. Geological Survey digital data 1:100,000, 1985
Universal Transverse Mercator Projection
Zone 15

EXPLANATION

—450- - -   POTENTIOMETRIC CONTOUR--Shows altitude at which water levels would have stood in tightly cased wells. Dashed where approximately located. Contour interval, in feet, is variable. Datum is sea level

▪   CONTROL POINT

Figure 22. Predevelopment potentiometric surface of the deep aquifer.

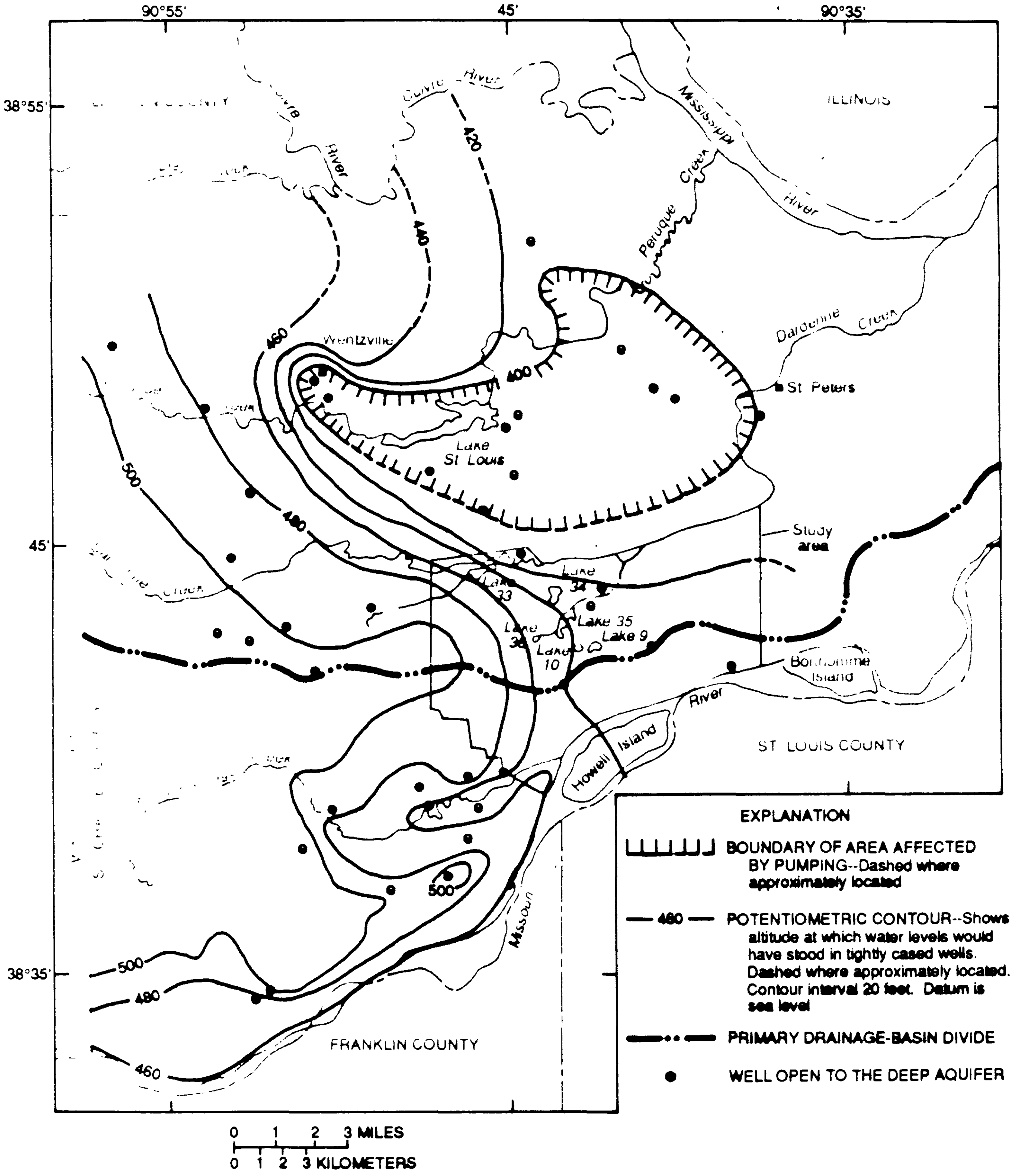


Figure 23. Potentiometric surface of the deep aquifer, summer 1984 (modified from Kleeschulte and Emmett, 1986).

levels were supplemented with water-level measurements made in two wells during 1989. These two additional wells are within 4 miles of the site. One is north of the chemical plant and the other is south of it. Both wells are in areas that were affected only slightly by pumpage from the deep aquifer. Because the two additional wells were used only for monitoring purposes and were not continually pumped as the public-water-supply wells, these data were added to supplement the 1984 potentiometric map.

The obvious difference between the 1984 map and the predevelopment map is the drawdown cone on the 1984 map in the northern part of the county extending from Wentzville to St. Peters. This drawdown is caused by municipal and public-water-supply pumpage (Kleeschulte and Emmett, 1987). Most of the deep public-water-supply wells in St. Charles County are located in the northern part of the county. The ground-water withdrawals in St. Charles County from the deep aquifer have increased from 0.8 million gallons per day in 1962 (first year data were available) to 3.4 million gallons per day in 1985 (last year water use from the deep aquifer was calculated).

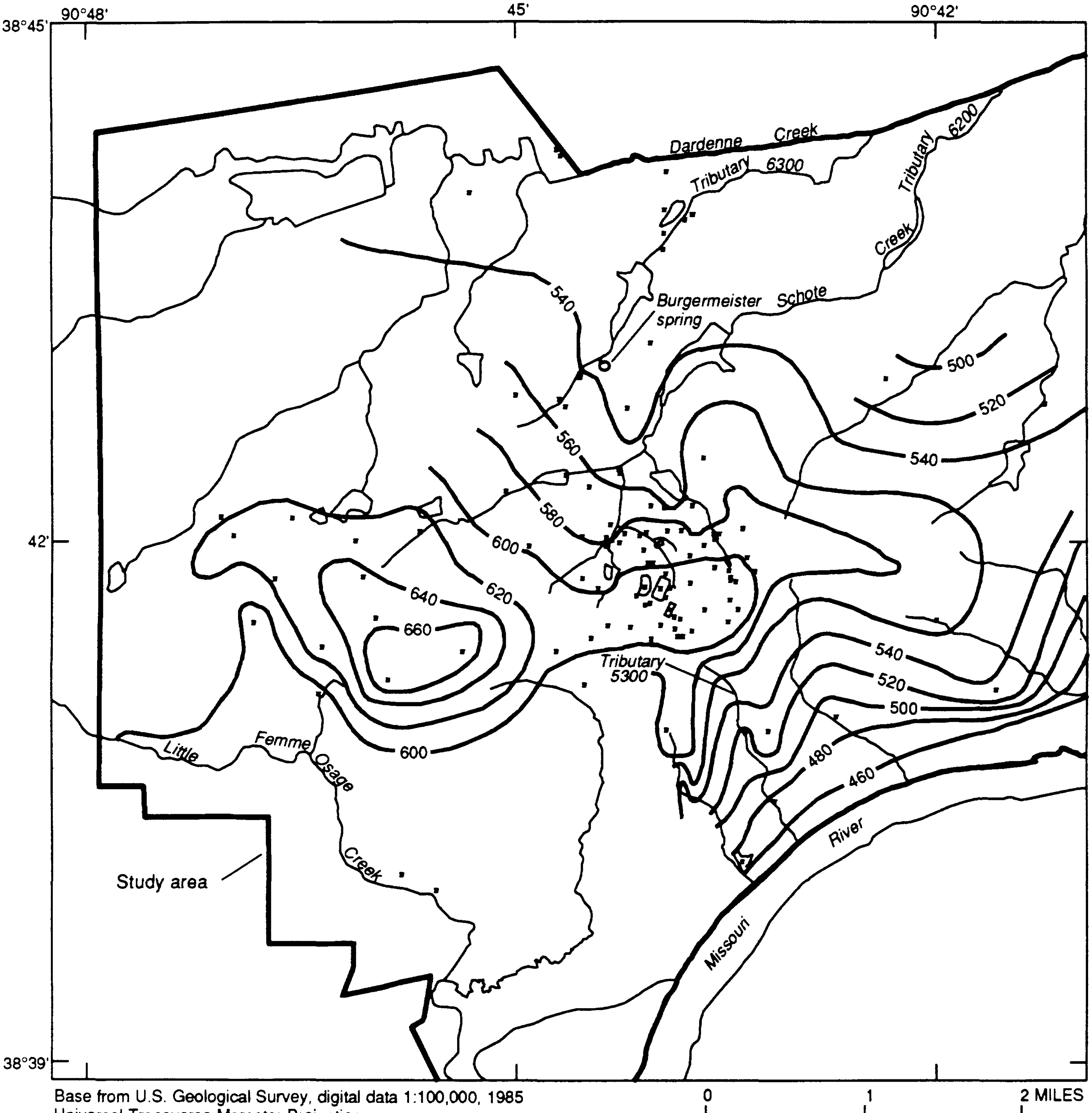
Miller (1977) reports water from the deep aquifer in western St. Charles County generally is a calcium magnesium bicarbonate type, and in the eastern part of the county, water from the deep aquifer is a sodium chloride type. Dissolved solids concentrations typically increased with depth. Dissolved-solids concentrations in water from the rock sequence from the St. Peter Sandstone through the Gasconade Dolomite, the bedrock formations used for public-water supply in the county, ranged from 252 to 915 milligrams per liter.

Water Levels and Aquifer Hydraulic Properties

The shallow aquifer at the site can be described as one that has discrete flow zones superimposed on an otherwise diffuse flow regime. Water-level monitoring, borehole drilling, aquifer testing, ground-water tracing tests, vertical hydraulic gradient analyses, and spring monitoring have provided geohydrologic data about the shallow aquifer.

Water levels in U.S. Department of Energy, U.S. Army, and U.S. Geological Survey wells were measured during August 1989 and were supplemented with spring orifice altitudes to complete the water-table map shown in figure 24. Previous water-table maps on file at the U.S. Geological Survey, Rolla, Missouri, indicate the same basic features as this map. The ground-water divide located along the ridge apparently does not fluctuate sufficiently to cause a significant change in the ground-water flow pattern onsite. With the addition of water-level measurements from the U.S. Army wells, a previously unknown ground-water high was mapped west of the site. The water-level measurements also show two ground-water troughs adjoining the site and extending north toward Burgermeister spring. The location of these troughs correlate with troughs on the top of the weathered limestone unit (figs. 7 and 8). Throughout most of the site, ground-water levels are 10 feet or more below the top of the weathered limestone unit. However, along the troughs formed on the top of the bedrock, ground-water levels are above or not more than 5 feet below the top of the weathered limestone unit. These water-level measurements indicate that the depressions on the top of the weathered limestone unit may be areas of increased permeability that may help to drain the area.

Monitoring of water levels in wells in the study area and specifically at the site indicate the water levels at the site do not substantially vary with time. Water-level measurements made quarterly between February 1986 and November 1990 in wells located in the study area were compiled by the Missouri Department of Natural Resources (1991). The measurements indicate that in 46 of the 61 wells monitored, the water level varied less than 3 feet. Ten wells had water-level fluctuations between 3 and 6 feet, and five wells had fluctuations of more than 6 feet (with the maximum fluctuation of 21 feet). Water-level fluctuations do not seem to be related to well depth. Shallow wells (those less than 65 feet deep), intermediate wells (65 to 100 feet deep), and deep wells (more than 100 feet deep) were all represented in the 15 wells that had fluctuations of more than 3 feet. The degree of water-level fluctuation also does not seem to be related to any specific location because these wells were scattered across the study area. No consistent increase or decrease in



Base from U.S. Geological Survey, digital data 1:100,000, 1985
Universal Transverse Mercator Projection
Zone 15

EXPLANATION

—— 600 —— WATER-TABLE CONTOUR--Shows altitude of measured water table. Contour interval 20 feet. Datum is sea level

▪ CONTROL POINT

Figure 24. Water table in part of the study area, August 1989.

water levels was documented throughout the study area.

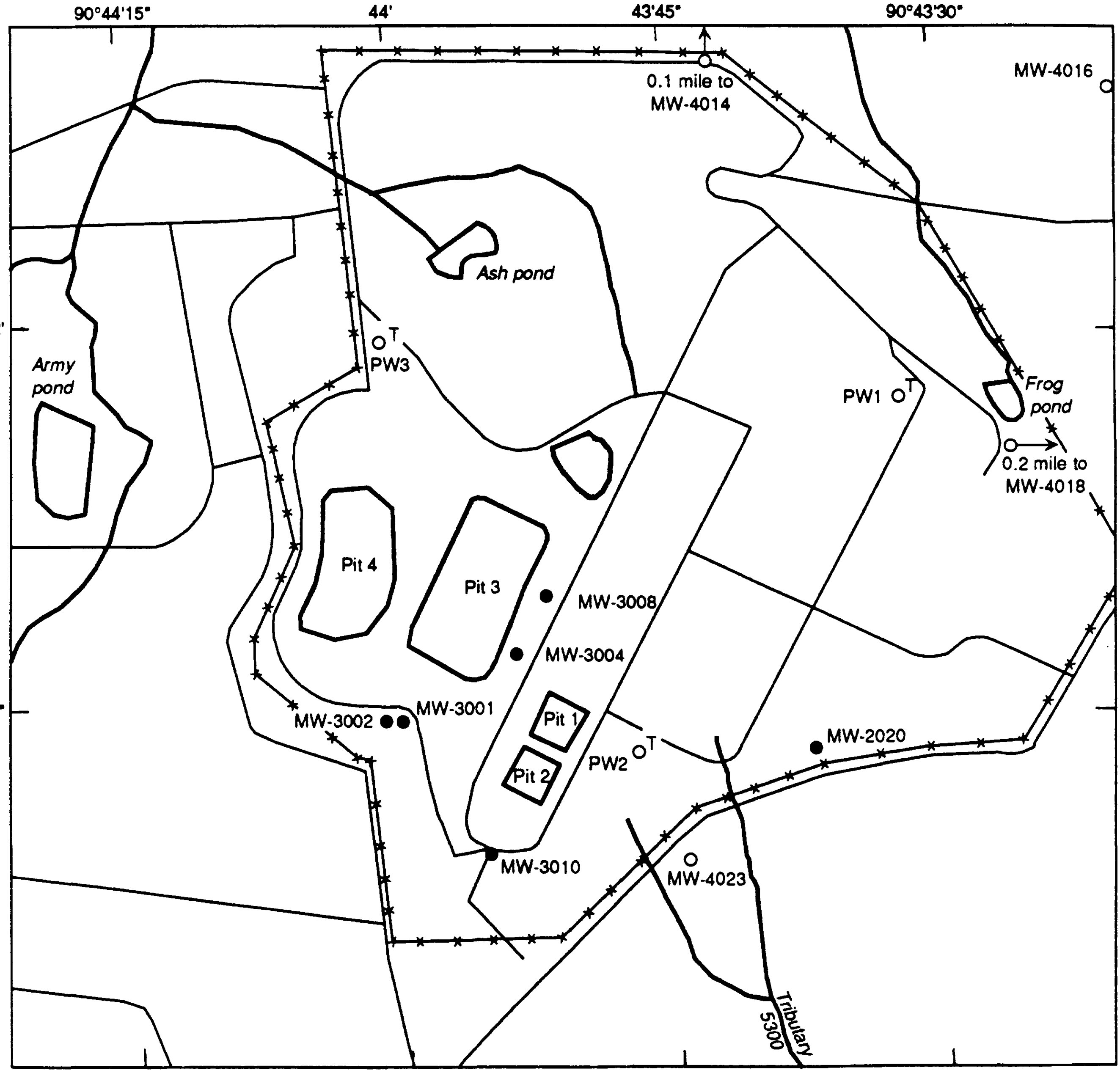
As part of the phase II study at the site, six pressure transducers with data loggers were installed in wells to monitor water-level fluctuations at hourly intervals during different climatic conditions (fig. 25). Three of the wells (MW-2020, MW-3008, and MW-3010) had annual water-level fluctuations ranging from 4 to 10 feet. Two clustered wells (MW-3001 and MW-3002) were monitored for vertical hydraulic gradients; one was an intermediate depth well (75 feet deep) and the other a deep well (147 feet deep). The remaining well (MW-3004) was chosen because it was completed in the overburden; however, this well had less than a 0.5 foot change in the water level between January 1988 and July 1989 (hydrograph data are on file at the U.S. Geological Survey office in Rolla, Missouri). After sampling well MW-3004, it took months to recover, indicating the well was completed in low permeability clays. Testing of the clayey soils from the site indicated permeability values of less than 3.3×10^{-9} foot per second (MK-Ferguson Company and Jacobs Engineering Group, 1990a).

The data from the three wells (MW-2020, MW-3008, and MW-3010) with annual water-level fluctuations of 4 to 10 feet indicate that, during precipitation, water levels increased as much as 1 foot. Although water levels in each of the three wells responded similarly, the magnitude of the increase varied. It is not clear if this variation is because of porosity or permeability differences between wells. Daily fluctuations in water levels observed during dry weather were as much as 1 foot, which indicates that ground-water levels are affected by factors other than precipitation. The water-level fluctuations may be caused by infiltration of water, a decrease in the barometric pressure associated with storms and low-pressure systems, or a combination of these factors.

Annual cyclic variations can be seen in the baseline ground-water levels of the six monitoring wells. The dominant trend in wells is that the lowest ground-water levels occurred during the late fall or early winter months, when water levels were from 0.5 to 1 foot lower than in the spring when the base ground-water level was at its maximum. The lowest water levels for the period of record (May 1987 through November 1989) occurred in November 1989 for many of the wells, which may have been an accumulative effect caused by the dry summers during the period of record. The total water-level fluctuation was caused by the daily fluctuations being superimposed on the annual cyclic trend. A shallower water level would be expected on a spring day with low atmospheric pressure (a rainy day) than a fall day with large atmospheric pressure (sunny day). The magnitude of the rise or fall in water level varied for the different wells, but generally changes in most of the wells had a similar trend.

Variable drilling fluid losses (0 to 100 percent) were noted while drilling boreholes onsite in the weathered limestone. Drilling fluid losses indicate zones with large porosity materials. Drilling fluid and core losses occurred in the top 20 to 30 feet of bedrock in about one-half of the 94 boreholes drilled onsite between 1986 and 1989. Fluid was lost in the overburden at four wells; three of these wells are located to the north of the raffinate pits. Generally, drilling fluid losses did not occur on the southern part of the site, but most boreholes lost fluid on the northern part of the site (MK-Ferguson Company and Jacobs Engineering Group, 1990a). The permeability of the Burlington and Keokuk Limestones decreases with depth because of the lack of secondary permeability resulting from less weathering in the lower part of the limestones. The lack of permeability is evident when water is removed from the deep wells; typically, water levels in the deep wells take several days to recover.

Three aquifer tests were performed at the site during 1989 (table 1). The observation wells used during these aquifer tests generally were completed in the weathered unit of the Burlington and Keokuk Limestones. In one of the tests, an additional observation well was screened in the unweathered unit of the limestones at a depth of about 40 to 50 feet below the bottom of the screen of the test well being pumped. This observation well had no measurable drawdown during pumping of the test well (MK-Ferguson Company and Jacobs Engineering Group, 1990a). The lack of drawdown would indicate limited hydraulic connection between the weathered and unweathered units of the Burlington and Keokuk Limestones. Interpretation of the three aquifer tests data by U.S. Department of Energy contractors indicate an anisotropy factor between



Base from U.S. Geological Survey, digital data 1:100,000, 1985
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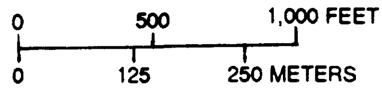
Zone 15



EXPLANATION

TYPE OF WELL

● Well with pressure transducer

○T Well used for aquifer test

○ Well used for dye injection

Figure 25. Ground-water data collection wells at the Weldon Spring chemical plant site.

Table 1–Summary of aquifer test results at Weldon Spring chemical plant using Hantush areal anisotropy analysis

[Tx, transmissivity along major axis, in feet squared per day; Ty, transmissivity along minor axis, in feet squared per day; Theta, orientation of major axis; S, storativity, in feet per day; reported from Carman (1991)]

Pumping well (fig. 25)	Tx	Ty	Theta	Anisotropy ratio	S
PW1	3.76	1.87	N. 72° W.	2:1	3.8×10^{-4}
PW2	9.68	2.67	N. 10° W.	3.5:1	1.1×10^{-3}
PW3	3.23	1.87	N. 10° E.	1.7:1	3.8×10^{-4}

1.7 and 3.5 (Carman, 1991). The orientations of the maximum transmissivity measured in well PW1 (fig. 25) correlates with the orientation of vertical fractures in outcrops along the northern bluff of the Missouri River about 3 miles south of the site. Carman (1991) explained that the transmissivity values from wells PW2 and PW3 probably are controlled by horizontal fractures (bedding planes). Bechtel National, Inc. (1987) reported the average permeability of the weathered limestone unit is about three orders of magnitude greater than the permeability of the unweathered limestone unit at the site. They concluded the Burlington and Keokuk Limestones have variable permeability in the horizontal plane and generally become less permeable with depth because of decreased weathering and associated solution features.

Hydraulic conductivity values were calculated from slug tests (Bouwer and Rice, 1976) on 69 wells at the site. These data indicate a range of hydraulic conductivity from 1.5×10^{-4} to 5.7×10^{-8} foot per second with an average hydraulic conductivity of 3.6×10^{-6} foot per second (Carman, 1991). These values correspond to the upper range of typical hydraulic conductivity values for limestones and dolostones and to the lower range for karst limestone (Freeze and Cherry, 1979). A large degree of variation of hydraulic conductivity values has been observed at various depths. Generally, wells with large hydraulic conductivity values are in areas where the upper weathered limestone unit and residuum are saturated. Dissolution and weathering have caused secondary porosity in these areas (Carman, 1991).

Loss of drilling fluids during drilling activities for the site characterization and exploration prompted the Missouri Department of Natural Resources to begin ground-water tracing tests (dye traces) using fluorescent dyes. Objectives of the tests were to determine rates and directions of ground-water flow in the area. Dye was injected into boreholes, then the hole was flushed by injecting water so the dye could be recovered at local springs or streams. A down-hole camera was used to help in selecting boreholes with the most probable chance of conducting dye into the shallow ground-water system. During the viewing of several holes, fracture zones, solution tubes, solution openings, fractures filled with residuum, and areas of broken rock were observed (Missouri Department of Natural Resources, written commun., 1989), indicating the existence of a conduit flow system. A limited number of dyes was available for the tests, so four wells were chosen that had poor core recovery or significant drilling fluid loss, which indicated probable connection to the conduit flow system. Monitoring wells 4014, 4016, 4018, and 4023 (fig. 25) were chosen for dye injection points. Most perennial springs, many wet-weather springs, and gaining stream segments in the study area were monitored for the presence of dye (Missouri Department of Natural Resources, 1991). Each of the four tracing tests was inconclusive as to the discharge point for the injected dye. The lack of a conclusive discharge point indicates that either dilution is a significant process affecting the injected dye onsite, the travel times from the wells to the springs are great, or the ground water in contact with the conduits intercepting these wells is not hydrologically connected to the monitored springs.

Vertical ground-water hydraulic gradients were determined for the shallow aquifer. The vertical gradients calculated from water-level measurements made on April 8, 1991, are shown in figure 26. The gradient was calculated by using:

$$\frac{\text{altitude of water level (shallow well) - altitude of water level (deep well)}}{\text{altitude of mid-point of screen (shallow well) - altitude of mid-point of screen (deep well)}}$$

Water-level measurements from 12 well clusters installed by the U.S. Department of Energy indicate a downward hydraulic gradient for most of the wells onsite. Each cluster consists of two adjacent wells, one typically about 50 to 60 feet deeper than the other, and both completed in the Burlington and Keokuk Limestones. Water levels from the U.S. Army well clusters on the August A. Busch Memorial Wildlife Area north of County Road D and on the Weldon Spring training area indicate an upward vertical gradient. The downward hydraulic gradient onsite is more pronounced near the ground-water divide, which is expected in a recharge area. The downward gradient decreases toward the north until an upward hydraulic gradient becomes present near and to the north of County Road D. An upward gradient is typical in discharge areas.

Burgermeister spring, a perennial spring in basin 6300, has been monitored for several years as a discharge point for ground water. On March 20, 1985, a weir equipped with a continual-gage-height recorder was installed across the Burgermeister spring branch. From March 20, 1985, through September 30, 1990, the daily discharge of Burgermeister spring ranged from 0.06 cubic foot per second during a base-flow period to 0.72 cubic foot per second following an intense storm. The mean annual discharge for this same period ranged from 0.19 to 0.26 cubic foot per second (Kleeschulte and others, 1986; Kleeschulte and Cross, 1990). The spring flowed even during the driest conditions throughout the period of record. This indicates that the Burgermeister spring has a component of flow that is sustained by an intermediate to regional ground-water system; however, the spring also has a local flow component that becomes evident during storms. Discharge at Burgermeister spring rapidly responds to precipitation and becomes turbid. When the flow at Burgermeister spring exceeds the capacity of the spring orifice, the water level increases in the solution opening that supplies the spring and emerges at a higher altitude at the orifice of a wet-weather spring located 140 feet south of Burgermeister spring. The rapid response and increased turbidity during precipitation at Burgermeister spring are documented (Kleeschulte and Emmett, 1987) and have been observed at many of the other perennial springs in the area (fig. 27).

Surface Water

Three streams north of the chemical plant site were of concern during phase II (fig. 27); Schote Creek (tributary 6200), which has two unnamed tributaries with headwaters on the chemical plant property, an unnamed tributary of Dardenne Creek that contains Burgermeister spring (hereafter referred to as tributary 6300), and the reach of Dardenne Creek from the western boundary of the study area to Cottleville (fig. 27). The phase I study determined the other northward flowing streams to Dardenne Creek were insignificant routes of migration of water originating from the site (Kleeschulte and Emmett, 1987). During the phase I study, the primary focus of the streams flowing southward to the Missouri River was on tributary 5300 (also locally known as the sewage outfall tributary or the southeast drainage, fig. 27) and only a cursory study was made on the other southward flowing streams. However, as part of this study (phase II), these other streams were studied in more detail.

The eastern tributary of Schote Creek receives runoff from the eastern part of the site and from a Missouri Highway and Transportation Department maintenance shed (fig. 2). This water flows into Busch lake 36 (hereafter referred to as lake 36), then into the mainstem of Schote Creek. The western tributary of Schote Creek also drains the site. This tributary has three forks; the headwaters of the east fork is in the central part of the site, the headwaters of the middle fork is located west of the site, and the west fork is on U.S. Army property. Runoff from the western part of the site and part of the U.S. Army property drains into the middle fork.

Stream-gaging stations on Schote Creek and tributary 6300 were operated in the study area (fig. 27) from August 1987 through September 1989. The Schote Creek gage was located immediately upstream from U.S. Highways 40 and 61. The tributary 6300

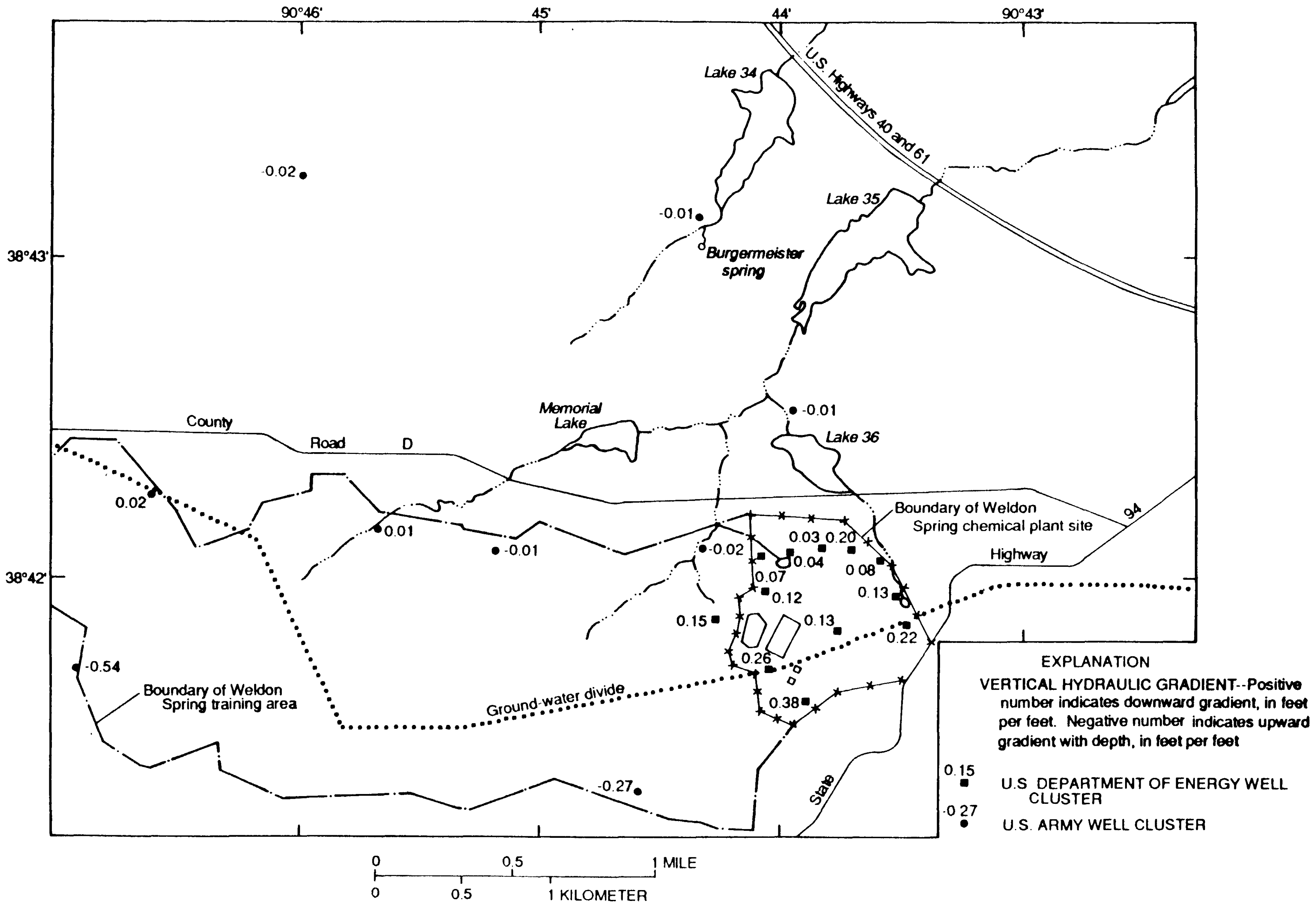
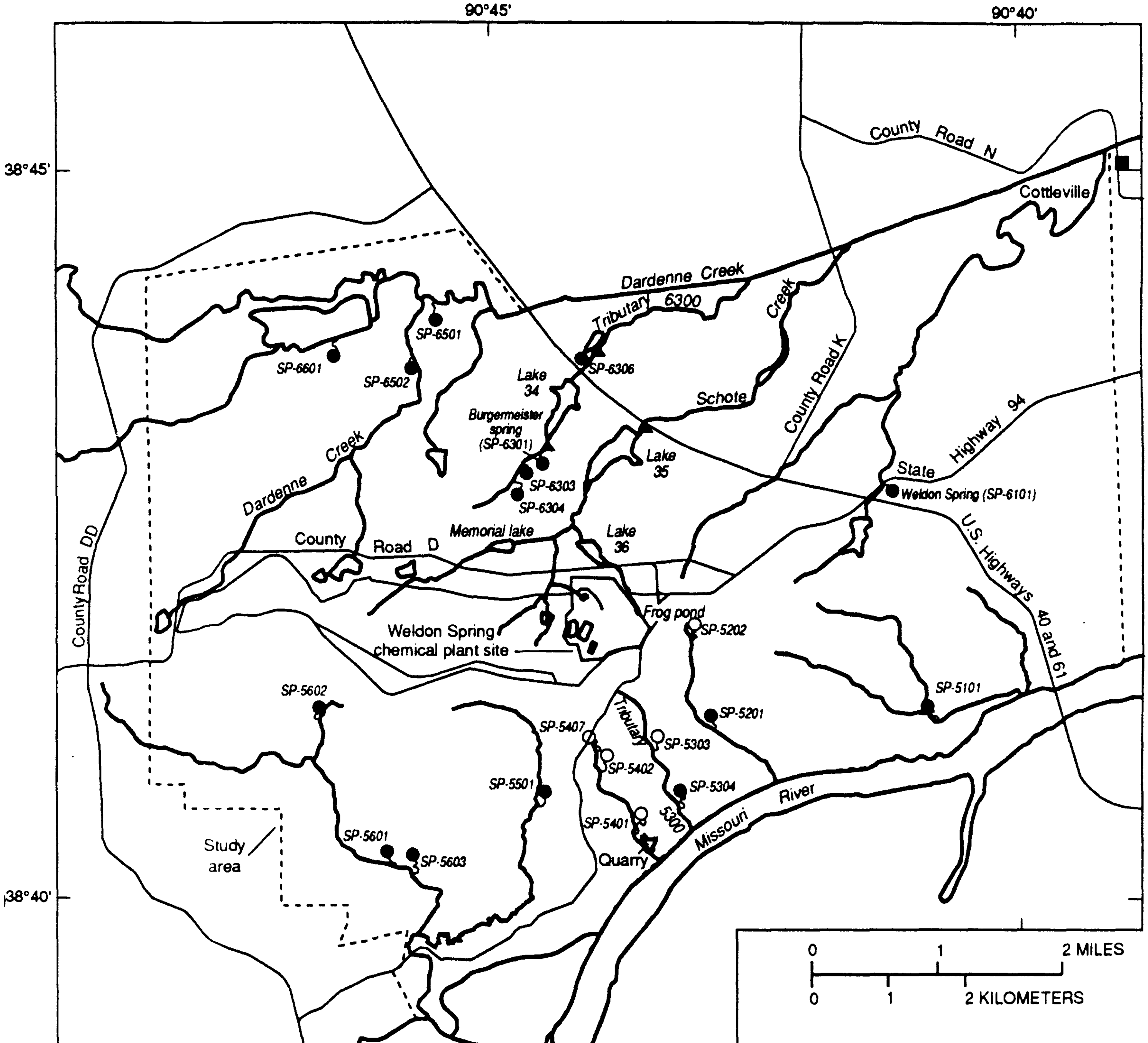


Figure 26. Vertical hydraulic gradients in the shallow aquifer, April 1991.



Base from U.S. Geological Survey, digital data 1:100,000, 1985
Universal Transverse Mercator Projection
Zone 15

EXPLANATION

SP-6303 ● PERENNIAL SPRING AND NUMBER

SP-5407 ○ WET-WEATHER SPRING AND NUMBER

▲ STREAM-GAGING STATION

Figure 27. Selected springs and stream-gaging stations in the study area.

stream-gaging station was installed approximately 0.25 mile downstream from U.S. Highways 40 and 61. A stage-discharge relation was developed for each site from current-meter discharge measurements. The mean daily discharges for these two streams are listed in a report by Kleeschulte and Cross (1990). The annual mean discharge at the gage on Schote Creek ranged from 0.12 to 0.21 cubic foot per second from October 1987 through September 1989. The annual mean discharge ranged from 2.38 to 4.03 cubic feet per second at the gage on tributary 6300 from August 1987 through September 1989. Both of these streams have at least one large lake located upstream from the stream gage on the August A. Busch Memorial Wildlife Area (fig. 2). These lakes were created for recreational purposes, but they also regulate stream flow by storing water and decreasing the peak discharge during storms by gradually releasing water from storage.

Three lakes are located on Schote Creek upstream from the gaging station. The Ahden-Hampton-Knight Memorial Lake, referred to as Memorial lake in this report, and Busch lake 35 (hereafter referred to as lake 35), are in the mainstem of Schote Creek; lake 36 is located on the eastern tributary that contains Frog pond. The drainage area of Schote Creek upstream from the gaging station is 3.3 square miles. During the period of record, the minimum discharge for Schote Creek was 0.01 cubic foot per second during August and September 1987, and the maximum discharge was about 6.8 cubic feet per second during December 1987.

Tributary 6300 has one large lake, Busch lake 34 (hereafter referred to as lake 34), in its drainage basin upstream from the gaging station. The drainage area of tributary 6300 upstream from the gaging station is 1.3 square miles. The minimum discharge for the period of record at this site was 0.44 cubic foot per second in July 1988, and the maximum discharge was about 58 cubic feet per second in December 1987 and February 1988. Schote Creek has about two and one-half times the surface drainage area of tributary 6300; however, because of losing stream reaches, the flow in Schote Creek is considerably less.

The ability of streams to maintain flow and transport sediment is significant in determining potential surface transport routes of contaminants. Flow-duration curves are indicators of hydrologic characteristics of drainage basins. Generally, the small tributary streams in St. Charles County have flow-duration curves that are characteristic of streams that derive most of their flow from direct runoff (Miller and others, 1974). Many streams in the Dissected Till Plains have minimal low-flow potential because of the small permeability of the underlying clay and shale. However, if the streambed fully penetrates the underlying clay or shale, it is possible for the streams to either gain or lose water.

Flow-duration curves were plotted from the discharge data collected from Schote Creek and tributary 6300 for their period of record (fig. 28). The steep slope of the flow-duration curve for Schote Creek indicates this stream derives much of its flow from direct runoff. The flattening of the curve at the smaller flows may be indicative of the seepage of surface water that is in storage in lake 35. Although flow in Schote Creek is affected by several lakes, this curve represents the general characteristics of the creek. Most of the year the reach of Schote Creek between Memorial lake and lake 35 has no flow.

Lake 34 is located upstream from the tributary 6300 stream-gaging station and tends to regulate peak flows in the stream. Four perennial springs in the basin also affect stream base flow. The flat slope of the flow-duration curve of tributary 6300 (fig. 28) indicates that the stream derives most of its flow from surface- or ground-water storage. Even though the drainage area of this stream is smaller than that of Schote Creek Basin, it has a larger sustained low flow than Schote Creek because the recharge area for springs in tributary 6300 (fig. 29) includes much of the surface-water basin drained by Schote Creek (fig. 24). The spring recharge areas were indicated by results of dye-tracing tests by the Missouri Department of Natural Resources (1991). Dye traces in losing stream reaches of Schote Creek and its tributaries indicate tributary 6300 receives water from the Schote Creek Basin upstream from U.S. Highways 40 and 61 and also receives flow from both the eastern and western unnamed tributaries of Schote Creek that drain the site (fig. 30). These dye traces are discussed in more detail in the "Surface- and Ground-Water Interaction" section of this report.

From August 1987 through September 1989, the total flow past the gage in tributary 6300 was 4,720

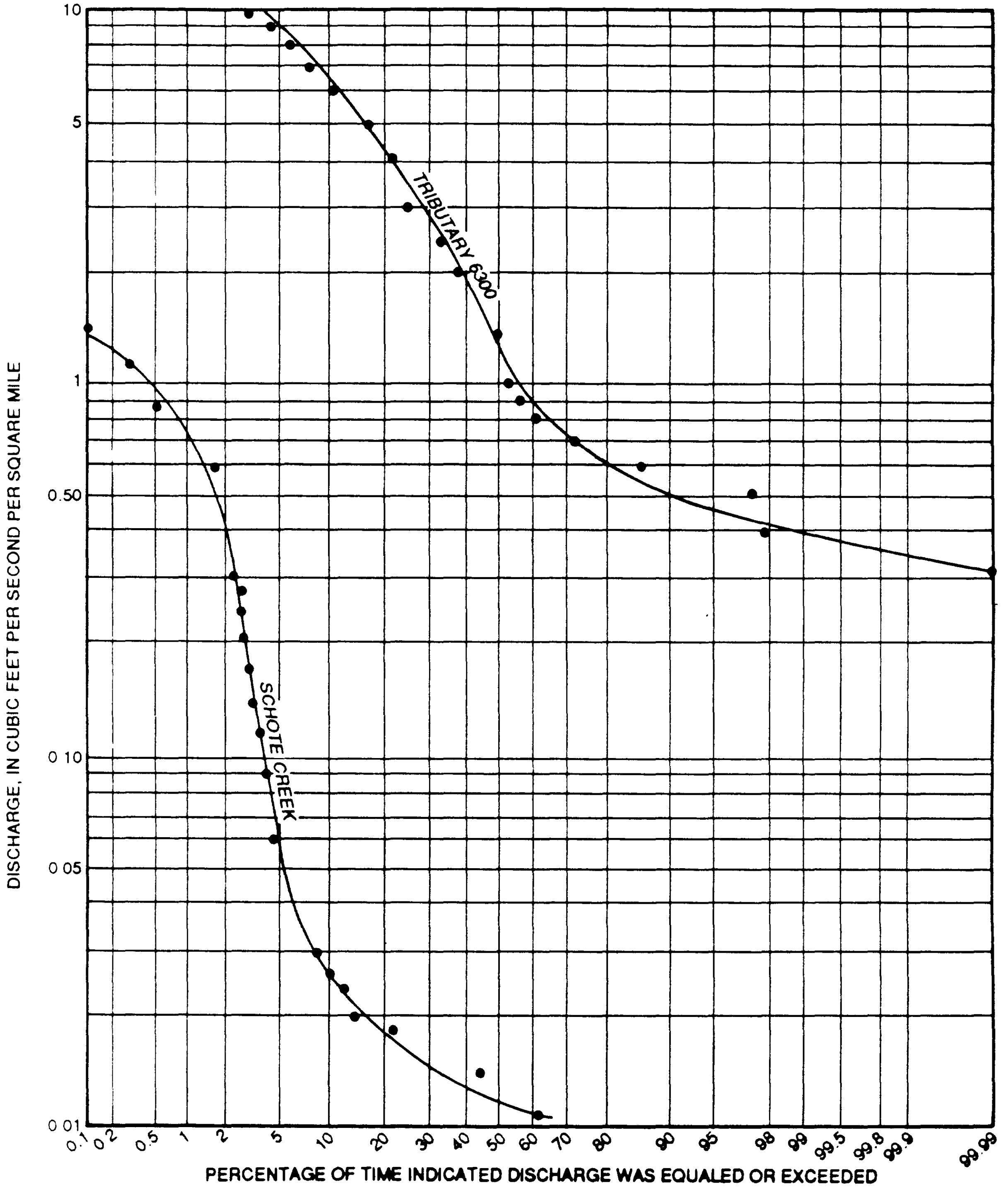


Figure 28. Flow-duration curves for Schote Creek and tributary 6300.

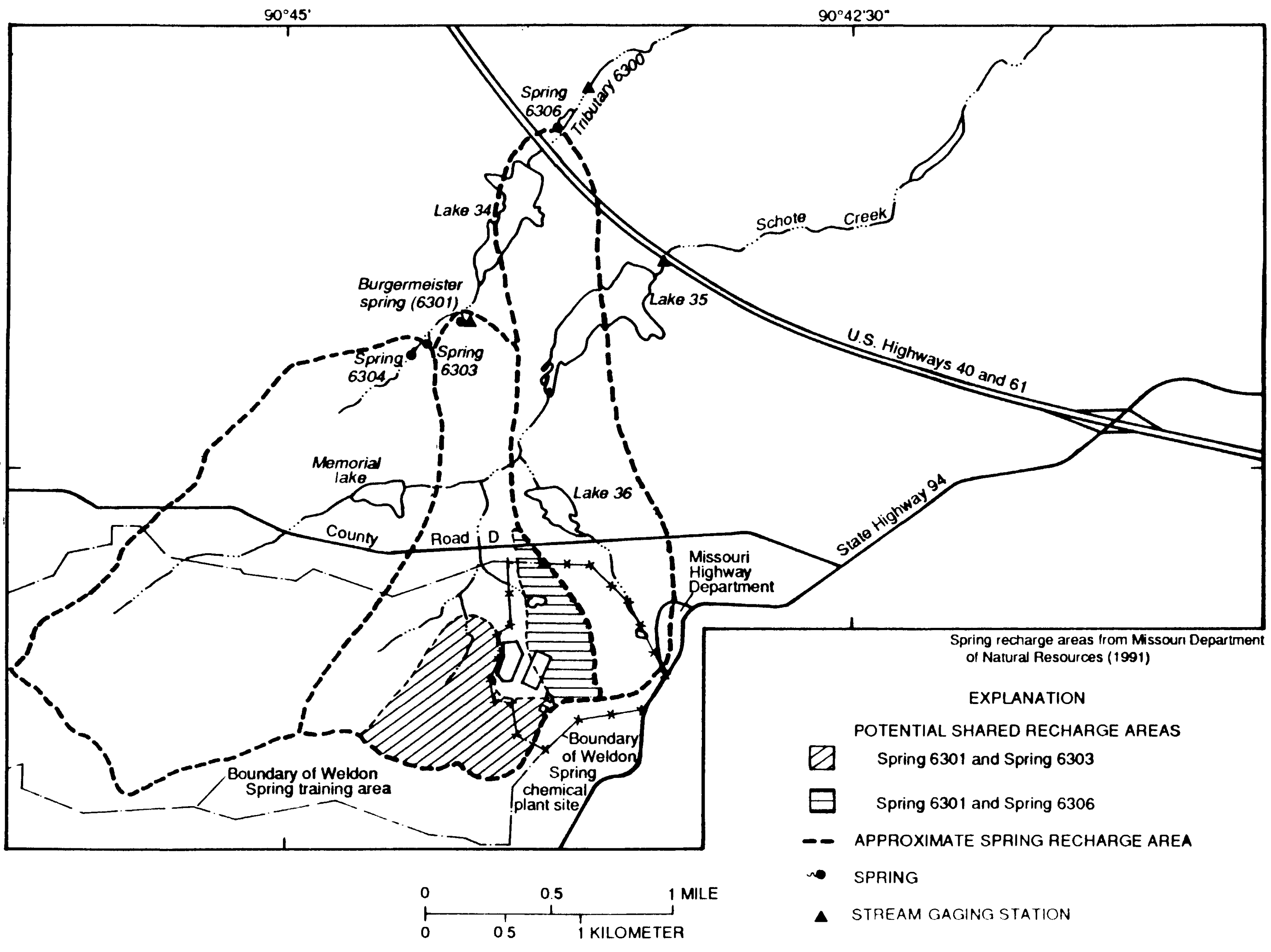


Figure 29. Spring recharge areas and stream-gaging stations in the study area.

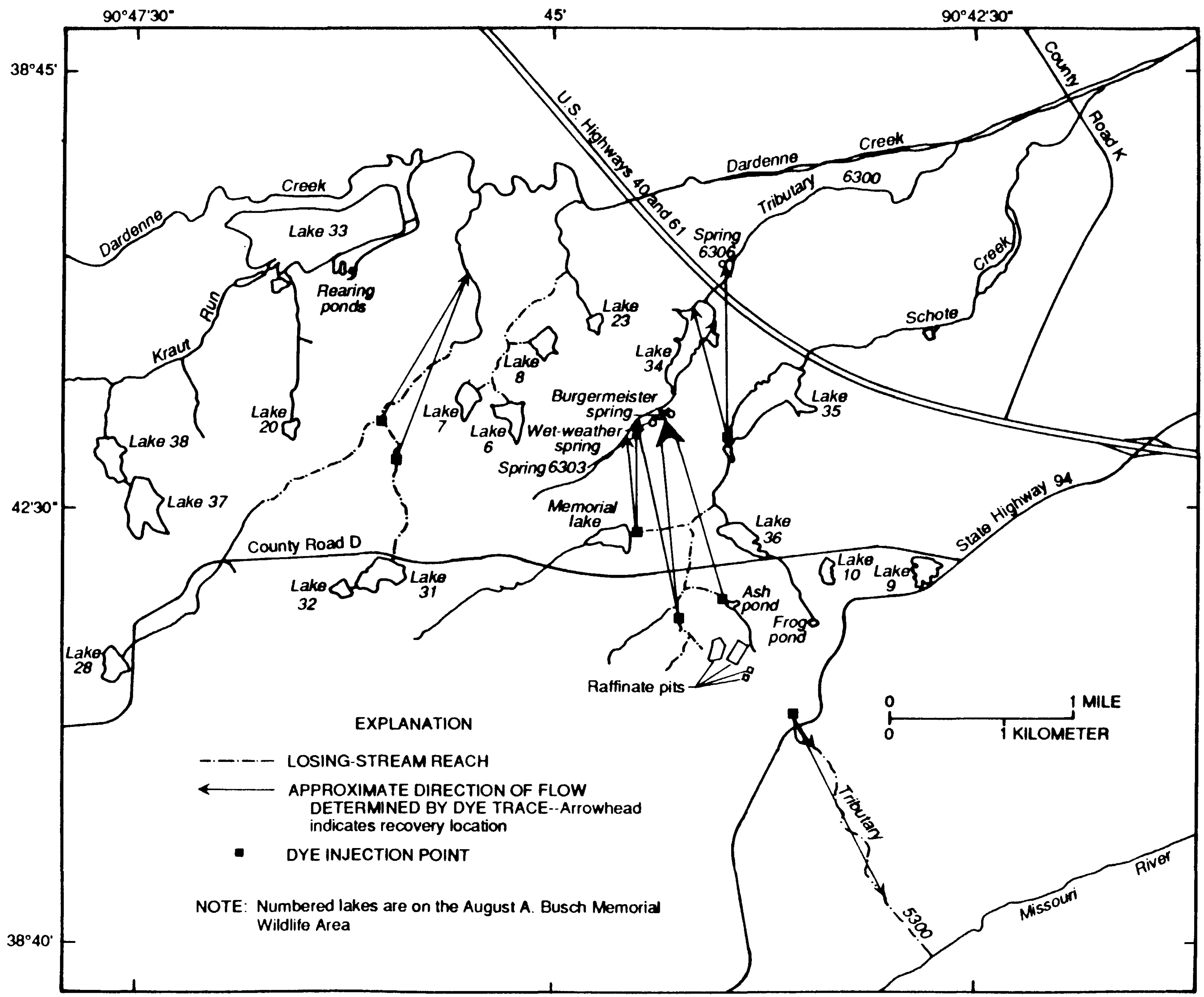


Figure 30. Dye-trace tests and results near the Weldon Spring chemical plant site (modified from Kleeschulte and Emmett, 1987; Missouri Department of Natural Resources, 1991).

acre-feet, and the total flow at the gage on Schote Creek was 242 acre-feet (Kleeschulte and Cross, 1990). During this same period, total-catch rain gages were maintained so precipitation in the 4.6-square-mile area, which includes the Schote Creek and 6300 tributary drainages, could be measured. Total measured precipitation to this area was 18,700 acre-feet (Kleeschulte and Cross, 1990). Based on the comparison of these precipitation data to the stream-flow data, about 25 percent of the precipitation to the area leaves as surface-water runoff.

Dardenne Creek is the third stream located north of the site that is of concern. It is a gaining stream throughout much of the measured reach. No continual stream-flow data were collected on this stream. However, a seepage run was made on Dardenne Creek in June 1990. Data obtained from the seepage run are discussed in the "Surface- and Ground-Water Interaction" section of this report. The potentiometric map (fig. 14) for the shallow aquifer also indicates that Dardenne Creek is a drain for the area north of the ground-water divide.

South of the chemical plant property, tributary 5300 (fig. 27) is the stream of primary concern. The Missouri Department of Natural Resources (1991) used a hydrant as a water source that kept the discharge constant and observed the flow characteristics of this stream. Water from the headwaters eventually, through gaining and losing segments of the stream, reached the mouth of the stream. No net water loss was detected. The lower part of the stream typically has sustained flow.

Water from streams in the study area typically is a calcium bicarbonate type. This includes water from the streams that flow to the Missouri River and drain the areas where the middle and deep aquifers crop out and the streams that flow north toward the Mississippi River. Crooked Creek (fig. 2) has larger sodium and chloride concentrations than the other streams, but the water still is predominantly a calcium bicarbonate type.

Surface- and Ground-Water Interaction

Streams in the study area usually are dry in their headwater reaches where the streambed is higher than the water table. Streamflow in these upper reaches occurs only when rainfall exceeds the rate of infiltration through the streambed and the storage capacity of the streambed. Downstream from the point where the streambed intersects the water table, streamflow usually increases and is continuous. Surface- and ground-water interaction through the streambed is affected by permeability of the streambed and permeability and porosity of the rock that have developed in the upper part of the aquifer.

In limestone and dolostone, permeability can vary greatly over short distances because of solution-enhanced permeability. Water percolating underground dissolves the rock, thereby enlarging subsurface flow paths. In time this process can cause streamflow characteristics to change. As flow paths enlarge, ground-water movement in the bedrock changes from flow through many small openings in the rock to flow in a few large, interconnected conduits. As the conduits become larger, more drainage occurs. Ground-water flow in these conduits can be turbulent, with velocities measured in hundreds of feet per hour. The conduits commonly terminate at springs that respond rapidly to storms. Streams flowing over limestone and dolostone where the water table lies below the streambed and where large solution openings have developed lose water to the subsurface (losing stream) because of the increased capacity of the aquifer to store and transport infiltrated water.

Several dye-trace tests have been made on the losing stream reaches of Schote Creek and its western unnamed tributary (fig. 30; Missouri Department of Natural Resources, 1991). During one of the tests, dye was injected in the middle fork of the western tributary of Schote Creek west of raffinate pit 4. The dye emerged at or in the vicinity of Burgermeister spring, which is in an adjoining surface-water drainage basin about 6,500 feet to the northwest. The estimated time of travel was 48 to 72 hours. Another test was done on the east fork of the western tributary of Schote Creek downstream from Ash pond. Four days after injection, dye was detected at Burgermeister spring and a wet-weather spring in the vicinity of Burgermeister spring. A third dye-trace test was performed using a swallow hole in the headwaters of lake 35 that was draining water from the lake. The dye was detected at lake 34, spring 6306, and in seeps on the right abutment or immediately downstream from the dam for lake 34 (Missouri Department of Natural Resources, 1991).

One method for determining the flow characteristics of a stream and the ability of the stream to exchange surface and ground water is by conducting a "seepage run." A seepage run is a series of stream discharge measurements made within a short period of time when flow is stable. Discharge measurements made during a seepage run on Dardenne Creek, during June 25 and 26, 1990 (fig. 31), indicated a net increase in flow from 3.1 cubic feet per second at County Road DD to 9.1 cubic feet per second at County Road N (fig. 31; Schumacher and others, 1993). Most of this increase in flow was from tributaries to Dardenne Creek. The seepage run was conducted during a transition between the high base-flow condition that occurs in the spring and the lower base-flow condition that occurs in the summer. Flow in the tributaries to Dardenne Creek were sustained by inflowing ground water from springs, and not by runoff from precipitation. On June 25, the reach between County Road DD to U.S. Highways 40 and 61 gained 2.1 cubic feet per second from tributary streams and another 0.7 cubic foot per second that is interpreted to be from diffuse ground-water inflow. The seepage run on Dardenne Creek was continued June 26. The measured flow at U.S. Highways 40 and 61 decreased 0.8 cubic foot per second from the previous day to a rate of 5.1 cubic feet per second. The reach from U.S. Highways 40 and 61 to County Road K gained 2.3 cubic feet per second from inflow of tributary streams and 1.9 cubic feet per second that could not be attributed to inflow from tributaries and thus is interpreted to be diffuse ground-water inflow. The reach from County Road K to County Road N lost 1.0 cubic foot per second of flow to the streambed. About 0.8 cubic foot per second entered Dardenne Creek from tributary streams; however, the flow at the downstream site at County Road N was 0.2 cubic foot per second less than at County Road K.

Before phase II began, another seepage run was conducted on six north-flowing tributaries to Dardenne Creek from Kraut Run to Crooked Creek during April 1 to 4, 1985 (Kleeschulte and others, 1986). During this seepage run, flow in tributary 6300 gradually increased downstream to the reach where Burgermeister spring flows into the tributary. Flow continued to increase until the stream entered the Dardenne Creek flood plain, where some flow was lost. Schote Creek lost flow for 0.7 mile downstream from Memorial lake. The middle and east forks of the western unnamed tributary of Schote Creek that drain the chemical plant and raffinate pits areas lost flow throughout most of their length. The eastern unnamed tributary of Schote Creek that drains Frog pond did not seem to lose flow.

WATER QUALITY

The water-quality sampling plan that was used in this project included the sampling of wells, springs, and surface-water sites. This approach was used because of the different ground-water flow systems present in the study area. Losing streams, sinkholes, springs, caves, and solution cavities are typical in karst environments; all are present in the St. Charles county area. At the Weldon Spring chemical plant site a system of conduit flow through fractures and solution openings in the weathered unit in the Burlington and Keokuk Limestones of the shallow aquifer is superimposed on a diffuse flow system in which the water moves through small interconnected openings in the unweathered unit (MK-Ferguson Company, 1987). Quinlan and Ewers (1986) state contaminant and ground-water flow in most karst aquifers and some fractured aquifers does not follow the dispersive diffuse flow characteristic of granular aquifers. They also stated that placement of solely sampling monitoring wells downgradient from a site in karst terrane is not an adequate monitoring approach because ground-water flow in these terranes is anisotropic, nonhomogeneous, and predominately confined to conduits and fractures. The probability of a well intercepting these flow zones is small. Because of the difference in the nature of ground-water flow through granular and karst aquifers, a ground-water sampling plan was developed to monitor both aspects, which included sampling monitoring wells and springs.

Twenty-seven surface-water sites, 19 springs, and 58 wells (figs. 31 and 32) were sampled in the study area from 1985 to 1989. The purpose of this sampling was to determine locations where water contami-

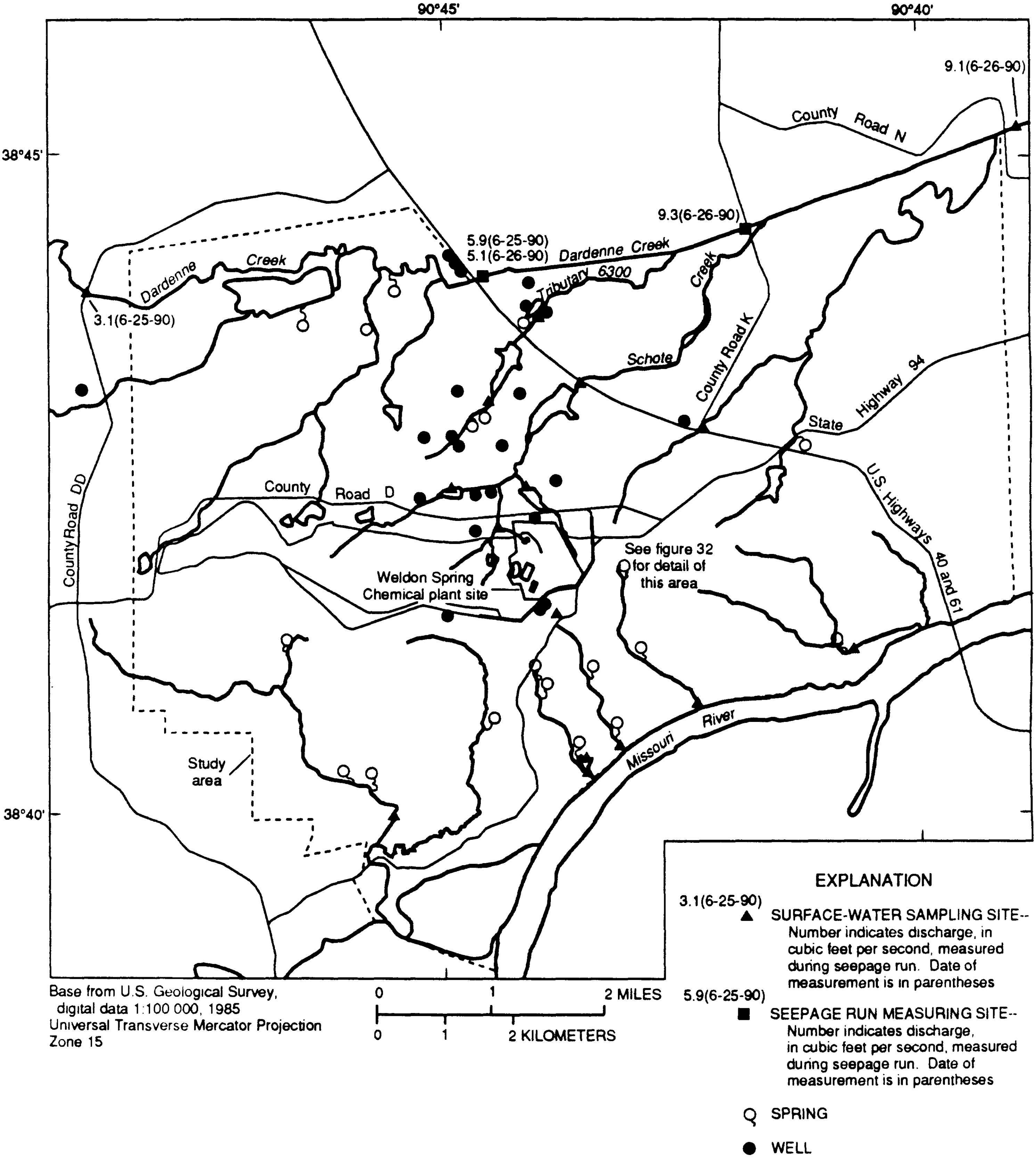
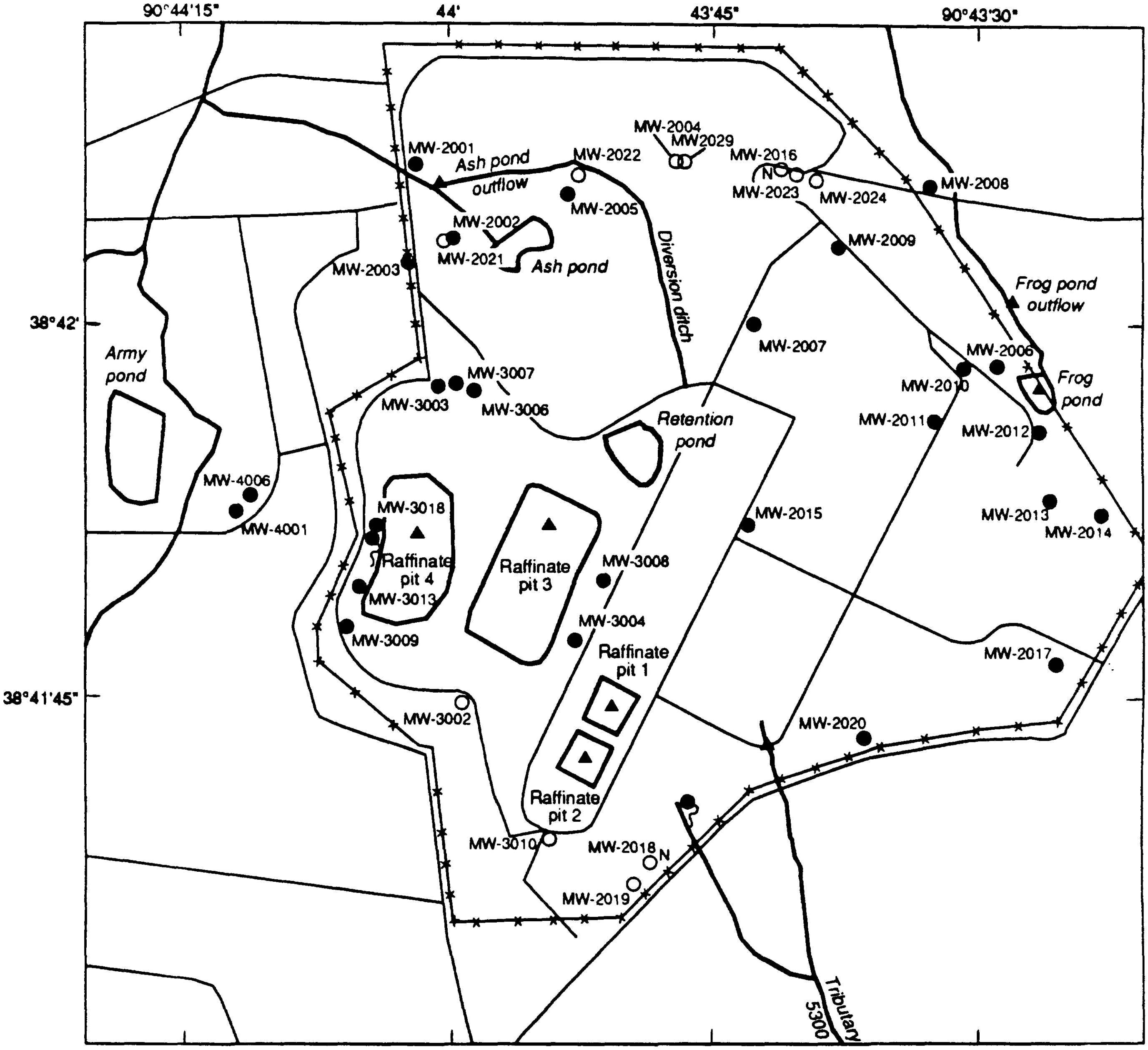


Figure 31. Summary of results of the Dardenne Creek seepage run, June 25 and 26, 1990, and sampling sites in the study area.



Base from U S. Geological Survey, digital data 1:100,000, 1985
Universal Transverse Mercator Projection
Zone 15

0 500 1,000 FEET
0 125 250 METERS

EXPLANATION

▲ SURFACE WATER SAMPLING SITE

SPRING OR SEEP

MW-2016
N○ MONITORING WELL AND NUMBER– Solid circle indicates concentrations of one or more chemical constituents were larger than background concentrations. Open circle indicates well that represents background conditions. N indicates data were inconclusive as to whether well represents background conditions

Figure 32. Sampling sites on and in the vicinity of the Weldon Spring chemical plant site.

nation that might be associated with the Weldon Spring chemical plant site has occurred. The sampling sites encircle the chemical plant except along the topographic ridge on the west side where there are no springs, and until the summer of 1989, no wells had been drilled. The sampled sites extend north to and include Dardenne Creek and south to the Missouri River. Many of these water-quality analyses have previously been reported by Kleeschulte and others (1986) and by Kleeschulte and Cross (1990).

The water-quality sampling sites initially selected and used for determination of background concentrations for the study area include wells and springs that were not located directly downgradient from the plant site and streams not affected by drainage from the site. Summary statistics of the water-quality analyses for these sampling sites were calculated by site type and are listed in table 2, at the back of this report. Categorizing the data by site type was done to better define the expected background concentrations for each chemical constituent. Variation in the concentrations of the same chemical constituent can be detected between streams, springs, and wells. For instance, ground water that has been in contact with geologic formations for an extended period has had an opportunity to dissolve minerals present in the rock. Thus, a water sample from a well in limestone or dolostone would be expected to have larger concentrations of calcium, magnesium, and bicarbonate than water from a stream. Similarly, ground water that has traveled through conduits in the subsurface and that discharges from springs would not have long residence times in the subsurface. The opportunity to dissolve minerals would be decreased, creating a possible discrepancy between the quality of water from a spring and that from a nearby well that is recharged by diffuse flow.

The calculated summary statistics used for the determination of background concentrations (table 2) include maximum, minimum, and mean values, as well as the 5th, 25th, 50th (median), 75th, and 95th percentiles. The 95th percentile value for each chemical constituent represents the concentration at which 95 percent of the samples is either equal to or less than. This calculated value was used to determine if a sampling site did indeed represent background conditions. An iterative procedure was followed. If a constituent value from one of these background sampling sites exceeded the 95th percentile range, the site was reevaluated to determine if the anomalous concentration was caused by contaminant migration from the chemical plant or if it was caused by another identifiable factor. If the water quality at a sampling site may have been affected by contaminants at the chemical plant, the sampling site was removed from background water-quality sites and listed as being contaminated. Then, the summary statistics were recalculated.

Because the water-quality-sampling program for this project has evolved during several years, analyses for some chemical constituents have been discontinued and others have been added. This variation in data set size caused an inability to calculate the 95th percentile for certain constituents, especially when the data set included a value that was much larger or smaller than the rest of the data set. When an outlier was present in a small data set, only the mean and median values were calculated to give an indication how the data were distributed. Also, when the data set contained numerous values less than the detection limit, the percentiles were not calculated because the calculated percentile values were considered unreliable and only maximum and minimum values were reported. These data are included in table 2 to give a range of background chemical concentrations but were not used in the determination of contaminant migration.

Weldon Spring Chemical Plant Site

Surface-water samples were collected from 10 locations at the chemical plant site that were known to have elevated uranium concentrations (Kleeschulte and others, 1986; Kleeschulte and Cross, 1990). These sampling sites include the four raffinate pits, Ash pond outflow, Frog pond, Frog pond outflow, a drainage ditch that flows into tributary 5300, and two seeps (fig. 32). One seep flows into tributary 5300 and the other is at the base of the west levee of raffinate pit 4 and flows into the west tributary of Schote Creek. These 10 sites were sampled to determine, in addition to uranium, the most probable chemical constituents associated with wastes at the chemical plant that have the potential to affect local surface and ground water because they are present in concentrations larger than background.

Affected offsite locations (fig. 33) also were determined. Results of the water-quality sampling are shown in table 3 along with background concentrations for the different site types. When a chemical concentration exceeded background concentrations at a sampling site, the site was listed in table 3 along with the maximum concentration detected at the site. Surface-water impoundments are considered as streams in table 3 because their water quality would most resemble a stream instead of a well or spring. Most of the water-quality data used in table 3 are listed in reports by Kleeschulte and others (1986) and by Kleeschulte and Cross (1990).

Water samples from the raffinate pits contained anomalously large concentrations of calcium, magnesium, sodium, sulfate, nitrate, lithium, strontium, and uranium (Kleeschulte and others, 1986; Kleeschulte and Cross, 1990). Additionally, analysis of the interstitial water and sludge in the bottom of raffinate pit 3 indicated concentrations of most of these constituents increased with depth (Schumacher, 1993).

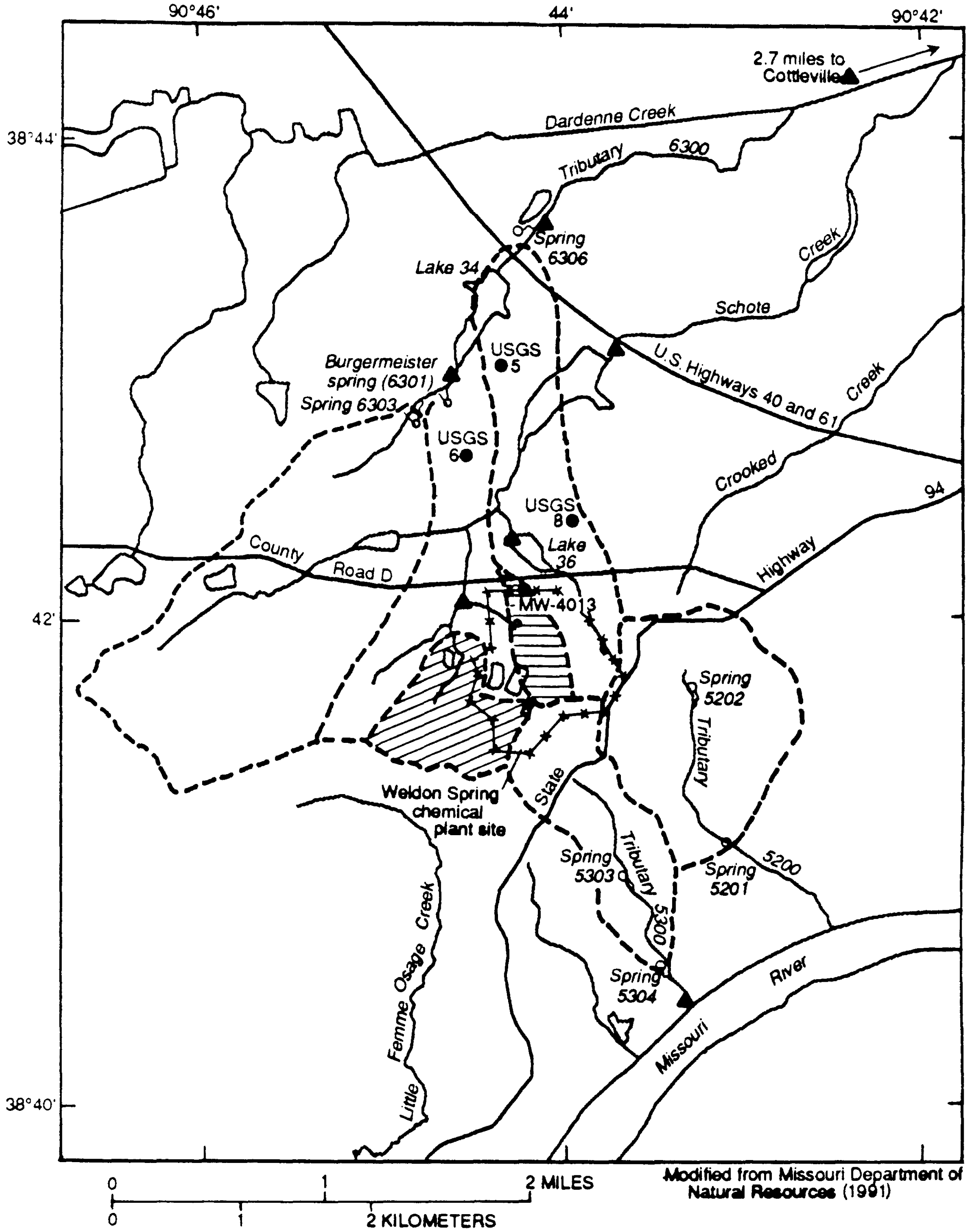
Water samples from Ash pond have large concentrations of uranium and elevated concentrations of nitrate and lithium. During one of the five sampling events, water from Ash pond had elevated concentrations of either sulfate or strontium. Ash pond received runoff from the north and west part of the site. One source of the large uranium concentration in Ash pond water is radiologically contaminated sediments in the Ash pond drainage basin that were transported into the pond by runoff (Kleeschulte and Emmett, 1987). During 1989, to decrease the flow of water into and out of Ash pond, the U.S. Department of Energy constructed a retention pond at the upstream reach of the Ash pond drainage and a diversion ditch to drain runoff around Ash pond (fig 32). These structures decreased the volume of water flowing into Ash pond and, therefore, decreased the volume of water available for leaching uranium out of the sediments in the pond and the volume of water flowing from the pond. However, water-quality data collected from October 1989 through July 1991 for the retention pond (data on file at U.S. Geological Survey, Rolla, Missouri) indicates the retention pond typically has a large uranium concentration (the maximum sampled concentration was 500 micrograms per liter) and elevated sulfate, nitrate, lithium, and strontium concentrations.

Water from Frog pond has large concentrations of sodium, chloride, and uranium and elevated concentrations of lithium and strontium. The large sodium and chloride concentrations probably are caused by runoff from a maintenance shed during intense rainfall. Salt is stored at the maintenance shed for road deicing during winter storms; some of this salt has washed off the storage area into the eastern tributary of Schote Creek, thereby increasing the sodium and chloride concentrations in the water (Kleeschulte and others, 1986; Kleeschulte and Cross, 1990). Corrective measures made during 1991 on the maintenance shed property are expected to remediate this situation. Water from Frog pond enters the east tributary of Schote Creek and flows into lake 36 before reaching the main stem of Schote Creek.

A drainage ditch on the southern part of the chemical plant site which occasionally has flowing water and a seep about 400 feet southeast of raffinate pit 2 both discharge into tributary 5300. Both of these sources have elevated concentrations of sulfate and uranium (table 3). The drainage ditch had one nitrate and one strontium concentration that exceeded the background concentration during the two sampling events. The seep typically also contains elevated concentrations of calcium, magnesium, sodium, nitrate, lithium, and strontium.

Water samples from a seep at the west levee of raffinate pit 4 has elevated concentrations of calcium, magnesium, sodium, sulfate, lithium, strontium, and uranium. Water from this seep flows into the middle fork of the west tributary of Schote Creek (fig. 32).

Water from 26 wells sampled onsite by the U.S. Geological Survey had concentrations of various chemical constituents that were larger than background water-quality concentrations (table 3 and fig. 32). The constituents with elevated concentrations listed in table 3 were detected in various combinations in the different wells. Water from one well located onsite (MW-2016) had a constituent concentration that was larger than background; however, the data were considered inconclusive as to whether the well was affected by the site. Well MW-2016 had one lithium concentration that exceeded the background concentration during the three



EXPLANATION

POTENTIAL SHARED RECHARGE AREAS

- Spring 6301 and Spring 6303
- Spring 6301 and Spring 6306

APPROXIMATE SPRING RECHARGE AREA

SITES WITH CONCENTRATIONS OF ONE OR MORE CONSTITUENTS LARGER THAN BACKGROUND CONCENTRATIONS

- USGS 5 ● Well and number
- Spring 6303 Perennial spring and number
- ▲ Surface-water site

Figure 33. Locations outside the Weldon Spring chemical plant site where concentrations of one or more constituents in surface and ground water were larger than background concentrations.

Table 3—Maximum chemical constituent concentrations from water-quality samples with one or more constituent concentrations larger than background concentrations

[Ca, calcium; Mg, magnesium; Na, sodium; SO_4, sulfate; Cl, chloride; NO_3, nitrate; Li, lithium; Sr, strontium; U, uranium; background concentrations rounded to nearest whole number; NA, not applicable; --, indicates the site did not exceed the background concentration for this constituent]

Site (figs. 32 and 33)	Number of sampling events	Maximum constituent concentration: Dissolved, in milligrams per liter						Dissolved, in micrograms per liter		
		Ca	Mg	Na	SO_4	Cl	NO_3	Li	Sr	U
SAMPLING SITES AT WELDON SPRING CHEMICAL PLANT SITE										
Surface Water										
Background concentrations	NA	99	25	36	76	42	1	9	159	3
Raffinate pit 1	7	560	29	1,000	400	[a]51	668	300	1,400	46
Raffinate pit 2	7	380	90	220	1,200	--	205	280	780	1,200
Raffinate pit 3	11	880	600	3,300	830	--	1,990	4,200	2,800	350
Raffinate pit 4	8	--	52	190	150	--	92	660	190	4,000
Ash pond outflow	5	--	--	--	[a]84	--	12	23	[a]170	4,000
Frog pond	3	--	--	110	--	160	--	19	[a]200	280
Frog pond outflow	6	--	--	300	--	500	--	20	290	410
Drainage ditch tributary 5300	2	--	--	--	94	--	[a]5	--	[a]160	5,400
Springs										
Background concentrations	NA	97	24	17	54	14	1	11	140	1
Seep tributary 5300	5	140	25	51	130	--	61	24	330	2,400
Seep west levee raffinate pit 4	7	210	72	20	720	--	--	18	390	13
Wells										
Background concentrations	NA	82	47	30	32	8	2	13	220	3
MW-2001	2	[a]84	--	--	--	--	12	--	--	--
MW-2002	1	260	85	110	100	--	220	450	360	--
MW-2003	3	560	190	240	220	21	680	1,000	1,100	--
MW-2005	3	[a]86	--	--	--	--	36	39	--	--
MW-2006	3	130	56	81	[a]35	250	13	15	--	--
MW-2007	1	--	--	--	--	--	--	--	--	5
MW-2008	1	110	--	--	33	57	4	--	--	--
MW-2009	1	160	--	39	83	21	--	--	--	--
MW-2010	1	110	--	50	33	81	--	--	--	--
MW-2011	1	--	--	--	--	--	4	--	--	--
MW-2012	1	130	--	86	56	110	--	--	--	--
MW-2013	1	150	--	87	--	11	--	14	--	--
MW-2014	1	120	--	32	37	29	2	--	--	--
MW-2015	1	83	67	--	85	--	--	18	250	--
MW-2016	3	--	--	--	--	--	--	[a]21	--	--
MW-2017	1	170	140	37	660	17	--	39	440	10
MW-2018	1	--	--	46	--	--	--	18	290	--
MW-2020	3	150	70	54	270	9	--	40	270	49
MW-3003	2	320	150	230	200	13	440	740	830	23
MW-3004	1	110	--	170	39	--	130	20	390	--
MW-3006	2	--	52	37	71	--	14	45	230	--
MW-3007	3	820	320	340	320	35	940	1,700	1,600	6

Table 3—Maximum chemical constituent concentrations from water-quality samples with one or more constituent concentrations larger than background concentrations—Continued

Site (figs. 32 and 33)	Number of sampling events	Maximum constituent concentration: Dissolved, in milligrams per liter: Ca	Mg	Na	SO_4	Cl	NO_3	Dissolved, in micrograms per liter: Li	Sr	U
SAMPLING SITES AT WELDON SPRING CHEMICAL PLANT SITE--Continued										
Wells--Continued										
MW-3008	4	920	240	300	62	28	1,100	260	3,200	7
MW-3009	5	94	55	--	65	--	84	[a]16	--	110
MW-3013	1	190	73	--	700	--	2	22	1,200	--
MW-3018	1	200	55	230	220	11	130	40	440	9
SAMPLING SITES IN THE STUDY AREA										
Tributary 5300										
Background concentrations for stream sites	NA	99	25	36	76	42	1	9	159	3
Background concentrations for spring sites	NA	97	24	17	54	14	1	11	140	1
Spring 5303	4	--	--	[a]20	[a]59	--	2	[a]15	[a]150	390
Spring 5304	3	--	--	--	--	--	4	17	--	220
Tributary 5300 at mouth	3	--	--	--	--	--	2	17	--	220
Schote Creek										
Background concentrations for stream sites	NA	99	25	36	76	42	1	9	159	3
West tributary of Schote Creek near County Road D	4	--	--	--	--	--	--	--	--	4,600
East tributary of Schote Creek at Busch Lake 36 outflow	7	--	--	83	--	130	[a]5	[a]10	[a]200	51
Schote Creek at U.S. Highways 40 and 61	6	--	--	--	--	--	--	--	220	14
Tributary 6300										
Background concentrations for stream sites	NA	99	25	36	76	42	1	9	159	3
Background concentrations for spring sites	NA	97	24	17	54	14	1	11	140	1
Spring 6303	4	--	[a]25	19	--	--	16	12	150	4
Burgermeister spring	12	120	30	47	[a]57	37	54	77	220	250
Tributary 6300 upstream from Busch Lake 34	2	--	[a]26	[a]34	--	[a]24	28	[a]35	[a]180	94
Spring 6306	5	--	--	--	--	[a]18	--	--	150	18
Tributary 6300 near U.S. Highways 40 and 61	7	--	--	--	--	--	--	--	--	25

Table 3–Maximum chemical constituent concentrations from water-quality samples with one or more constituent concentrations larger than background concentrations–Continued

Site (figs. 32 and 33)	Number of sampling events	Maximum constituent concentration: Dissolved, in milligrams per liter: Ca	Mg	Na	SO_4	Cl	NO_3	Dissolved, in micrograms per liter: Li	Sr	U
SAMPLING SITES IN THE STUDY AREA--Continued										
Dardenne Creek										
Background concentrations for stream sites	NA	99	25	36	76	42	1.3	9.0	159	2.7
Dardenne Creek near Cottleville	6	--	--	--	--	--	--	--	--	4
Wells										
Background concentrations	NA	82	47	30	32	8	2	13	220	3
MW-4001	1	92	--	--	69	--	31	--	--	--
MW-4006	3	--	--	--	50	--	4	--	--	--
MW-4013	1	140	51	37	41	--	74	68	--	--
USGS 5	6	[a]86	--	--	--	--	--	[a]15	--	4
USGS 6	7	--	--	--	--	--	--	--	--	6
USGS 8	7	--	--	--	--	[a]12	10	--	--	--

[a]Indicates site exceeded background concentrations for this chemical constituent only during one sampling event.

sampling events, but all other constituents were within the range for background concentrations.

Study Area

After the water sources with large chemical constituent concentrations were identified at the chemical plant site, the monitoring of streams, springs, and wells in the study area began to assess the possible effect of the chemical plant on area water quality. Several of these hydrologic features were identified as being affected by the chemical plant site (fig. 33) and they are listed in table 3. The stream and spring sampling sites in table 3 are arranged in downstream order in their respective basins.

Water-quality analyses from tributaries in the area identified four tributaries that are contaminated with various chemical constituents associated with the chemical plant site. These tributaries include tributary 5300, Schote Creek and its tributaries, tributary 6300, and Dardenne Creek near Cottleville (fig. 33).

Tributary 5300 has large concentrations of uranium and elevated nitrate and lithium concentrations. This tributary receives surface runoff from the southern part of the site and small quantities of flow from the drainage ditch and seep onsite. Two perennial springs (springs 5303 and 5304) that discharge into tributary 5300 were identified as being contaminated with nitrate and uranium (fig. 33). Spring 5303 during four sampling events had one elevated sodium, sulfate, lithium, and strontium concentration. Water from spring 5304 typically also had elevated lithium concentrations.

The west and east tributaries of Schote Creek and Schote Creek mainstem have concentrations of one or more chemical constituents that exceeded background concentrations (table 3; fig. 33). Ash pond drainage and the seep at the west levee of raffinate pit 4 both discharge into the west tributary of Schote Creek (fig. 32). During base-flow conditions, the discharge in the west tributary near County Road D typically is 0.10 cubic foot per second or less. This tributary consists of losing stream segments that are hydrologically connected to Burgermeister spring (figs. 30 and 33; Missouri Department of Natural Resources, 1991). The uranium concentration at this site during one runoff sample was 4,600 micrograms per liter (Kleeschulte and others, 1986), more than an order of magnitude larger than the uranium concentration that typically is detected there during base-flow sampling. The additional uranium probably came from runoff out of Ash pond.

Water flowing out of lake 36 into the east tributary of Schote Creek generally had elevated concentrations of sodium, chloride, and uranium. During the seven sampling events there was one elevated nitrate, lithium, and strontium concentration (table 3). These constituent concentrations detected in water flowing from lake 36 were lower than the concentrations detected in Frog pond. The decreased concentrations may be caused by dilution because the lake also receives runoff from areas unaffected by the chemical plant. The east tributary is not considered a losing stream but the mainstem of Schote Creek downstream from where the east tributary enters Schote Creek has losing stream segments that are hydrologically connected to tributary 6300 (figs. 30 and 33).

The water sampled in the mainstem of Schote Creek at U.S. Highways 40 and 61 is a composite of the water flowing into the creek from the west and east tributaries. This water typically has elevated concentrations of strontium and uranium. This was also the site of a stream gaging station.

Analysis of water samples from tributary 6300 indicate three perennial springs (spring 6303, Burgermeister spring, and spring 6306) and two surface water sites that are contaminated (table 3; fig. 33). Spring 6303, the most upstream spring sampled in the tributary, had large concentrations of nitrate and elevated concentrations of sodium, lithium, strontium, and uranium. During one of the four sampling events the magnesium concentration increased. Flow in spring 6303 ranged from 0.02 to 0.20 cubic foot per second during sampling events (Kleeschulte and Cross, 1990). Water from Burgermeister spring generally had large concentrations of nitrate and uranium and elevated concentrations of calcium, magnesium, sodium, chloride, lithium, and strontium. During one sampling event sulfate concentrations were elevated.

A surface-water sampling site in tributary 6300 is 200 feet downstream from where Burgermeister spring branch enters tributary 6300 and 400 feet upstream from lake 34. Water at this site had large concentrations of nitrate and uranium, and during the two sampling events the site had elevated concentrations of magnesium, sodium, chloride, lithium, or strontium (table 3; fig. 33) during one sampling event. Discharge ranged from 0.10 to 0.60 cubic foot per second during the two sampling events at this site.

Spring 6306 is located north of U.S. Highways 40 and 61 and within 100 feet of tributary 6300 at the closest point. A buried channel or conduit has developed between the tributary and spring 6306 allowing surface water from tributary 6300 to enter the spring pool. While care was taken during sampling to collect water from the spring orifice, it is not certain that the entire water sample came from the spring orifice. Spring 6306 consistently had elevated strontium and uranium concentrations and on one occasion had an elevated chloride concentration. Discharge from the spring orifice was difficult to measure because of the added discharge from tributary 6300, but the sum of the two sources in the spring branch ranged from 0.40 to 1.0 cubic foot per second during the five sampling events. The water-quality data from spring 6306 were not similar to any of the upstream spring sites in tributary 6300.

The most downstream water-sampling site in tributary 6300 was north of U.S. Highways 40 and 61 (fig. 33) and also was the site of a stream-gaging station. Downstream from this location the flow in the tributary increased only slightly until it reached Dardenne Creek. This site had an elevated uranium concentration.

Elevated concentrations of uranium were identified in Dardenne Creek at County Road N near Cottleville. All the sampling was done during either low- or high-base-flow periods and the discharge ranged from 2.1 to 30 cubic feet per second during the sampling events. This is the most downstream site sampled north of the chemical plant.

Water-quality data from tributary 5200 were inconclusive as to whether the tributary is affected by the site (fig. 33). Also, water-quality data from spring 5202, which is in the headwater of this drainage basin, are considered inconclusive, and no determination was made as to whether the spring receives recharge from the site. Although the data were inconclusive, a discussion of the results is relevant. Concentrations of dissolved uranium less than 1.0, 2.9, and 5.0 micrograms per liter have been detected in spring 5202 (Kleeschulte and Cross, 1990). During the two sampling events when the uranium concentration was greater than the background concentration of 1.2 micrograms per liter, the discharge from the spring was less than 0.01 cubic foot per second. Discharge from the spring was 0.10 cubic foot per second during the other sampling event. No other chemical constituent was larger than background concentrations in this spring. The largest spring in tributary 5200 (spring 5201) is about 0.75 mile upstream from the mouth of the tributary and water-quality data do not indicate the spring is affected by the chemical plant.

Six wells offsite but in the study area have been identified as being contaminated using background concentrations as a criteria (table 3; figs. 32 and 33). Two wells are on the Weldon Spring training area (wells MW-4001 and MW-4006) and the other four wells are on the August A. Busch Memorial Wildlife Area (wells MW-4013, USGS 5, USGS 6, and USGS 8). Generally these wells have elevated concentrations of either calcium, sulfate, nitrate, or uranium, or various combinations of these constituents. However, water samples from well MW-4013 also had elevated concentrations of magnesium, sodium, and lithium; well USGS 5 had one elevated calcium and one elevated lithium concentration; and one sample from well USGS 8 had elevated chloride concentrations.

Conceptual Model of Contaminant Migration

Analyses of water samples from wells adjacent to the raffinate pits at the Weldon Spring chemical plant site indicated that contaminants from the pits have seeped downward through the unconsolidated surficial materials into the ground-water system and are present in the underlying bedrock (Kleeschulte and Emmett, 1987). Results of a water budget analysis for the raffinate pits for the period 1983 to 1985 is consistent with seepage of water from the pits through the underlying clays (Bechtel National, Inc., 1986b). These results help to explain the areas of saturated surficial materials seismically detected during 1983 beneath pit 3 and extending to the east and west of pit 3 (Bechtel National, Inc., 1984).

The water-quality data indicate the largest concentrations of the various chemical constituents detected in the ground water are at the site near the raffinate pits area. However, ground-water samples from the chemical plant had small concentrations of uranium when compared to concentrations of uranium in surface-water samples onsite. The calcium, magnesium, sodium, sulfate, nitrate, lithium, strontium, and uranium concentrations were largest in wells near the raffinate pits and decreased with distance from the pits. The number of reliable chemical indicators of affected ground water, including spring discharge, decreases as the distance of sampling sites from the chemical plant increases. Offsite, the reliable chemical indicators included nitrate and uranium, and to a lesser degree, lithium and strontium. Uranium was the only consistent indicator at the surface-water sites that showed water-quality effects from the site.

A conceptual model was developed to help explain why the concentrations of certain chemical constituents in ground water decreased rapidly with distance from known sources and why there was the lack of a well-defined plume of these chemical constituents detected offsite, particularly to the north. This conceptual model was aided by laboratory sorption experiments performed to evaluate the effect of solution pH value and equilibration time on sorption of the constituents of concern. These experiments showed calcium, sodium, sulfate, nitrate, and lithium were not substantially sorbed and, therefore, were likely to migrate from the pits. The experiments also showed that uranium should be completely sorbed within the overburden and is a possible explanation for the infrequent detections of uranium in monitoring wells except near the raffinate pits (table 3; fig. 32). The laboratory experiments were not conclusive as to the fate of magnesium and strontium; however, magnesium will be partially sorbed but strontium has the ability to migrate from the pits (Schumacher, 1993).

The conceptual model indicates that, during downward migration, water from the raffinate pits eventually reaches a zone where the horizontal permeability increases, such as the residuum layer (where present), the weathered limestone unit, or dissolution features or fractures oriented parallel to the bedding in the limestone. The water may then flow laterally through this permeable zone until a vertical fracture or other route is encountered where the water continues its downward migration to the water table. This explains why uranium is detected in monitoring wells near the raffinate pits when laboratory experiments show the uranium has the potential to be completely sorbed by the overburden. Other possible explanations are saturation of available sorption sites or the formation of weakly sorbed uranium carbonate complexes within the overburden (Schumacher, 1993).

No well-defined plume of large concentrations of chemical constituents has been detected offsite even though ground-water-quality changes have been detected north of the site in springs in tributary 6300 and in a few wells on the August A. Busch Memorial Wildlife Area and the Weldon Spring training area. The recharge areas for springs in tributary 6300 were defined by the Missouri Department of Natural Resources (1991) and are shown in figures 29 and 33. The recharge areas for Burgermeister spring (6301), spring 6303, and spring 6306 include areas that are areally within the drainage basin of Schote Creek and drain the northern part of the site. In these spring recharge areas, there is an interbasin transfer of water through preferred paths (conduits) from the Schote Creek Basin to tributary 6300. Contaminants leaving the site seem to be confined to conduits and fractures offsite. The likelihood of being able to delineate these flow zones is small because there are no surface expressions to aid in locating them.

The conceptual model also indicates that the preferred ground-water flow paths include the bedrock troughs found in the top of the Burlington and Keokuk Limestones. Well MW-4013 is located in the ground-water trough near County Road D and analyses of water samples from this well indicate effects from the site (table 3). The upper 10 to 50 feet of limestone at the chemical plant is weathered, highly to moderately fractured, and contains solution features ranging from vugs to small cavities; such conditions and features provide routes capable of transporting ground water rapidly. The water-table map for the study area (fig. 24) and the map of the top of the Burlington and Keokuk Limestones (fig. 8) indicate the ground-water troughs coincide with troughs formed in the top of bedrock. This coincidence extends from the chemical plant to Burgermeister spring and indicates the bedrock troughs may have formed in areas of large permeability and may drain or channel water toward Burgermeister spring. Wells MW-4001 and MW-4006 are located in the bedrock trough west of raffinate pit 4 and also indicate water-quality changes associated with the chemical plant.

Water in the shallow aquifer in the area north of Dardenne Creek would not be expected to show any water-quality effects associated with the chemical plant. This is based partially on work by V.C. Fischel and C.C. Williams (written commun., 1944) during the U.S. Army trinitrotoluene (TNT) production at the ordnance works (which included areas of the Weldon Spring chemical plant). During the production from November 1941 through January 1944, frequent spillover of red-sulfonate derivatives from wooden production-line disposal pipes and overflows of the catchment tanks occurred. These spills contaminated both the surface- and ground-water resources of the area and were large enough to cause the water in several springs near the ordnance works, as well as the water in Schote Creek, Dardenne Creek, and several of their tributaries, to be visibly red at times. These spills provided the first dye-trace tests (although unintentional and uncontrolled) to indicate subsurface hydraulic connections in the area. Using a systematic sampling program while investigating the extent of contamination, Fischel and Williams (written commun., 1944) concluded the contamination was limited to streams, springs, and wells south of Dardenne Creek and northwest of Schote Creek. Streams entering Dardenne Creek from the north contained uncontaminated water, as did the flowing tributaries downstream from Schote Creek that entered Dardenne Creek from the south.

Additional evidence that the chemical plant does not affect ground water in the shallow aquifer north of Dardenne Creek is the potentiometric surface map drawn on the basis of water-level measurements made in 1984 (fig. 14). Ground-water levels on both sides of Dardenne Creek are higher than the water level in the creek, which indicates that ground water on both sides of the creek drains toward the creek. The ground-water flow direction in the shallow aquifer immediately north of Dardenne Creek is to the south toward the creek, not from the creek into the ground-water system north of the creek. Most of the uranium detected at the Cottleville site probably enters the creek in flow from tributary 6300.

Tributary 5300 shows detectable ground-water-quality changes associated with the chemical plant site. Sources for these changes include the drainage ditch and seep on the southern part of the site. Another possible source for uranium in tributary 5300 includes residual uranium from the liquid radioactive wastes that were drained by way of the tributary into the Missouri River when the uranium feed material plant was in operation. The water-table map of the study area (fig. 24) indicates that ground water from the chemical plant south of the ground-water divide has the potential to discharge to springs in this tributary. Dye-tracing tests and other hydrologic studies performed in this basin by the Missouri Department of Natural Resources (1991) indicate tributary 5300 has several losing and gaining stream segments (fig. 30). However, the water flowing in the basin that is lost in the losing stream segments is not lost to adjacent basins. There is no interbasin transfer of water out of tributary 5300, so water introduced into this basin stays in the basin.

SIMULATION OF GROUND-WATER FLOW

The three-dimensional finite-difference ground-water flow model (MODFLOW) developed by McDonald and Harbaugh (1988) was used to test concepts of ground-water flow in the shallow aquifer (layer 1), the middle aquifer (layer 2), and the deep aquifer (layer 3) in the study area. The model was constructed and calibrated to steady-state conditions during both predevelopment conditions (no pumping stresses) and with the known pumping stresses that occurred in 1984. The rate of ground-water leakage between the aquifers was determined by simulating hydraulic head in the aquifers. The basic equation used to describe the ground-water flow in this model is:

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

where

K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes and are assumed to be parallel to the major axes of hydraulic conductivity, in feet per second;

h is the potentiometric head, in feet;

W is a volumetric flux per unit volume and represents sources or sinks, or both, of water, such as well discharge, leakage through confining units, streambed leakage, recharge, and water removed from the aquifers by drains, per second;

S_s is the specific storage of the porous material, per foot; and

t is time, in seconds.

The flow equation was solved by the strongly implicit procedure [(SIP); (McDonald and Harbaugh, 1988, p. 12-1)]. This is a method for solving a large number of simultaneous linear equations by iteration.

A geographic information system was used throughout the model development to aid in mapping and discretizing model layer data. Model layer data include aquifer areal extent, aquifer thickness, and saturated rock thickness data.

Description of Model

The modeled area is 31 miles by 34 miles; the Weldon Spring chemical plant is approximately in the center of the model. The 1,054-square-mile model includes almost the entire St. Charles County area and parts of Lincoln, Warren, and Franklin Counties. This area is represented by a variable grid that contains 54 rows and 53 columns (fig. 34). The grid spacing ranges from a maximum of 6,562 feet, to an intermediate of 3,281 feet, to a minimum of 1,640 feet. This smallest grid spacing was used to represent the chemical plant site so a more detailed analysis around the chemical plant could be made. The geologic and hydrologic data assigned to each model node were determined by interpolating contour-map data.

The model consists of three aquifers, each separated by a leaky confining unit. The shallow aquifer (layer 1) consists of the Burlington and Keokuk Limestones and the Fern Glen Formation because of the similar hydrologic properties of these formations. The upper confining unit lies beneath this aquifer and consists of the rocks from the Chouteau Group through the Maquoketa Shale. Included in this unit is the Bushberg Sandstone, which is capable of yielding small quantities of water. However, because the sandstone typically is less than 15 feet thick in the county and is between two units of minimal hydraulic conductivity, this unit was included as part of the confining unit. The middle aquifer (layer 2) consists of the Kimmswick Limestone, which typically is 90 to 100 feet thick in the study area. Wells in St. Charles County generally are multi-aquifer wells that penetrate the middle aquifer in conjunction with either the shallow or deep aquifers. The contrast in the hydraulic properties of the middle aquifer with the overlying and underlying confining units is sufficient to justify the inclusion of this unit as an aquifer in the model. Another approach would be to combine the upper and lower confining units with the Kimmswick Limestone to form one large confining unit. This approach was tried but abandoned because when these units were combined into one thick unit the overall sensitivity of the hydraulic heads in layer 1 to hydraulic parameter changes greatly decreased. The lower confining unit includes the Decorah Formation, Plattin Formation, and Joachim Dolomite. Imes (1985) included these three formations as part of the deep aquifer in the ground-water flow model of northern Missouri, but stated that locally these formations may be confining units. The deep aquifer (layer 3) consists of the formations from the top of the St. Peter Sandstone to the base of the Potosi Dolomite.

The hydrologic property of a confining unit that determines the rate at which water leaks through the unit is expressed by the leakage coefficient (L), where $L = K'/b$, where K' is the vertical hydraulic conductivity and b is the thickness of the confining unit. The vertical hydraulic conductivity is a function of several factors, including the presence of shale, the primary permeability of the rock, the presence of fractures, and post-depositional solution-enhanced permeability. In this report, the effective leakage coefficient governing vertical flow between the centerlines of adjacent aquifers is calculated by the following equation:

$$\frac{b}{K} = \frac{b_1}{2K_1} + \frac{b'}{K'} + \frac{b_2}{2K_2}, \tag{2}$$

where

b/K is the inverse effective leakage coefficient between midpoints of the upper and lower aquifer, in seconds;

b_1, b', b_2 are the thicknesses of the upper aquifer, confining unit, and lower aquifer, in feet; and

K_1, K', K_2 is the vertical hydraulic conductivity of the upper aquifer, confining unit, and lower aquifer, in feet per second.

The model simulations were performed during steady-state conditions; therefore, the storage of ground water in aquifers was omitted. The steady-state approach is considered valid because hydrologic conditions do not seem to be changing with time on the basis of hydrographs for monitoring wells located at O'Fallon and Wentzville (fig. 35). The water levels in both wells fluctuate throughout the year, but no continual drawdown is evident on either hydrograph.

The eastern part of St. Charles County is underlain by thick alluvial deposits in the Missouri and Mississippi River flood plains. Although these extensive deposits are water-supply sources, the alluvium was not part of the modeled system. The river and associated alluvium are regional discharge areas; therefore, any recharge applied to the alluvium either by precipi-

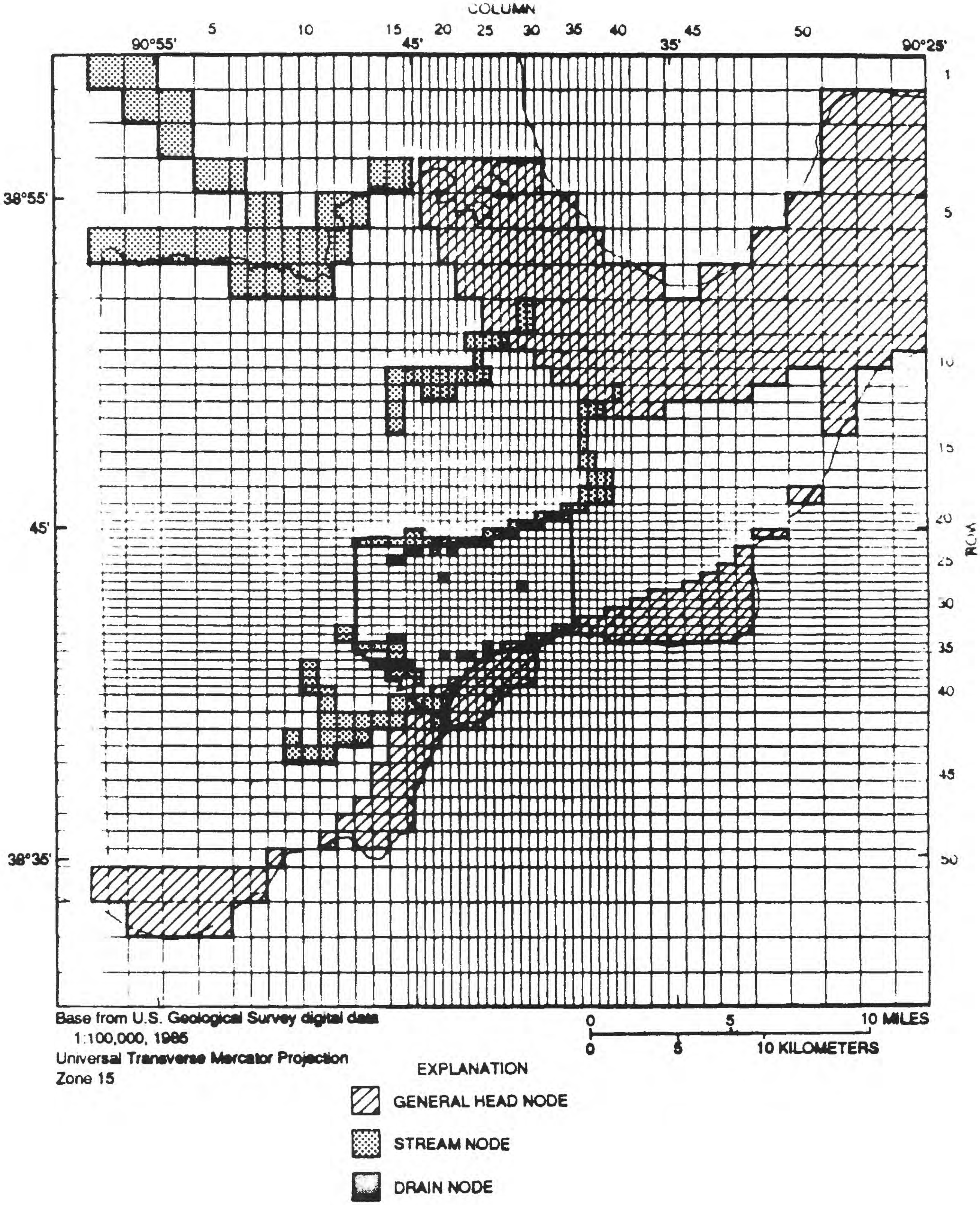


Figure 34. Grid numbering system and distribution of general head nodes, stream nodes, and drain nodes for the ground-water flow model of St. Charles County.

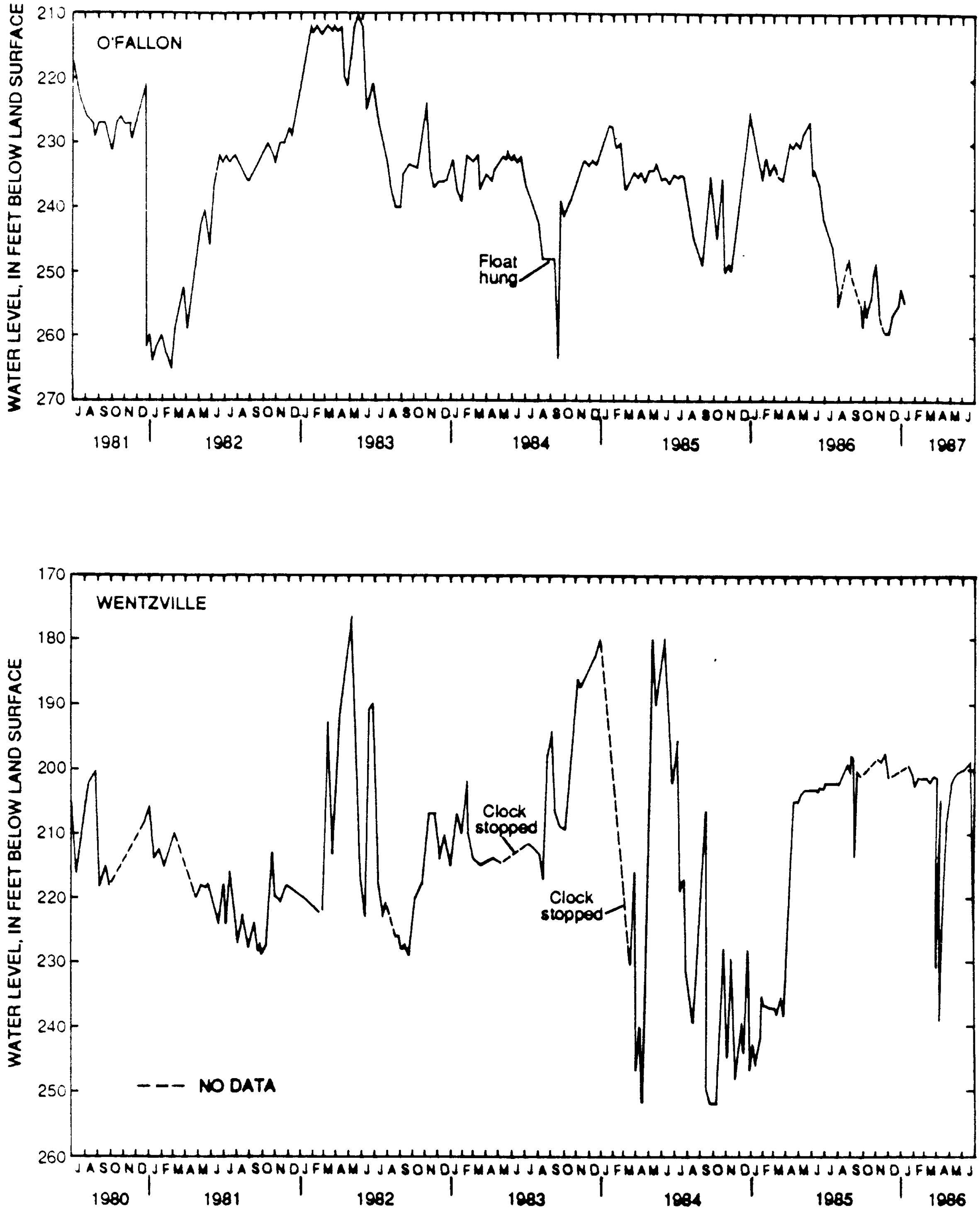


Figure 35. Water levels in monitoring wells at O'Fallon and Wentzville [data from Missouri Department of Natural Resources, Division of Geology and Land Survey (written commun., 1981-87) and Berkas and others (1989)].

tation or from the aquifers is assumed to move through the alluvium to the river, and then out of the modeled area. The alluvium along the Missouri and Mississippi Rivers was represented by specified heads and the hydraulic connection to the subjacent aquifer was simulated using a general head boundary (discussed in more detail in the "Boundary Conditions" section). This approach was used because of the good hydraulic connection between the alluvium, rivers, and the subjacent aquifers. The hydraulic heads used for the Missouri and Mississippi Rivers alluvium were obtained from a report by Emmett and Jeffery (1968).

Streams were simulated in the model (fig. 34) because of their relation to the ground-water flow in the study area. The streams can contribute water to the ground-water system or drain water from it depending on the hydraulic gradient between the stream and the ground-water system. The rate of water exchange between the stream and aquifer in each cell was calculated by multiplying the streambed conductance by the hydraulic head differential between the river and the ground-water system. The streambed conductance was calculated from the following equation (McDonald and Harbaugh, 1988, p. 6-1):

$$C_{str} = \frac{KLW}{M} , \qquad (3)$$

where

- C_{str} is the is the hydraulic conductance of the stream-aquifer interconnection;
- K is the hydraulic conductivity of the streambed material;
- L is the length of a stream reach in a cell (calculated from the geographic information system data);
- W is the stream width (estimated to be 30 feet for all streams); and
- M is the streambed thickness (assumed to be 5 feet in all streams).

Streams were simulated by assigning the average stream altitude shown on 7.5-minute U.S. Geological Survey topographic maps at each stream node location and assigning an estimated streambed conductivity to that stream node. Stream length and altitude data are summarized in table 4. The hydraulic conductivity between the stream and subjacent aquifer was determined from the streambed area in the cell and the hydraulic conductivity of the subjacent aquifer. The streambed conductances were derived by calibration. The Cuivre River, Big Creek, Peruque Creek, and Dardenne Creek are located in the Dissected Till Plains part of the study area and generally have clay and silt streambeds. This fact caused the streambed conductance to be lower in these streams than in the streams in the southern part of the county that are in the Salem Plateau and have rock and gravel streambeds.

Drain nodes were added to the model at known spring locations to simulate the effects of springs in the study area. Simulated drains remove water from the aquifer at a rate proportional to the hydraulic head differential between the aquifer and a fixed altitude when the hydraulic head in the aquifer is above the drain altitude (McDonald and Harbaugh, 1988, p. 9-1). This operation of the model represents the function performed by springs in nature in which the spring orifice altitude serves as the drain altitude. Drains were simulated at each model cell that contains a known spring by assigning an altitude for the drain and an estimated hydraulic conductance of the interface between the aquifer and the drain. When the hydraulic head in the aquifer was above the drain altitude, the discharge rate of the drain was calculated as the product of the hydraulic conductance of the drain and the difference in hydraulic head between the aquifer and the drain. The hydraulic conductance for the drains was determined through calibration. The drain locations, drain altitude, and hydraulic conductance values are shown in table 5.

Boundary Conditions

The area of the ground-water model includes most of St. Charles County and parts of adjacent counties so that natural hydrologic boundaries could be incorporated into the flow system of the model. The following discussion pertains to all three aquifer layers. The boundary conditions for each of the model layers are shown in figures 36, 37, and 38. The lateral boundaries to the northeast, east, and south are the regional discharge areas of the Missouri and Mississippi Rivers. In all aquifer layers, these boundaries are represented as no-flow boundaries. However, where the southern

Table 4—Summary of river simulation data used in St. Charles County model simulations

Model layer	Row (fig. 34)	Column (fig. 34)	Stream stage, in feet above sea level	Stream length, in feet	Streambed, in feet above sea level
		Cuivre River			
1	1	2	458	10,092.4	453
1	1	3	457	7,356.0	452
1	2	3	455	13,442.2	450
1	2	4	453	3,133.4	448
1	3	4	451	10,479.5	446
1	4	5	448	7,188.8	443
1	4	6	447	7,979.4	442
1	4	14	428	3,602.6	423
1	4	15	426	3,477.9	421
1	4	16	425	2,073.6	420
1	5	7	446	1,706.1	441
1	5	8	444	9,183.5	439
1	5	11	433	1,292.7	428
1	5	12	432	8,658.6	427
1	5	13	430	3,410.1	425
1	6	8	443	2,437.8	438
1	6	9	442	7,444.6	437
1	6	10	440	3,402.4	435
1	6	11	436	7,671.0	431
1	6	12	435	1,522.4	430
1	7	9	439	7,556.2	434
1	7	10	438	4,104.6	433
1	7	11	438	5,538.4	433
		Big Creek			
1	6	2	454	5,473.7	449
1	6	3	451	8,169.7	446
1	6	4	448	8,169.7	443
1	6	5	445	7,313.4	440
1	6	6	443	3,166.2	438
1	6	7	443	39.4	438
1	6	9	442	1,952.2	437
1	7	6	442	393.7	437
1	7	7	442	4,721.4	437
1	7	8	441	4,015.9	436
1	7	9	439	485.6	434
		Peruque Creek			
1	8	29	430	4,600.0	425
1	8	30	428	2,345.9	423
1	9	23	438	2,372.2	433
1	9	24	438	3,733.8	433
1	9	25	436	1,788.1	431
1	9	26	435	1,925.9	430
1	9	27	434	2,870.9	429
1	9	28	433	3,386.0	428
1	9	29	432	1,886.6	427

Table 4--Summary of river simulation data used in St. Charles County model simulations--Continued

Model layer	Row (fig. 34)	Column (fig. 34)	Stream stage, in feet above sea level	Stream length, in feet	Streambed, in feet above sea level
			Peruque Creek--Continued		
1	10	24	434	108.3	429
1	11	15	461	3,799.4	456
1	11	16	455	2,368.9	450
1	11	17	451	2,939.8	446
1	11	18	448	4,268.6	443
1	11	19	447	1,250.1	442
1	11	20	446	1,578.2	441
1	11	21	445	1,889.9	440
1	11	22	444	1,893.1	439
1	11	23	443	1,758.6	438
1	11	24	442	1,886.6	437
1	11	25	442	2,323.0	437
1	12	15	468	3,819.1	463
1	12	18	447	452.8	442
1	12	19	447	843.2	442
1	12	20	447	324.8	442
1	12	21	446	95.1	441
1	13	15	476	4,143.9	471
1	14	15	479	357.6	474
			Dardenne Creek		
1	12	40	427	3,855.2	422
1	13	36	434	2,943.1	429
1	13	37	433	2,273.7	428
1	13	38	433	4,058.6	428
1	13	39	430	2,339.3	425
1	13	40	430	190.3	425
1	14	36	436	4,157.0	431
1	15	36	438	5,023.2	433
1	16	36	440	1,834.1	435
1	16	37	441	2,113.0	436
1	17	37	442	876.0	437
1	17	38	443	4,219.4	438
1	17	39	444	4,884.8	439
1	18	36	447	62.3	442
1	18	37	446	1,758.6	441
1	18	38	445	1,935.8	440
1	18	39	446	2,142.3	441
1	19	34	448	1,342.0	443
1	19	35	447	1,748.8	442
1	19	36	449	1,673.3	444
1	20	31	456	715.3	451
1	20	32	453	1,768.5	448
1	20	33	453	1,758.6	448
1	20	34	452	410.1	447
1	21	28	463	521.7	458
1	21	29	462	1,752.1	457
1	21	30	459	1,709.4	454

Table 4–Summary of river simulation data used in St. Charles County model simulations–Continued

Model layer	Row (fig. 34)	Column (fig. 34)	Stream stage, in feet above sea level	Stream length, in feet	Streambed, in feet above sea level
		Dardenne Creek--Continued			
1	21	31	457	1,013.8	452
1	22	16	500	1,171.3	495
1	22	17	498	111.6	493
1	22	25	498	32.8	493
1	22	26	470	1,738.9	465
1	22	27	467	1,735.6	462
1	22	28	464	1,246.8	459
1	23	13	513	49.2	508
1	23	14	508	4,127.5	503
1	23	15	503	3,681.3	498
1	23	16	498	1,164.8	493
1	23	17	496	2,982.4	491
1	23	18	492	3,162.8	487
1	23	19	489	1,243.5	484
1	23	20	487	1,735.7	482
1	23	21	485	1,666.7	480
1	23	22	483	1,653.6	478
1	23	23	481	1,650.3	476
1	23	24	478	1,653.6	473
1	23	25	473	1,637.2	468
1	24	19	489	820.3	484
		Calloway Fork			
1	37	10	505	1,913	500
1	38	10	498	1,838	493
1	39	10	492	1,680	487
3	42	11	472	2,936	467
3	42	12	464	881	459
3	43	12	458	1,680	453
		Little Femme Osage Creek			
1	33	12	675	820	670
1	34	12	645	2,460	640
1	35	13	585	3,281	580
1	35	14	545	4,100	540
1	35	15	515	2,050	510
1	36	15	505	1,640	500
1	37	15	495	1,640	490
1	38	15	490	820	485
1	38	16	485	1,640	480
1	38	17	478	1,640	473
1	39	17	465	1,910	460

Table 4--Summary of river simulation data used in St. Charles County model simulations--Continued

Model layer	Row (fig. 34)	Column (fig. 34)	Stream stage, in feet above sea level	Stream length, in feet	Streambed, in feet above sea level
			Femme Osage Creek		
3	41	15	457	1,145.1	452
3	41	16	456	1,870.2	451
3	41	17	455	4,271.9	450
3	41	18	454	1,683.2	449
3	41	19	452	45.9	447
3	41	20	450	869.5	445
3	42	13	468	8,038.5	463
3	42	14	461	4,475.3	456
3	42	15	457	3,077.6	452
3	42	19	452	1,650.3	447
3	42	20	450	771.0	445
3	43	9	488	2,595.3	483
3	43	11	480	2,660.9	475
3	43	12	475	5,869.7	470
3	43	13	471	1,807.8	466
3	44	9	486	1,689.7	481
3	44	10	484	3,566.4	479
3	44	11	482	1,069.6	477

areal extent of layers 1 and 2 does not extend to the Missouri River, no-flow boundaries were used where these layers terminate.

The northern boundary for the model is a ground-water trough that Imes (1985) shows extending to the northwest of St. Charles County through Lincoln County in both the Mississippian and Cambrian-Ordovician aquifers. This boundary is represented in layer 1 as a specified head boundary because it corresponds to the Cuivre River, which is a perennial stream. Because the ground-water flow is parallel to the trough in layers 2 and 3, the trough is represented as a no-flow boundary in these layers.

The western boundary is not a natural hydraulic boundary; to use the closest physical boundary, the model would have to be expanded about 30 miles to the west where a ground-water divide is present. However, if the model was expanded westward to incorporate this divide as a boundary, the physical boundary (ground-water trough) that is present north of St. Charles County could no longer be used because it does not extend 30 miles to the west. To avoid this, a specified head boundary was used as the western boundary. By representing this boundary as a specified head boundary, a condition is created where the model was able to supply an unlimited source of water along this boundary. Because this makes the model less sensitive to calibrated hydraulic parameters in that area, the modeling results were analyzed to determine the effects. The analysis indicated the boundary is a sufficient distance from the pumping centers that the drawdowns created by the wells that are pumped do not extend to this boundary. The hydraulic heads along this boundary were set to the hydraulic heads drawn for the potentiometric maps created from water-level measurements made in the summer of 1984.

The lower model boundary is considered to be an impermeable layer so that no leakage occurs between the Potosi Dolomite and underlying rocks. Few hydrologic data on which to base this assumption are available; however, the Derby-Doe Run Dolomites and the Davis Formation are confining units elsewhere in

Table 5--Summary of drain simulation data used in St. Charles County model simulations

Model layer	Row (fig. 34)	Column (fig. 34)	Drain altitude, in feet above sea level	Hydraulic conductance, in feet per second	Measured discharge, in cubic feet per second	Simulated discharge, in cubic feet per second
1	24	16	530	40	0.04	0
1	24	17	505	40	.15	.12
1	24	21	485	40	.4	.24
1	25	15	540	40	.2	0
1	27	20	532	40	.1	.12
1	28	29	540	40	.15	0
1	34	30	460	40	.20	0
1	35	25	475	40	.10	.12
1	36	20	530	40	.05	0
1	36	22	495	40	.02	.06
1	36	23	480	40	.05	0
1	37	15	595	40	.10	0
1	37	16	595	40	.10	0

the State. These formations are about 300 feet thick in the study area (fig. 5) as determined from geologic well-log data (data on file at the Missouri Department of Natural Resources, Division of Geology and Land Survey in Rolla).

Net recharge was applied to the outcrop area of each model layer (fig. 39). The distribution of net recharge was varied depending on the topographic setting of the model cell (fig. 40). The largest net recharge values were applied to model cells located on ground-water divides. Net recharge was applied at lesser rates along the slopes of ridges in the proximity of the midline (a line located at land surface midway between and parallel to the valley bottom and the ground-water divide) between the ground-water divide and the valley bottoms. No net recharge was applied to large lowland areas or the alluvial deposits. This approach was taken because the potential for net recharge to an aquifer is greatest along the ridges. Near the midline, the ground-water-flow system is thought to change from recharge to discharge areas (Toth, 1963) and, therefore, recharge to the aquifer in these areas decreases. In lowland areas, the potential for net recharge is minimal because, generally, these topographic settings are ground-water discharge areas.

A modification was made to this general concept of applied net recharge. Where the aquifer is overlain by Pennsylvanian formations, which typically are composed of shale and clay in St. Charles County, the recharge rate was limited to 1×10^{-10} foot per second (the estimated vertical hydraulic conductivity of the Pennsylvanian formations). Where one of the confining units cropped out, the recharge rate applied to the subjacent aquifer was limited to the vertical hydraulic conductivity of the confining unit.

The general hydraulic head boundary allows water to move to or from a model cell based on altitude differences between the reference and the simulated hydraulic heads. The hydraulic heads used for the Missouri and Mississippi Rivers alluvium were obtained from a report by Emmett and Jeffery (1968). The exchange of water between the alluvium and the underlying aquifers is controlled by the hydraulic conductance between the alluvium and subjacent unit. The hydraulic conductance was calculated using one of two methods, depending on whether the alluvium was in contact with an aquifer or confining unit. If the subjacent unit

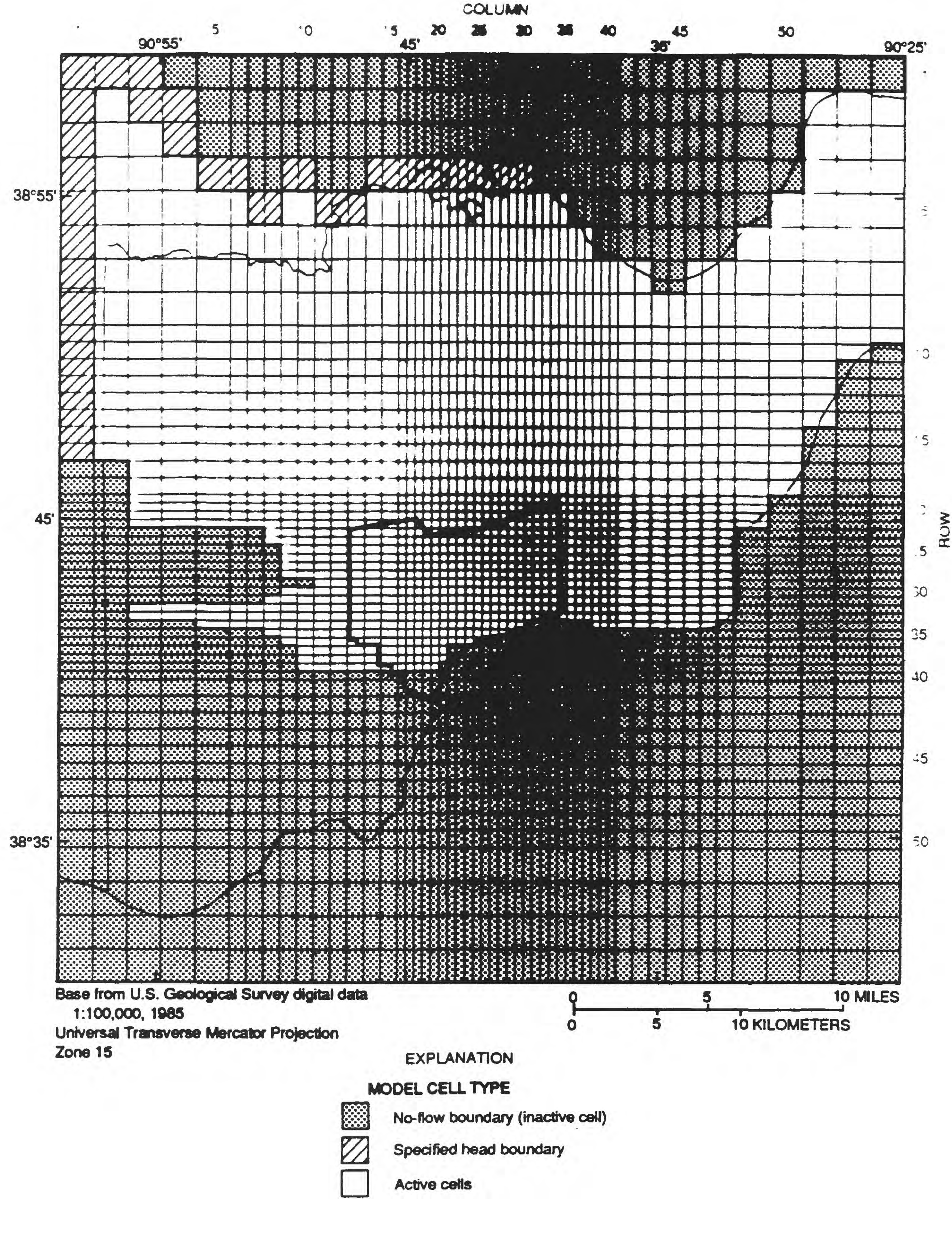


Figure 36. Model cell representation for model layer 1.

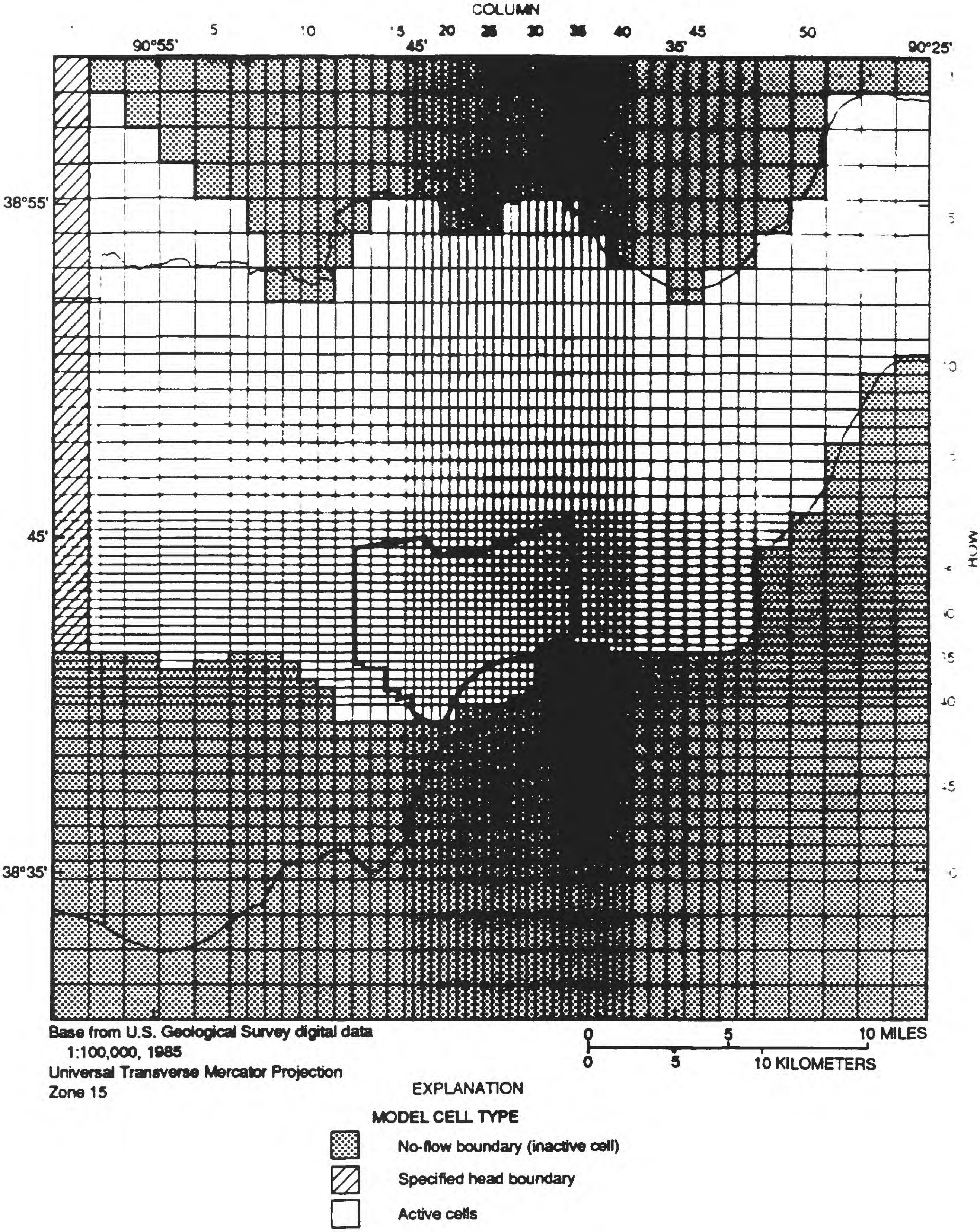


Figure 37. Model cell representation for model layer 2.

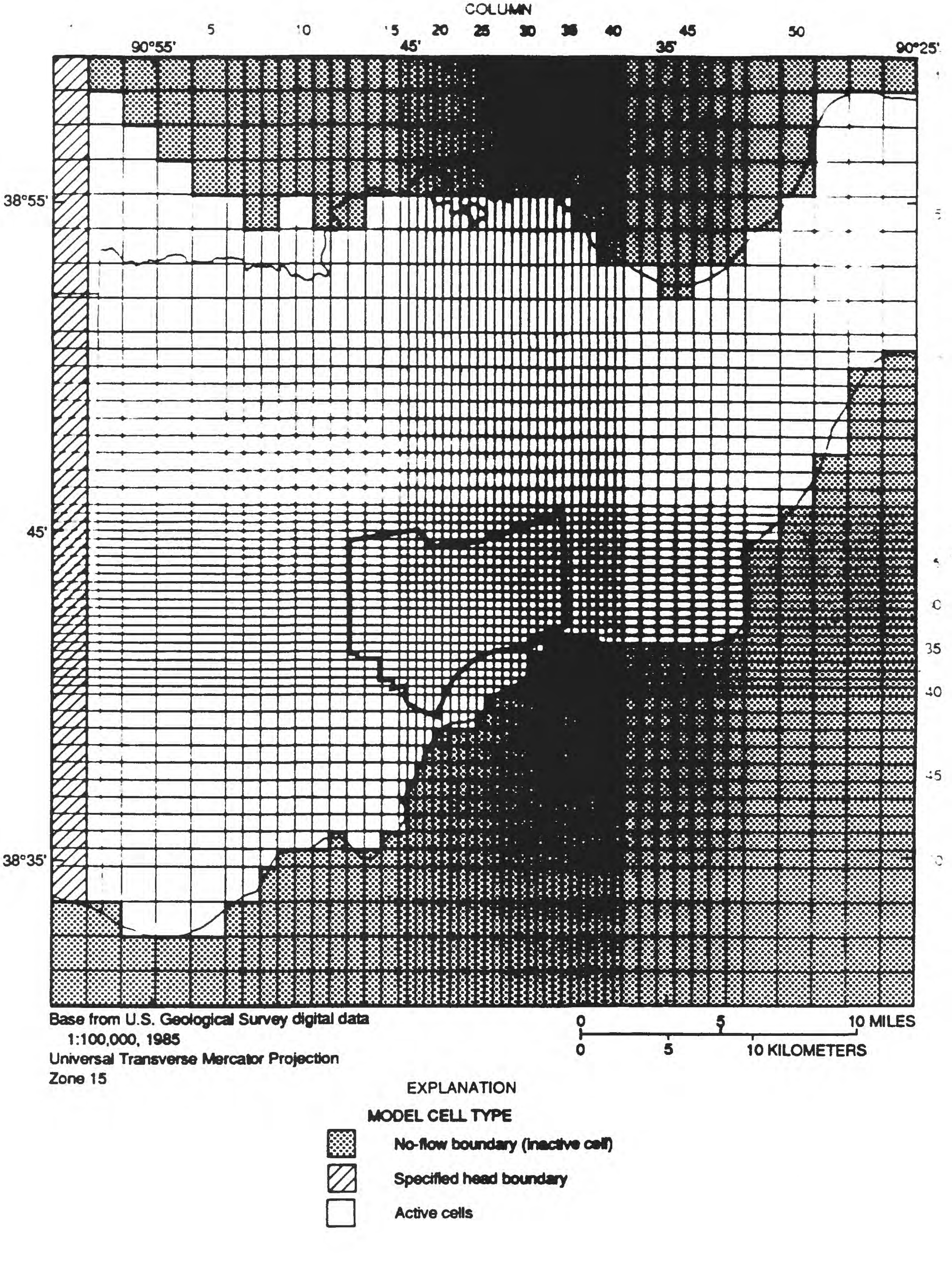


Figure 38. Model cell representation for model layer 3.

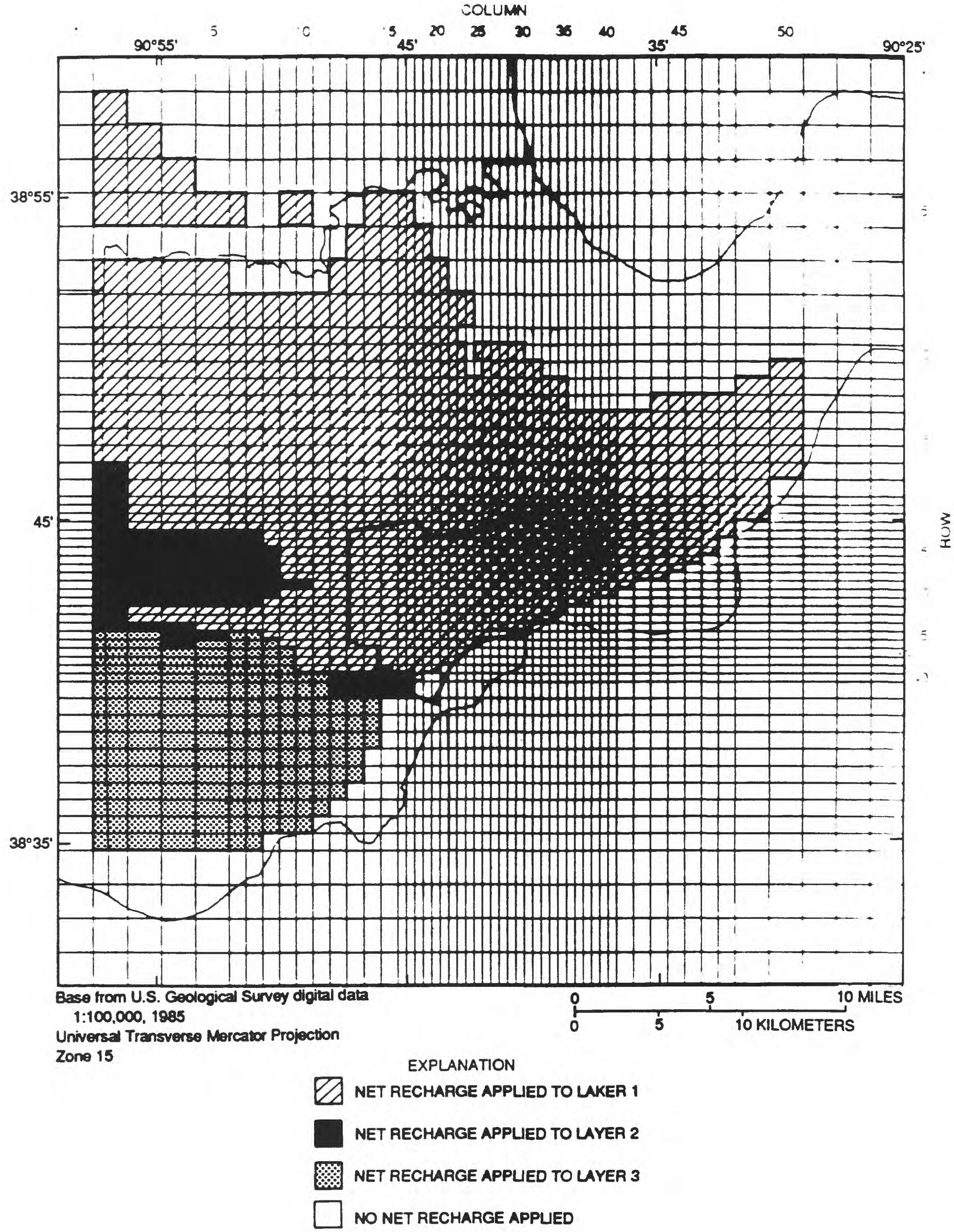


Figure 39. Model layer to which net recharge was applied.

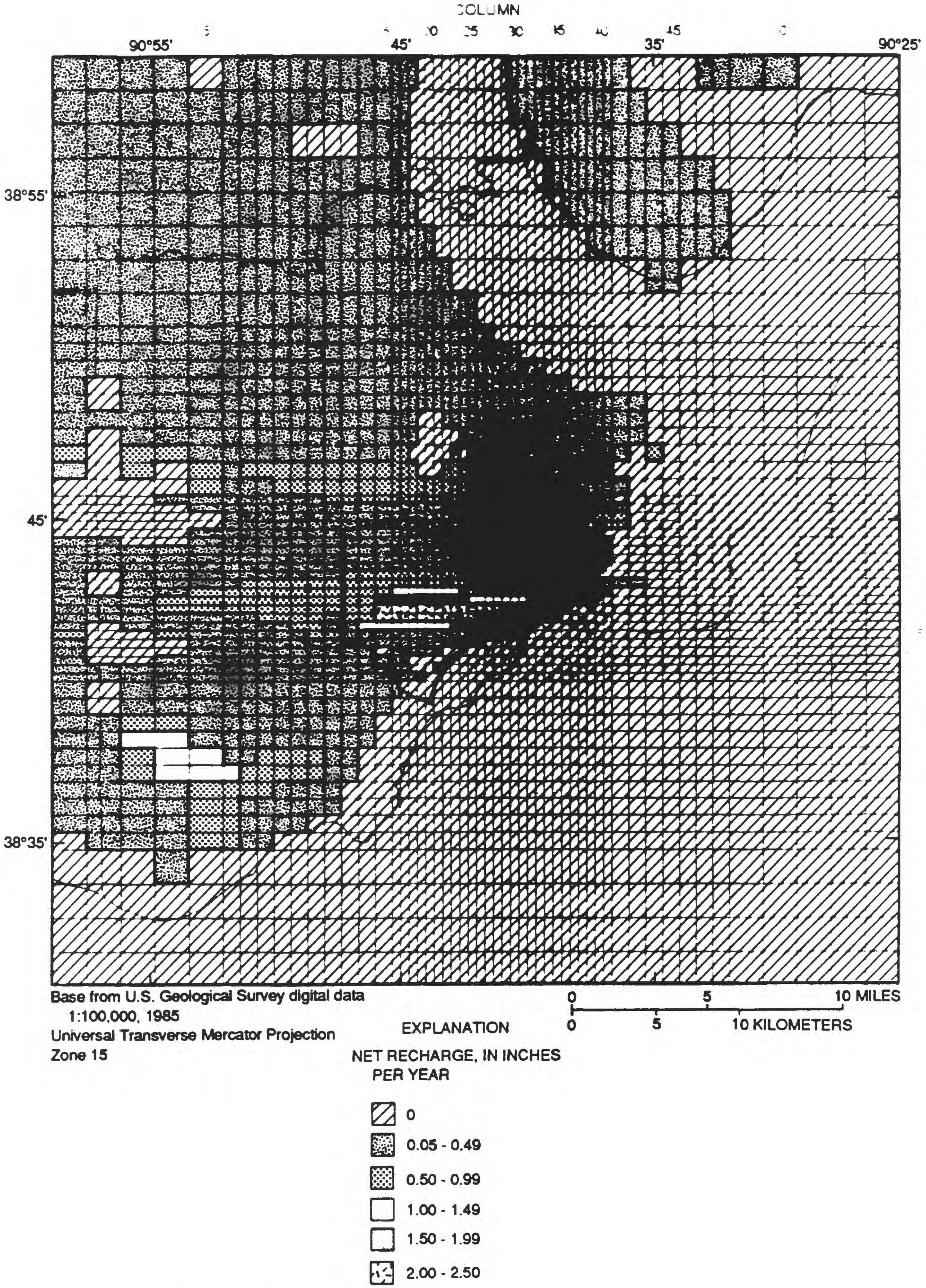


Figure 40. Net recharge distribution for the modeled area.

was an aquifer, the conductivity was calculated using the vertical hydraulic conductivity of the aquifer, the area of the cell that contained alluvial material, and 50 percent of the thickness of the subjacent aquifer. If the subjacent unit was a confining layer, the hydraulic conductance was calculated using the vertical hydraulic conductance of the confining unit, the area occupied by the alluvium, and the total thickness of the confining unit.

Calibration

The ground-water flow model was calibrated by minimizing the calculated root mean square (RMS) error between actual water-level measurements made in wells and the model-derived simulated hydraulic heads. The RMS error is a measure of the overall deviation between measured and simulated hydraulic heads regardless of whether or not the simulated hydraulic heads are greater than or less than the measured hydraulic heads. The accepted hydraulic parameter values for the model were determined by using the difference between RMS errors calculated during the predevelopment and pumping scenarios. Certain parameter changes would minimize the RMS error for the predevelopment scenario but would adversely affect the hydraulic heads in the pumping scenario. Also, when parameters were changed to improve the RMS error in the pumping scenario, the RMS error in the predevelopment scenario became worse. The accepted parameter values minimized the combined errors using both scenarios. The equation used to calculate RMS error was:

$$RMS_{error} = \sqrt{\frac{e_1^2 + e_2^2 + e_3^2 + \ldots + e_n^2}{n}}; \qquad (4)$$

where

- e is the difference between measured hydraulic heads and the simulated hydraulic heads; and
- n is the number of control points.

The hydraulic head measurements used for the predevelopment conditions were obtained from water-level measurements recorded on driller's logs (data on file at the Missouri Department of Natural Resources, Division of Geology and Land Survey in Rolla). Water-level measurements made before the mid-1950's were considered to represent predevelopment conditions. The hydraulic heads used in the pumping scenario were based on water-level measurements made in the modeled area since 1984 by U.S. Geological Survey personnel.

The criterion used during calibration to determine if the model simulation was acceptable was an RMS error of less than 25 feet for each layer in both model scenarios (predevelopment and pumping). This degree of accuracy was chosen on the basis of the following conditions. The vertical accuracy of the topographic maps used to determine land-surface altitudes of the measured wells is 0.5 of the contour interval. In areas of large relief, the topographic maps have contour intervals of 20 feet. Because the methods used to measure the water levels during predevelopment conditions were not noted on the drilling logs, the accuracy of these measurements is unknown; however, many water-level values seemed to have been rounded to the nearest 5 or 10 feet. The post-1984 water-level measurements were measured to the nearest 0.1 foot, but it is uncertain if these hydraulic heads represent true static-water conditions. Many of the measured wells were equipped with pumps and were used to supply domestic or public-water needs. While care was taken to shut off the pump for a period before measuring the water levels, many of the measurements were noted as being taken after the well was recently pumped. These measurements would indicate that some water levels may reflect drawdown conditions, and the static-water levels may actually be higher than those measured, which is particularly significant for the measured water levels in the public-water supply wells. Because these wells continually are pumping large volumes of water and the wells are needed back on line within 30 minutes after shutting them off, it is probable some of water-level measurements from the deep aquifer were taken before the water reached a static level. This drawdown condition is recognized as possibly introducing error in the hydraulic heads of the pumping scenario. To resolve this condition, the simulated heads in layer 3 were allowed to exceed the actual measured hydraulic heads in the areas of intense pumping.

The public-supply water-use data used in the pumping scenario were either obtained directly from the files of public-water-supply managers or, when these data were not available, from the Missouri Department of Natural Resources (1985). Withdrawal of water was simulated by the model using a constant rate that equalled the yearly total pumpage from the wells. This withdrawal was from the model cell that represented the location of the well. These withdrawal data are shown in table 6.

The hydraulic conductivity values used in this model were derived by calibration, but are consistent with available aquifer-test data. The hydraulic conductivity for layer 1 was considered to be anisotropic, which is consistent with results of aquifer tests of the upper aquifer at the chemical plant site (Carman, 1991). The north-to-south hydraulic conductivity was assigned a value of 4.8×10^{-6} foot per second, and east-to-west hydraulic conductivity a value of 1.6×10^{-5} foot per second. A vertical hydraulic conductivity of 1.6×10^{-5} foot per second was assigned to the layer. Emmett and Imes (1984) used a hydraulic conductivity of 1.5×10^{-6} foot per second for the Burlington and Keokuk Limestones in a ground-water flow model for Audrain County, which is located about 45 miles northwest of St. Charles County. This value of 1.5×10^{-6} foot per second was based on specific capacity data of several wells in Audrain County that were completed to the base of the shallow aquifer. Slug tests performed at the site indicate an average hydraulic conductivity of 4×10^{-6} foot per second for the shallow aquifer. The transmissivity distribution in layer 1, which is the product of aquifer hydraulic conductivity and saturated thickness, is shown on figure 41.

The weathered and unweathered areas of the upper confining unit were assigned different vertical hydraulic conductivity values. The weathered zone was simulated where the upper confining unit is exposed at land surface or is not buried deeply in the subsurface and weathering of the unit is considered appreciable. The vertical hydraulic conductivity assigned to the weathered zone was 5.7×10^{-6} foot per second. The unweathered zone was simulated where the upper confining unit is buried in the subsurface and no appreciable weathering is expected. The vertical hydraulic conductivity assigned to this zone was 1.3×10^{-9} foot per second. Imes (1985) used a vertical hydraulic conductivity of 1.0×10^{-10} foot per second for the Maquoketa Shale because of estimates made by Walton (1960) for the vertical hydraulic conductivity of the Maquoketa Shale in northeastern Illinois. For this study, the Maquoketa Shale was combined with the equivalents Imes called the limestone confining units. Imes assigned a vertical hydraulic conductivity of 1.0×10^{-9} foot per second for the limestone confining units of Devonian and Silurian age. No aquifer test data were available in the modeled area for the upper confining unit to refine these values, but they are within the range of hydraulic conductivity values for shale (Freeze and Cherry, 1979). The leakage coefficient distribution in the upper confining unit is shown in figure 42.

Imes (1985) combined layers 2 and 3 and the lower confining unit of this model into one layer with a hydraulic conductivity of 1.5×10^{-6} foot per second. However, Imes stated that the Decorah Formation, Plattin Formation, and Joachim Dolomite (lower confining unit) yielded a limited quantity of water, and locally they can be a confining unit. Layers 2 and 3 were assigned hydraulic conductivities that are isotropic. A hydraulic conductivity of 3.9×10^{-6} foot per second was assigned to layer 2. The transmissivity distribution in layer 2 is shown in figure 43. The lower confining unit was assigned a hydraulic conductivity of 2.4×10^{-8} foot per second. The leakage coefficient distribution for the lower confining unit is shown in figure 44. A hydraulic conductivity of 4.2×10^{-6} foot per second was assigned to layer 3. The transmissivity distribution in layer 3 is shown in figure 45.

These hydraulic conductivity values are within the range of values calculated from specific capacity data available for the modeled area. A summary of 15 specific capacity calculations were tabulated in Miller and others (1974). Estimates of hydraulic conductivity were made using these data. Many of these tests were performed in multi-aquifer wells and for these data to be of use the major aquifer was determined for each well. Categorizing these data by major aquifer, the results indicated the hydraulic conductivity data for the middle aquifer range from 1×10^{-6} to 2×10^{-7} foot per second. Wells open strictly to the St. Peter Sandstone

Table 6--Summary of well-withdrawal data used in St. Charles County model simulations

Model layer	Row (fig. 34)	Column (fig. 34)	Withdrawal rate, in cubic feet per second
3	9	19	0.0740
3	10	2	.0110
3	11	25	.6140
3	12	26	.0310
3	13	25	.6140
3	13	27	.6140
3	13	7	.8480
3	14	20	.2500
3	14	30	.0230
3	14	30	.0090
3	14	23	.0140
3	16	28	.2500
3	16	14	.0050
3	16	13	.0150
3	17	25	.5000
3	27	25	.0320
3	29	5	.1550
3	30	29	.0560
3	42	18	.0060

had hydraulic conductivities near 1 x 10^{-5} foot per second; wells open to the middle part of the deep aquifer had calculated hydraulic conductivities near 1 x 10^{-6} foot per second, and the one well open to the bottom part of the deep aquifer had a calculated hydraulic conductivity of 3 x 10^{-6} foot per second. None of the wells with specific capacity data were open to the entire deep aquifer.

The streambed conductance for the rivers was determined by calibration and set so the fluxes to the rivers approximated the annual minimum 7-day average discharge with a recurrence interval of 2 years (7-day Q_2) for each stream. The low-flow frequencies for the streams were obtained from Miller and others (1974) and are shown in table 7.

Sensitivity Analysis

The sensitivity of the model simulation to changes of the various input parameters was determined to assess the accuracy of the accepted model simulation. When changes to an input parameter causes changes in simulated hydraulic heads, the model is said to be sensitive to that parameter. When the model is insensitive to an input parameter, it is difficult to determine if that parameter was properly determined during the model calibration because large changes in the variable cause only slight changes in the simulated hydraulic heads.

Changes to the hydraulic conductivity of each aquifer layer, the leakance of both confining units, the recharge flux, and the anisotropy of layer 1 were varied during the sensitivity analysis. The RMS errors were plotted for each layer with each change made to the input parameter analyzed. The results are shown for both the predevelopment and pumping scenarios in figure 46. The plots generally show that by increasing the hydraulic conductivities in the various layers, the RMS errors for the predevelopment scenario improved but caused the RMS errors for the pumping scenario to increase. Also, by decreasing the hydraulic conductivities for the layers, the RMS errors for both the predevelopment and pumping scenario generally increased. The hydraulic conductivity values used in the

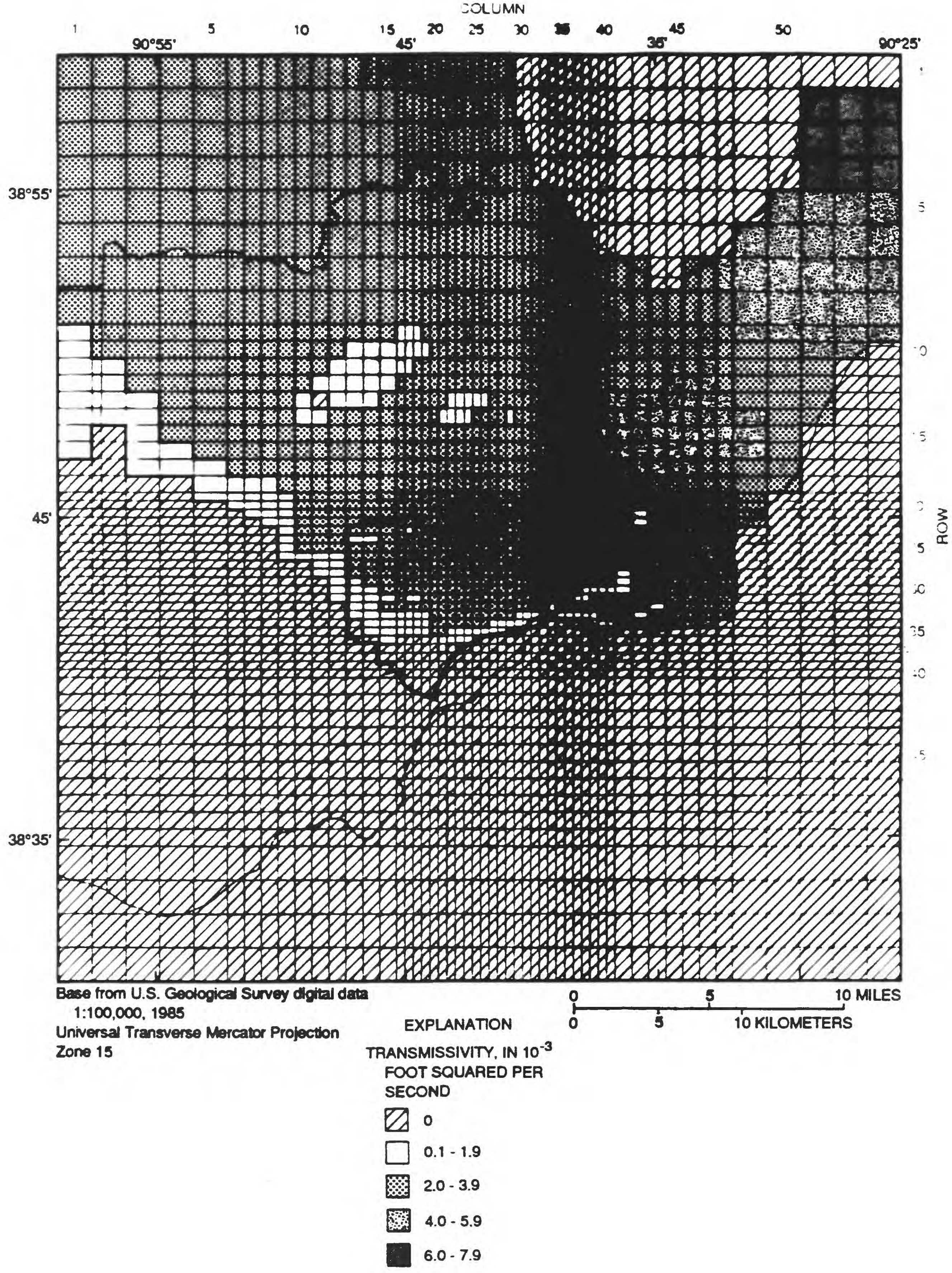
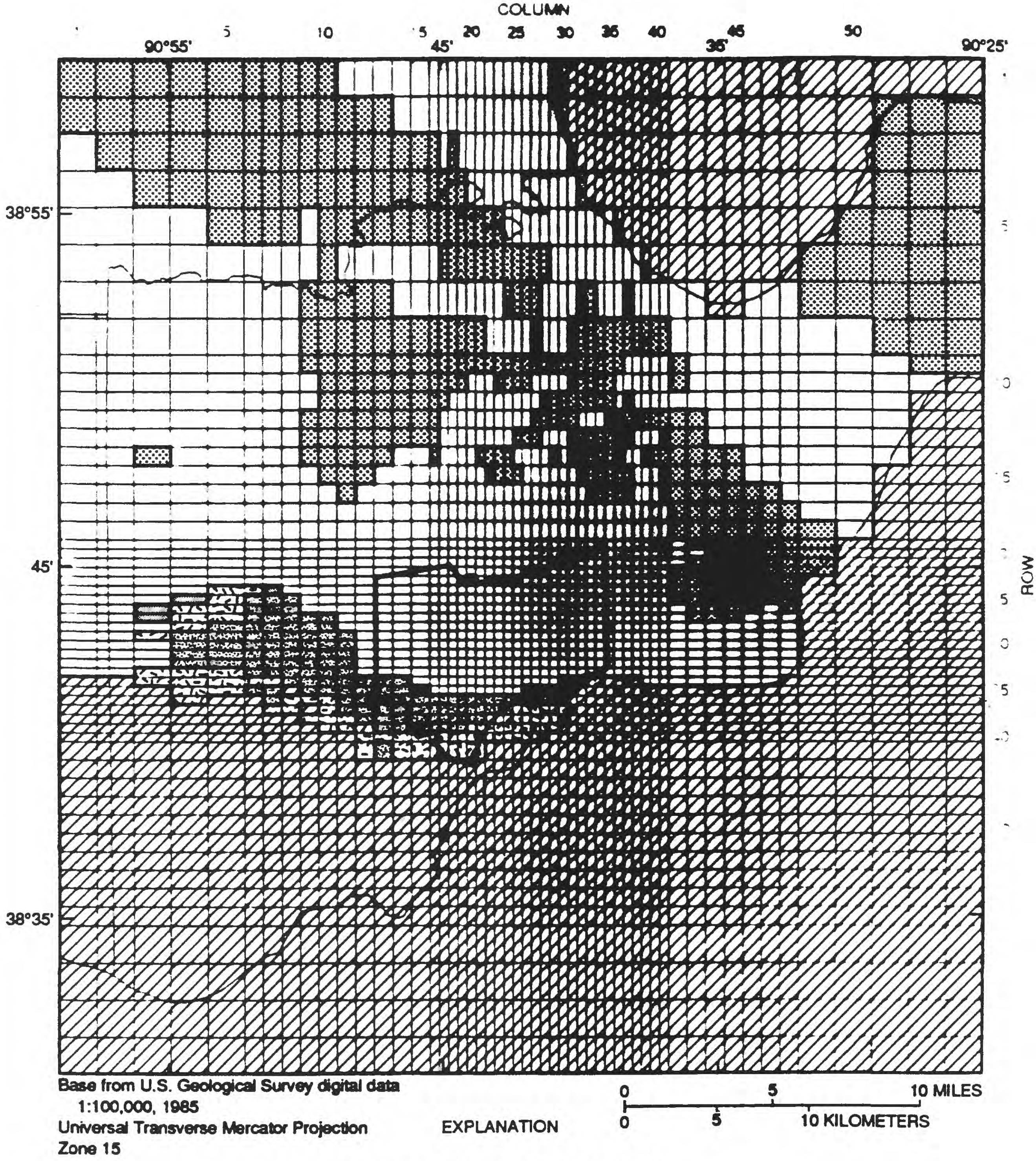


Figure 41. Distribution of transmissivity values used in model layer 1.



EXPLANATION

LEAKAGE COEFFICIENT, IN SECONDS^{-1}

- 0
- 1.0×10^{-12} to 9.9×10^{-12}
- 10.0×10^{-12} to 39.9×10^{-12}
- 40.0×10^{-12} to 99.9×10^{-12}
- 1.0×10^{-8} to 9.9×10^{-8}
- 10.0×10^{-8} to 100.0×10^{-8}

Figure 42. Leakage coefficient distribution in the upper confining unit.

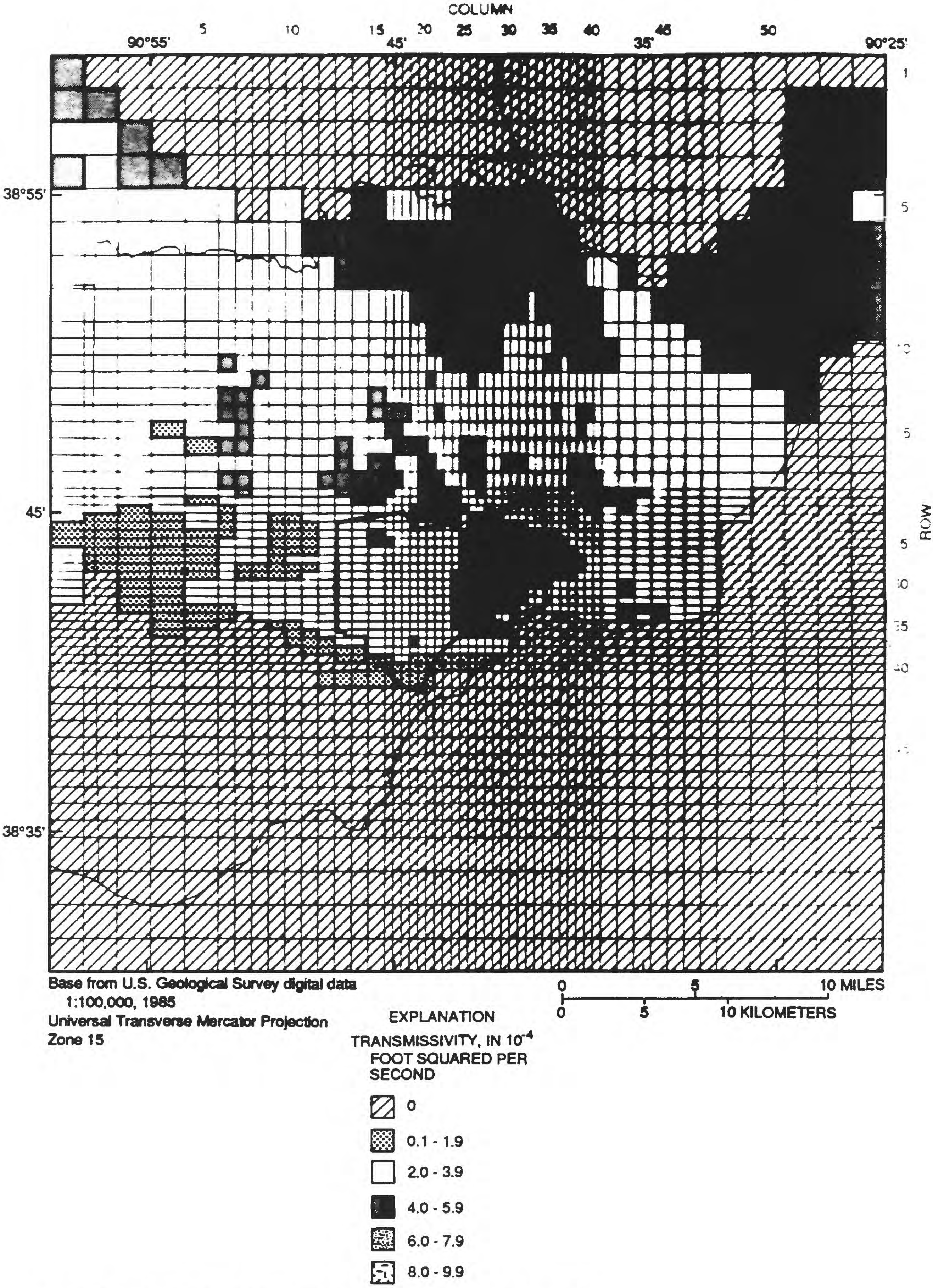
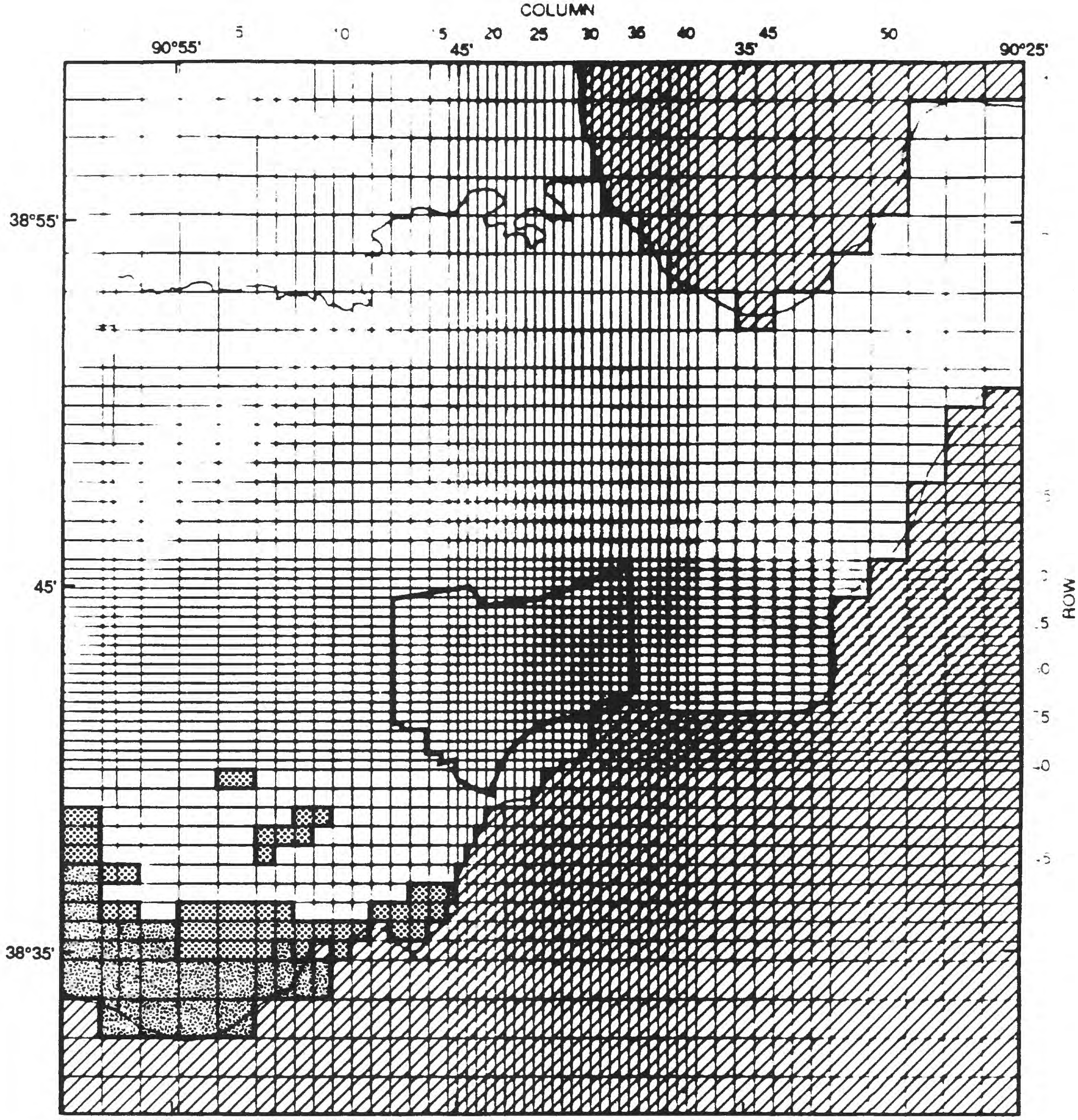


Figure 43. Distribution of transmissivity values used in model layer 2.



Base from U.S. Geological Survey digital data
1:100,000, 1985
Universal Transverse Mercator Projection
Zone 15

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

LEAKAGE COEFFICIENT, IN 10^{-10} $SECOND^{-1}$

- 0
- 1.0 - 9.9
- 50.0 - 59.9
- 60.0 - 69.9

Figure 44. Leakage coefficient distribution in the lower confining unit.

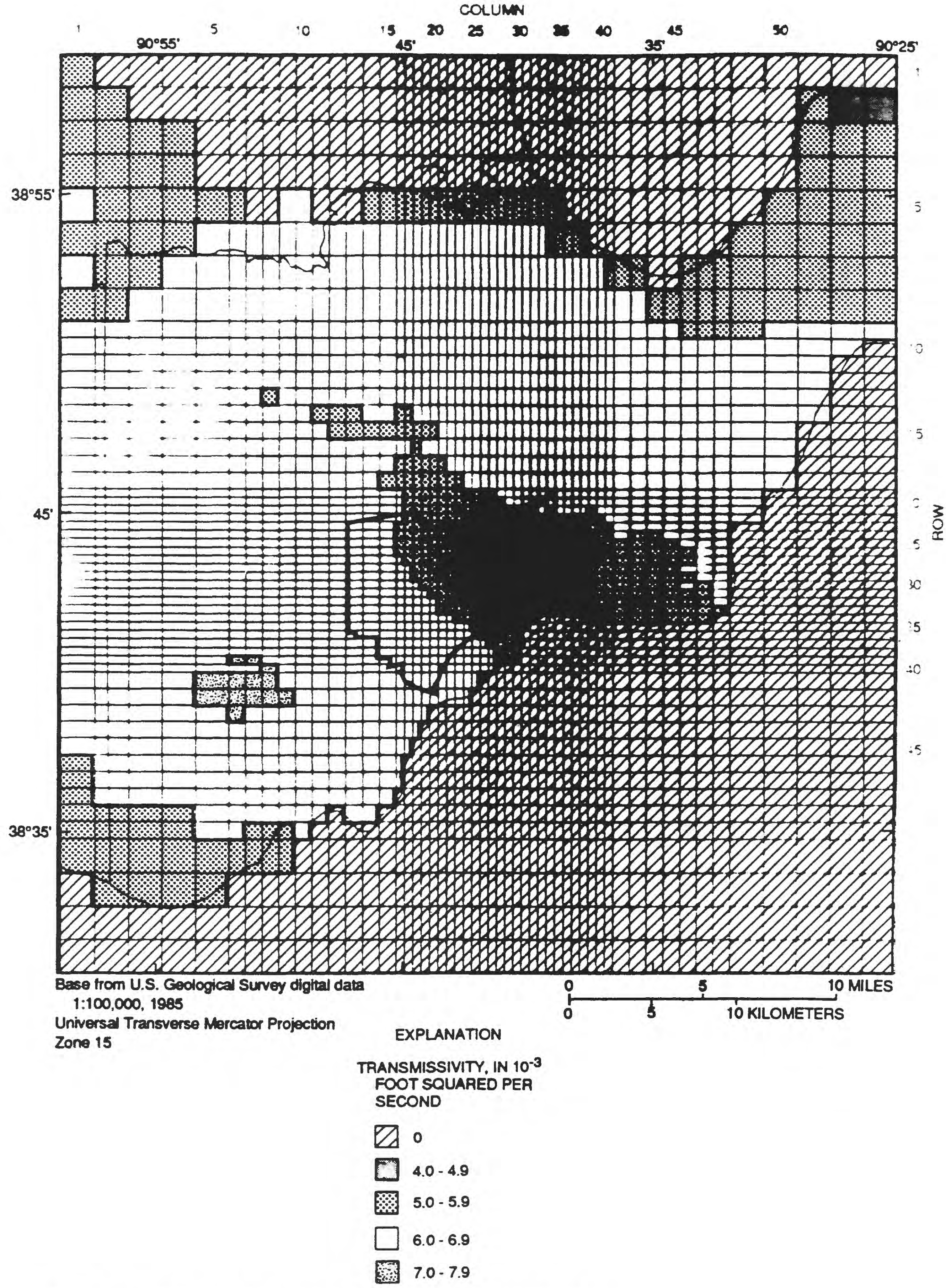


Figure 45. Distribution of transmissivity values used in model layer 3.

Table 7–Simulated stream discharges and 7-day Q_2 discharges for streams in St. Charles County model simulations

[7-day Q_2 is the annual minimum 7-day average discharge with a recurrence interval of 2 years; 7-day Q_2 data from Miller and others (1974)]

Stream (fig. 1)	Simulated stream discharge, in cubic feet per second	7-day Q_2, in cubic feet per second
Cuivre River	[a]0.02	0.3
Big Creek	.22	.2
Peruque Creek	.12	.1
Dardenne Creek	.15	.1
Calloway Fork	.08	[b].02
Little Femme Osage Creek	[c]-.03	[b]0
Femme Osage Creek	.23	.2

[a] The Cuivre River is a specified head boundary; therefore, the model was unable to adequately simulate 7-day Q_2 stream discharge.
[b] Discharges from actual discharge measurements made during median low-flow conditions (7-day Q_2) in 1967.
[c] Negative discharge represents water lost from stream into the aquifer.

calibrated simulation were determined by making a compromise between the two scenarios.

Increasing the hydraulic conductivity of layer 1 by 50 percent caused hydraulic heads along the ridge separating Peruque Creek and Dardenne Creek to decrease about 10 feet during both the predevelopment and pumping scenarios. This 50 percent change also caused hydraulic heads on the ridge at the site to decrease by 10 to 30 feet during the predevelopment scenario and to decrease by 10 to 20 feet during the pumping scenario. In the predevelopment scenario the simulated hydraulic heads in layers 2 and 3 decreased about 10 feet north of Dardenne Creek, but increased about 10 feet in the western one-third of the model. No substantial changes were observed in the hydraulic heads of layers 2 and 3 during the pumping scenario; however, hydraulic heads decreased slightly in both layers.

Decreasing the hydraulic conductivity of layer 1 by 50 percent caused the hydraulic heads in layer 1 in both scenarios to increase 10 to 20 feet on the ridge separating Peruque Creek and Dardenne Creek and increase 10 to 40 feet on the ridge where the chemical plant is located. Water levels in layers 2 and 3 during the predevelopment scenario increased about 10 feet along the ridge separating Peruque Creek and Dardenne Creek and on the ridge where the chemical plant is located. No substantial effects were observed in either layers 2 or 3 during the pumping scenario, but hydraulic heads increased slightly.

Increasing the hydraulic conductivity of the upper confining unit by 50 percent affected hydraulic heads in layer 1 during both the predevelopment and pumping scenarios, but had minimal effects on layers 2 and 3. Hydraulic heads decreased about 10 feet in the western part of layer 1 along the ridge separating Peruque Creek and Dardenne Creek and decreased on the ridge at the chemical plant by 10 feet. There were no substantial effects to either layer 2 or 3 in the predevelopment scenario, and the only observable effect in the pumping scenario was that hydraulic heads increased about 10 feet in the area between Peruque Creek and Dardenne Creek in layer 2.

Decreasing the hydraulic conductivity of the upper confining unit by 50 percent had the most significant effects on hydraulic heads in layer 1. Hydraulic heads on the western side of the ridge separating Peruque Creek and Dardenne Creek increased about 10 feet in the predevelopment scenario and increased 20 to 30 feet in the pumping scenario. In the predevelopment scenario the area north of Peruque Creek had hydraulic head declines ranging from 10 to 20 feet in both layers 2 and 3. In the pumping scenario the central part of the modeled area in layer 2 had hydraulic head declines of

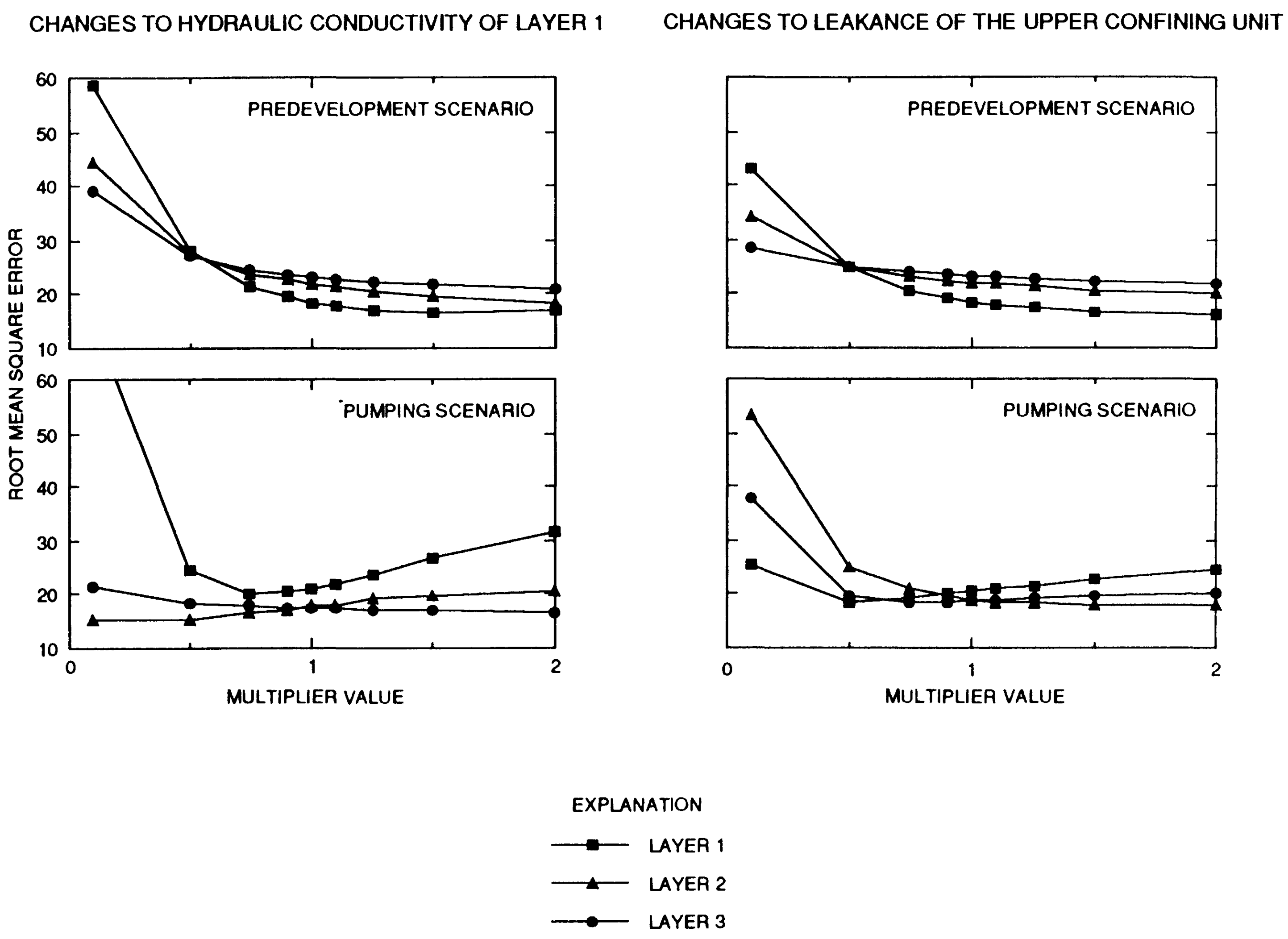


Figure 46. Sensitivity analysis for the model layers for both the predevelopment and pumping scenarios.

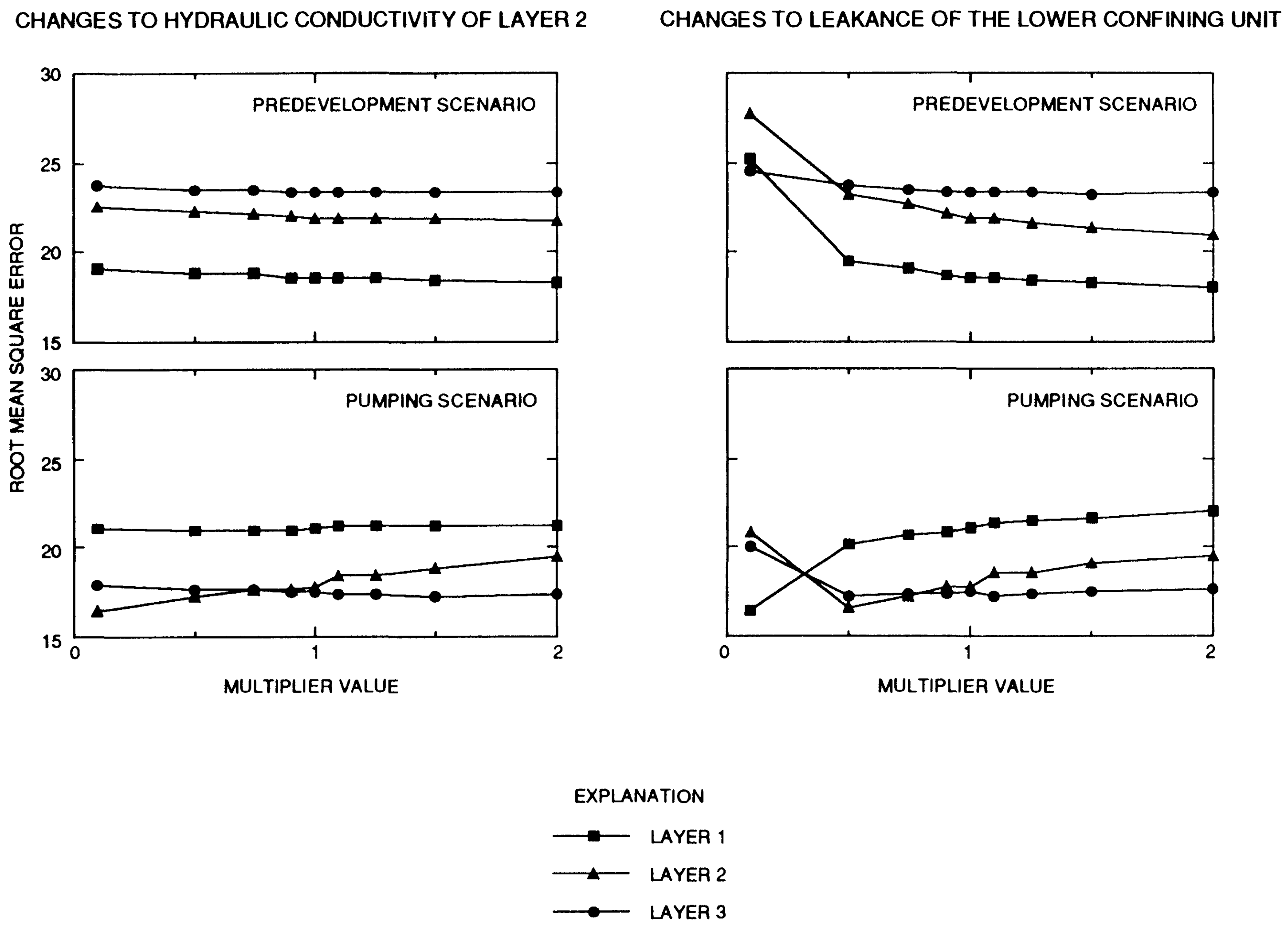


Figure 46. Sensitivity analysis for the model layers for both the predevelopment and pumping scenarios--Continued.

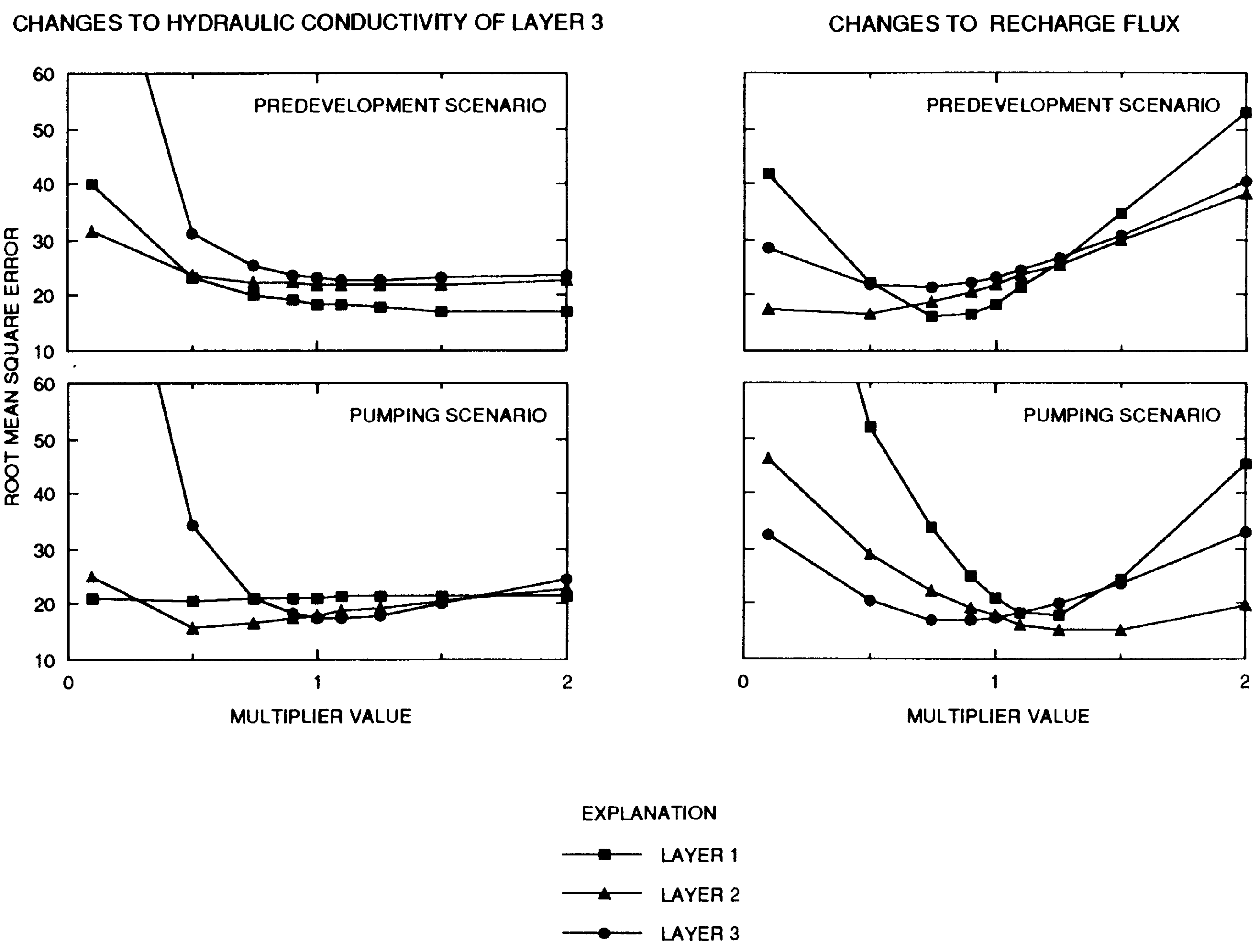


Figure 46. Sensitivity analysis for the model layers for both the predevelopment and pumping scenarios--Continued.

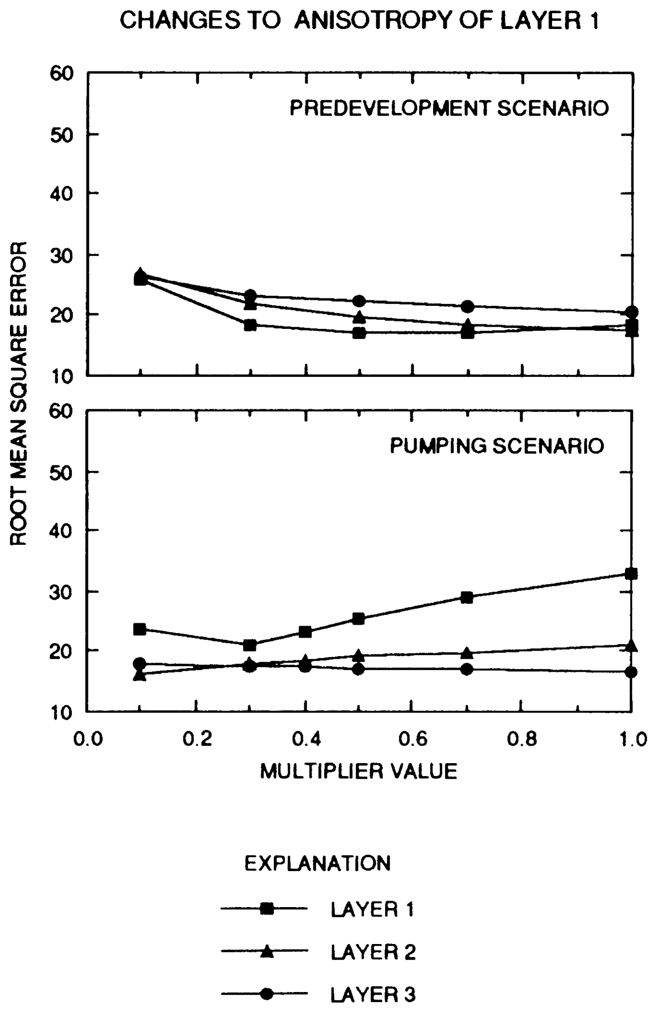


Figure 46. Sensitivity analysis for the model layers for both the predevelopment and pumping scenarios--Continued.

about 20 feet, and these declines extended from Peruque Creek south to the Missouri River. In the pumping scenario layer 3 had hydraulic head declines of 10 to 20 feet in the pumping center.

Increasing or decreasing the hydraulic conductivity in layer 2 had, in general, no substantial effect on the hydraulic heads in any of the aquifer layers. Increasing the hydraulic conductivity in the predevelopment and pumping scenarios decreased water levels slightly in the three layers. Decreasing the hydraulic conductivity in both the predevelopment and pumping scenarios had no substantial effect to any of the three layers. The insensitivity of layer 2 may be a result of the layer being thin in comparison to the other layers.

Increasing the hydraulic conductivity of the lower confining unit had minimal effects on the hydraulic heads in layers 1 through 3 in the predevelopment scenario. The hydraulic heads decreased slightly in layers 1 and 2 in the pumping scenario, but in layer 3 there were no observable changes in hydraulic head.

Decreasing the hydraulic conductivity of the lower confining unit during the predevelopment scenario had limited effects on layer 1, but hydraulic heads increased about 10 feet in a small area southwest of the site. In layer 2 this change caused hydraulic heads to increase 10 to 50 feet in the same area. No substantial changes were noted in layer 3, but hydraulic heads increased slightly. Decreasing the hydraulic conductivity of the lower confining unit during the pumping scenario caused no significant changes to hydraulic heads in layers 1 and 3, but hydraulic heads in layer 2 increased about 10 feet in a small area north of Dardenne Creek and increased 10 to 30 feet in a small area southwest of the site.

Increasing the hydraulic conductivity of layer 3 in the predevelopment scenario caused no substantial effects to layer 1, but hydraulic heads decreased slightly. Hydraulic heads in layers 2 and 3 decreased about 10 feet on the western side of the layers. Hydraulic heads in layer 1 increased slightly during the pumping scenario, and in layers 2 and 3 hydraulic heads increased 10 to 30 feet at the pumping center and decreased 10 to 20 feet southwest of the site.

Decreasing the hydraulic conductivity of layer 3 in the predevelopment scenario caused hydraulic heads in all three layers to increase 10 to 40 feet on the west side of the modeled area. Also hydraulic head increases of about 10 feet were observed to extend along the ridges to the east in layer 1, but in layers 2 and 3, hydraulic heads were not affected at the ridges. However, hydraulic head increases of 10 feet affected the entire western one-half of both layers. During the pumping scenario, hydraulic heads increased slightly in layer 1, but in layers 2 and 3, hydraulic head increases of 10 to 30 feet occurred at the pumping center and 10 to 20 feet hydraulic head decreases were observed southwest of the site.

The hydraulic heads in all three layers were sensitive to changes in recharge. Increasing recharge by 50 percent in the predevelopment scenario caused hydraulic heads to increase 30 to 40 feet on the west side of layer 1 and to increase about 10 feet throughout the rest of the layer. In layers 2 and 3, hydraulic heads increased 10 to 20 feet in the western two-thirds of both layers. Increasing the recharge in the pumping scenario by 50 percent caused hydraulic heads to increase 20 to 30 feet on the west side of layer 1; the increases in hydraulic head decreased to about 10 feet on the east side of layer 1. In layers 2 and 3 hydraulic heads increased 10 to 20 feet across the entire modeled layer.

Decreasing recharge 50 percent in the predevelopment scenario caused hydraulic heads in layer 1 to decrease 40 to 50 feet on the western one-half of the layer and to decrease 10 feet on the eastern one-half of the layer. Along the ridge tops, hydraulic heads decreased 50 to 60 feet. Hydraulic heads in layers 2 and 3 decreased 20 feet in the western one-half and decreased 10 feet throughout the rest of the layer. Decreasing recharge by 50 percent in the pumping scenario caused hydraulic heads in layer 1 to decrease 40 to 50 feet in the western part of the layer and along ridges. Hydraulic head decreases of 10 feet occurred on the eastern part of the layer. In layers 2 and 3 hydraulic heads decreased 10 to 20 feet throughout both layers.

Increasing the anisotropy in layer 1 during the predevelopment and pumping scenarios by 50 percent caused hydraulic heads to increase 10 to 20 feet on the ridge separating Peruque Creek and Dardenne Creek, and to increase 10 to 40 feet along the ridge at the site in layer 1. There were no significant changes to the hydraulic heads in layers 2 and 3 during either scenario, but hydraulic heads increased slightly. Decreasing the anisotropy in layer 1 by 50 percent caused the hydraulic heads in both the predevelopment and pumping scenarios to decrease 10 to 20 feet along the ridges in layer 1. Hydraulic heads in layers 2 and 3 showed no significant changes in either scenario, but hydraulic heads decreased slightly.

The sensitivity analysis indicates that no substantial improvement could be made by further refining the model calibration. Slight improvements could be made to simulated water levels in each layer at the expense of the other layers by adjusting hydraulic conductivity, leakance, recharge, and anisotropy. Layer 1 seems to be most sensitive to changes in hydraulic conductivity, leakance in the upper confining unit, and recharge. Layer 2 seems to be most sensitive to hydraulic conductivity changes to layer 3, leakance changes to the upper confining unit, and recharge. Layer 3 is most sensitive to changes in the hydraulic conductivity of layer 3 and to recharge. The model seems to be the least sensitive to changes in the hydraulic conductivity of layer 2 and to the leakance of the lower confining unit.

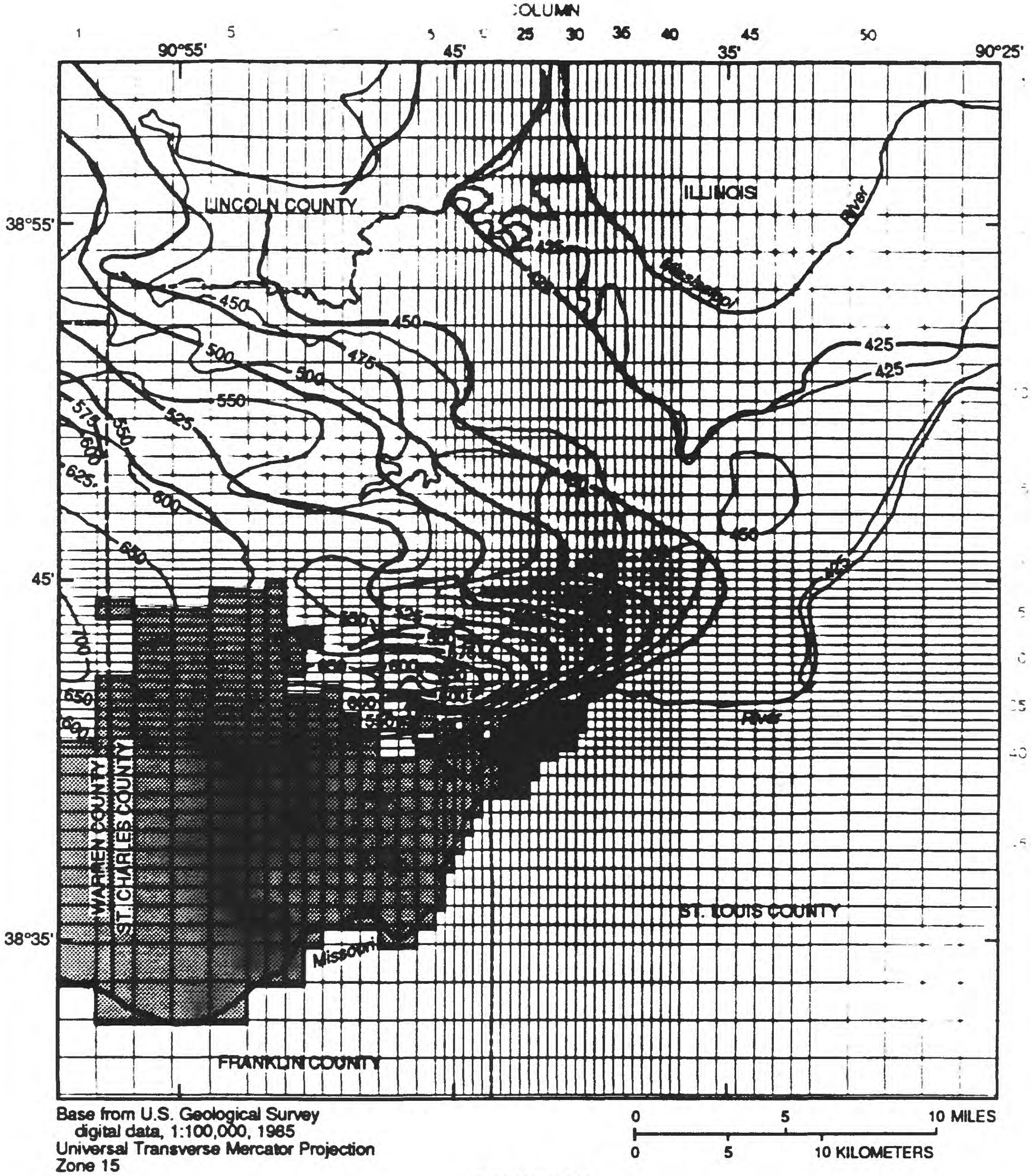
Accuracy of Model Simulations

The accuracy of the model simulations was evaluated by monitoring the RMS error. The RMS error in layer 1 for the accepted predevelopment model simulation was 18.6 feet based on 47 measured water levels and simulated hydraulic heads. The pumping scenario for layer 1 had an RMS error of 21.1 feet based on 72 measured and simulated heads. Generally, the simulated hydraulic heads in layer 1 agreed with the measured water levels with a few notable exceptions. The obvious deficiency in the simulated hydraulic heads in layer 1 during the pumping scenario was the inability to reproduce the measured hydraulic heads in the vicinity of Peruque Creek, which also corresponds to the area where most of the pumping wells were located (fig. 47). The simulated hydraulic heads in this area generally were 30 to 40 feet too low. In the predevelopment scenario, the most obvious deficiency in the model was that the simulated hydraulic heads generally were 10 to 30 feet too high along the ground-water ridge between Peruque Creek and Dardenne Creek.

A detailed analysis of the effectiveness of the model simulation of layer 2 is not possible because of the few known wells open to only the middle aquifer. Twelve wells were measured for the predevelopment scenario, and on the basis of measured water levels and simulated hydraulic heads, layer 2 had a RMS error of 21.9 feet. The difference between the measured water levels in the 6 available wells in the pumping scenario and the simulated hydraulic heads gave an RMS error of 17.9 feet.

The RMS error of 23.4 feet for the predevelopment scenario in layer 3 was based on 30 water-level measurements. The obvious deficiency for this scenario is that the model simulated hydraulic heads 10 to 20 feet too high in the eastern part of the model. This is a large area where the alluvium typically is more than 100 feet thick. Because of the abundant water supply at shallow depths in the alluvium, there is only one known well that completely penetrates the 1,300 feet of bedrock overlying the deep aquifer in this area. When this exploratory well penetrated the deep aquifer, water began to flow from the well. The simulated hydraulic heads on the potentiometric map for the deep aquifer in this area are based on the altitude of the Missouri and Mississippi Rivers in the vicinity of the model cells because these major rivers are discharge areas even for the deep aquifer. Even though the simulated hydraulic heads were too high, the error may not be as large as calculated because of the confined hydraulic head in the deep aquifer that was illustrated by the flowing exploration well.

The RMS error of 17.5 feet was calculated for the pumping scenario in layer 3, which was based on 21 water-level measurements. The measured potentiometric surface of layer 3 during summer 1984 and the simulated hydraulic heads in layer 3 for the pumping scenario are shown in figure 48. The model was calibrated using higher hydraulic heads in the area where most of the pumping withdrawals occurred instead of the measured water levels. This was done because of the expected drawdown effects discussed earlier.



EXPLANATION

AREA WHERE THE SHALLOW AQUIFER IS ABSENT

—450— POTENTIOMETRIC CONTOUR--Shows altitude at which water levels would have stood in tightly cased wells. Contour interval is variable. Datum is sea level

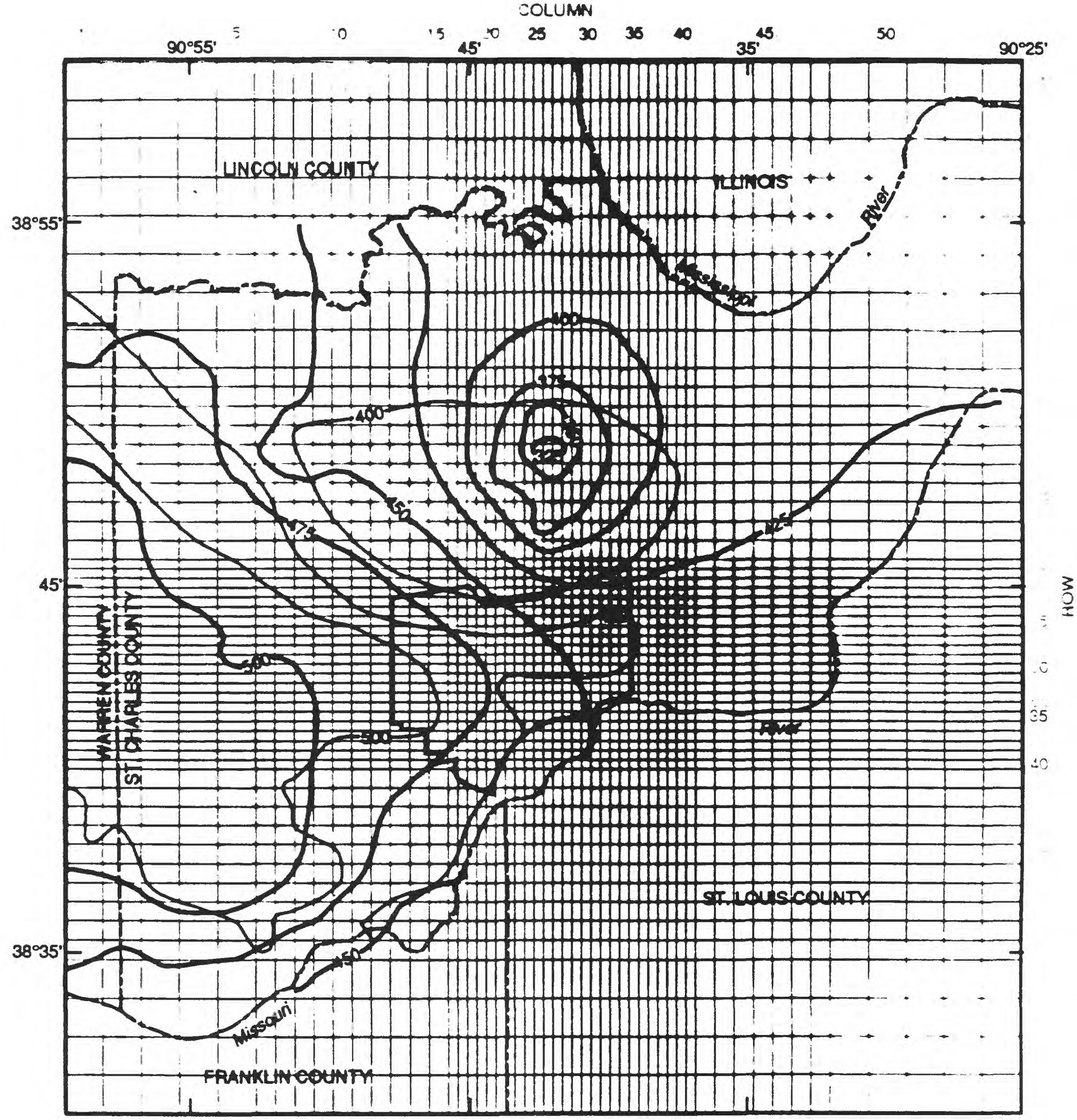
—450— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of simulated water levels. Contour interval 25 feet. Datum is sea level

Figure 47. Measured and simulated potentiometric surface for the pumping scenario for model layer 1.

Water Budget at Weldon Spring Chemical Plant Site

The results of the accepted steady-state model simulation using the pumping scenario are illustrated in figure 49. The net-flow rate going into or out of each model layer for nine model cells at the site is shown. These rates show 75 percent of the inflow to layer 1 in the area occupied by the chemical plant is from precipitation and 25 percent is lateral inflow from the west. Twenty-one percent of this inflow leaks downward into layer 2, 19 percent flows to the north, 40 percent flows to the east, and 20 percent flows to the south.

Ninety-four percent of the total flow into layer 2 is inflow through the upper confining unit. Inflow from the west accounts for the other 6 percent. Approximately 80 percent of the flow going out of layer 2 infiltrates into layer 3, about 4 percent flows to the north, 11 percent flows to the east, and 6 percent flows to the south. Round-off errors cause the percentages to exceed 100 percent. In layer 3, 22 percent of the flow is to the north, 61 percent to the east, and 17 percent flows to the south. Because the bottom of layer 3 was modeled as a no-flow impermeable boundary, no flow is lost downward.



Base from from U.S. Geological Survey digital data, 1:100,000, 1985
Universal Tranverse Mercator Projection
Zone 15

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

—500— POTENTIOMETRIC CONTOUR--Shows altitude at which water levels would have stood in tightly cased wells. Contour interval 50 feet. Datum is sea level

—500— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of simulated water levels. Contour interval 25 feet. Datum is sea level

Figure 48. Measured and simulated potentiomentric surface for the pumping scenario for model layer 3.

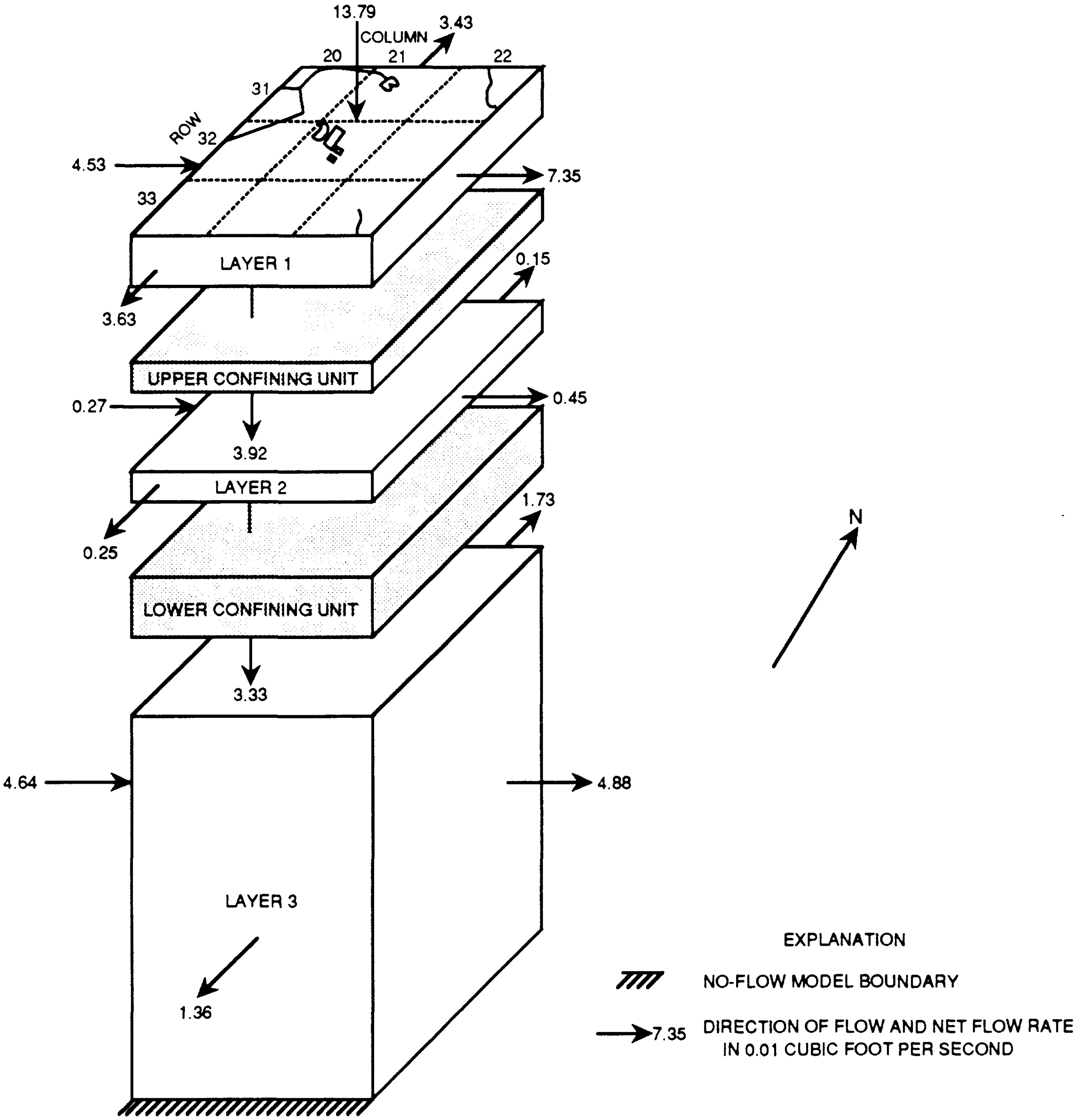


Figure 49. Steady-state water budget for the Weldon Spring chemical plant site.

SUMMARY AND CONCLUSIONS

The Weldon Spring chemical plant in St. Charles County is located on a ridge separating the Ozark Plateaus from the Dissected Till Plains. Unconsolidated surficial materials on the site consist of six units that primarily are clays, silty clays, and clayey silts that range from 15 to 60 feet thick. A residuum unit, however, consists of cobbles and boulders of limestone and chert in a silty, sandy, clay matrix and ranges from 0 to 26 feet thick onsite. The permeability of this unit is variable but substantial in places.

The uppermost bedrock formation at the chemical plant is the undifferentiated Burlington and Keokuk Limestones. These formations are about 100 to 120 feet thick under the site and can be divided into two units based on lithologic and hydrologic properties. The uppermost unit is extremely to moderately weathered, extremely to moderately fractured, and contains solution features ranging from vugs to small cavities. This weathered unit ranges from 10 to more than 50 feet thick. The underlying unit is slightly weathered to fresh, contains few fractures, and solution features are limited to occasional vugs.

The geologic formations in St. Charles County are separated into six geohydrologic units in this report. Bedrock formations younger than the Osagean Series of the Mississippian System were not considered significant because of their limited occurrence or because they lie beneath thick alluvial deposits. The remaining formations from the top of the Osagean Series of the Mississippian System to the base of the Potosi Dolomite were separated into three aquifers and two confining units.

Considerable surface- and ground-water interaction takes place in stream reaches north of the Weldon Spring chemical plant site. Losing stream reaches occur in the middle and east forks of the western tributary of Schote Creek that drains the chemical plant site and raffinate-pit areas. The mainstem of Schote Creek also was determined to lose water for about 0.7 river mile downstream from Memorial lake. Dye-tracing tests on the losing stream reaches of Schote Creek and the middle and eastern forks of the western tributary of Schote Creek indicate a hydrologic connection with Burgermeister spring; therefore, an interbasin transfer of water occurs. A hydrologic connection also was determined by dye-tracing tests between lake 35 and lake 34 and spring 6306. Lake 34 and spring 6306 are located downstream from Burgermeister spring.

Water samples from wells adjacent to pits (raffinate pits containing radioactive wastes from plant processing operations) at the chemical plant site indicate that water from the pits has entered the ground-water system and is present in the underlying bedrock. Surface water from the raffinate-pit area probably is seeping downward through the unconsolidated surficial materials. On its downward migration, this water eventually reaches zones of higher permeability, either the residuum layer, where present, or the weathered limestone unit of the Burlington and Keokuk Limestones. In areas where the water encounters the residuum layer, the water flows laterally until it reaches a fracture or other route to continue its downward movement to the water table. Because the upper part of the bedrock is weathered, highly to moderately fractured, and contains solution features ranging from vugs to small cavities, routes capable of transporting water are available. The general slope of the bedrock and gradient of the water table is toward the north throughout most of the chemical plant site, making this the most probable direction of flow through permeable zones. Also, troughs have formed in the top of limestone between the chemical plant site and Burgermeister spring that have potential to channel water to the north.

Water from 26 wells located on the chemical plant property, 2 wells on the U.S. Army property, and 4 wells on the August A. Busch Memorial Wildlife Area contained elevated concentrations of chemical constituents associated with the chemical plant. The offsite chemical constituent indicators of contaminant migration in wells included calcium, sulfate, nitrate, or uranium; also elevated concentrations of magnesium (51 milligrams per liter), sodium (37 milligrams per liter), and lithium (68 micrograms per liter) were detected in one well. Generally increased concentrations of these constituents are present in various combinations. Analyses of samples from 5 springs in tributaries 5300 and 6300 indicate that they receive recharge from the chemical plant site. The chemical indicators of contamination at these springs include elevated concentrations of sodium, chloride, nitrate, lithium, strontium, and uranium. The tributaries that receive drainage from the chemical plant site are the southeast drainage (tributary 5300), Schote Creek (tributary 6200), including both the west and east tributaries, and tributary 6300. The mainstem of Dardenne Creek has elevated concentrations of uranium at County Road N during low-flow periods. These elevated concentrations are thought to be caused by the inflow of water from tributary 6300 into Dardenne Creek. The number of reliable chemical indicators in water decreases with increased distance from the chemical plant. The two indicators that were most persistent are nitrate and uranium. Presently (1992), ground-water-quality changes associated with the Weldon Spring chemical plant have been detected north of the site but are limited to the recharge areas for the springs in tributary 6300. To the south of the chemical plant site, contaminants from the plant have been detected only in tributary 5300.

A three-dimensional ground-water flow model was developed to qualitatively assess the flow between aquifers at the chemical plant site and to address the potential for contaminated water to enter the deep aquifer from directly under the chemical plant. The modeled area includes almost the entire St. Charles County and parts of Lincoln, Warren, and Franklin Counties, but the smallest grid spacing was used in the area of the site. The model, which consisted of three aquifers, separated by leaky confining units, was calibrated to steady state conditions using a predevelopment and pumping scenario.

The shallow aquifer (layer 1) consisted of the Burlington and Keokuk Limestones and the Fern Glen Formation. Layer 1 is considered to be anisotropic with the hydraulic conductivity north to south 4.8×10^{-6} foot per second and east to west 1.6×10^{-5} foot per second. These values were based on specific capacity data and slug tests performed in the study area and in a nearby county.

The upper confining unit consists of the formations from the top of the Chouteau Group to the base of the Maquoketa Shale. Where the upper confining unit was exposed at land surface or not buried sufficiently in the subsurface, and weathering could occur a vertical hydraulic conductivity of 5.7×10^{-6} was assigned. Where the unit is buried in the subsurface and weathering is not thought to have occurred, a vertical hydraulic conductivity of 1.3×10^{-9} foot per second was assigned.

The middle aquifer (layer 2) consists of the Kimmswick Limestone. This layer was considered isotropic and assigned a hydraulic conductivity of 3.9×10^{-6} foot per second. The lower confining unit consists of the formations from the top of the Decorah Formation to the base of the Joachim Dolomite and a hydraulic conductivity of 2.4×10^{-8} foot per second was assigned to this unit. The deep aquifer (layer 3) consists of the formations from the top of the St. Peter Sandstone to the base of the Potosi Dolomite. The unit was considered isotropic with a hydraulic conductivity of 4.2×10^{-6} foot per second.

The accepted model simulation using the predevelopment scenario had a RMS error of 18.6 feet for layer 1, 21.9 feet for layer 2, and 23.4 feet for layer 3. The accepted model simulation using the pumping scenario had a RMS error of 21.1 feet for layer 1, 17.9 feet for layer 2, and 17.5 feet for layer 3. The conclusions based on the steady-state model simulation using the pumping scenario indicate 21 percent of the flow in layer 1 infiltrates into layer 2 in a nine model cell area centered at the chemical plant site. Approximately 80 percent of the flow going out of layer 2 infiltrates into layer 3 in this same area.

REFERENCES

Allen, W.H., Jr., and Ward, R.A., 1977, The land--Soil, in The resources of St. Charles County, Missouri, land, water, and minerals: Rolla, Missouri Division of Geology and Land Survey, p. 108-145.

Bechtel National, Inc., 1984, Geologic report for Weldon Spring raffinate pits site, Weldon Spring, Missouri: U.S. Department of Energy, Oak Ridge Operations Office, 46 p. with appendices.

_____ 1986a, Weldon Spring site annual site environmental monitoring report, Weldon Spring, Missouri, calendar year 1985: U.S. Department of Energy, Oak Ridge Operations Office, 72 p. with appendices.

_____ 1986b, Report on water balance studies from 1983 to 1985 Weldon Spring raffinate pits, Weldon Spring, Missouri: U.S. Department of Energy, Oak Ridge Operations Office, 14 p. with appendices.

Bechtel National, Inc., 1987, Hydrogeological characterization report for Weldon Spring chemical plant: U.S. Department of Energy, Oak Ridge Operations Office, 94 p. with appendices.

Berkas, W.R., Endicott, Cynthia, and Cross, P.W., 1989, Groundwater level data for Missouri 1985-1986: Rolla, Missouri Division of Geology and Land Survey Water Resources Report 37, 79 p.

Bouwer, H., and Rice, R.C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: Water Resources Research, v. 12, no. 3, p. 423-428.

Carman, J.D., 1991, Aquifer characteristics of the shallow Burlington-Keokuk Limestone at the Weldon Spring site, in Proceedings of the Geosciences Workshop: U.S. Department of Energy, Oak Ridge Operations Office, p. 155-201.

Collinson, Charles, and Swann, D.H., 1958, Mississippian rocks of western Illinois: New York, Guidebook Series, The Geological Society of America, Illinois Geological Survey, 31 p.

Emmett, L.F., and Imes, J.L., 1984, Ground-water resources of Audrain County, Missouri: U.S. Geological Survey Open-File Report 84-245, 55 p.

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

Fenneman, N.M., 1938, Physiography of eastern United States: New York, McGraw-Hill, 714 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 524 p. with appendices.

Gerdemann, P.E., and Myers, H.E., 1972, Relationships of carbonate facies patterns to ore distribution and to ore genesis in the southeast Missouri lead district: Economic Geology, v. 67, p. 426-433.

Gilliom, R.J., and Helsel, D.R., 1986, Estimation of distributional parameters for censored trace-level water-quality data--1. Estimation techniques: Water Resources Research, v. 22, no. 2, p. 136-146.

Helsel, D.R., and Cohn, T.A., 1988, Estimation of descriptive statistics for multiple-censored water-quality data: Water Resources Research, v. 24, no. 12, p. 1,997-2,004.

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

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

International Technology Corporation, 1989, Draft remedial investigation report Weldon Spring training area Weldon Spring, Missouri: Kansas City, Missouri, U.S. Army, v. 1, 173 p.

Kisvarsanyi, Geza, and Martin, J.A., 1977, Structural lineament and pattern analysis of Missouri, using Landsat imagery: National Technical Information Service, E-77-10239.

Kleeschulte, M.J., and Cross, P.C., 1990, Hydrologic data for the Weldon Spring chemical plant site and vicinity property, St. Charles County, Missouri--1986-89: U.S. Geological Survey Open-File Report 90-552, 117 p.

Kleeschulte, M.J., and Emmett, L.F., 1986, Compilation and preliminary interpretation of hydrologic data for the Weldon Spring radioactive waste-disposal sites, St. Charles County, Missouri--A progress report: U.S. Geological Survey Water-Resources Investigations Report 85-4272, 71 p.

_____ 1987, Hydrology and water quality at the Weldon Spring radioactive waste-disposal sites, St. Charles County, Missouri: U.S. Geological Survey Water-Resources Investigations Report 87-4169, 65 p.

Kleeschulte, M.J., Emmett, L.F., and Barks, J.H., 1986, Hydrologic data for the Weldon Spring radioactive waste-disposal sites, St. Charles County, Missouri--1984-1986: U.S. Geological Survey Open-File Report 86-488, 61 p.

Koenig, J.L., ed., 1961, The stratigraphic succession in Missouri: Rolla, Missouri Division of Geology and Land Survey, v. 40, 185 p.

Kurtz, V.E., Thacker, J.L., Anderson, K.M., and Gerdemann, P.E., 1975, Traverse in Late Cambrian strata from the St. Francois Mountains, Missouri, to Delaware County, Oklahoma: Rolla, Missouri Division of Geology and Land Survey Report of Investigations 55, 112 p.

Linebach, Ray, 1977, Geomorphic history of field trip area, in Geology in the area of the Eureka-House Springs anticline with emphasis on stratigraphy-structure-economics: Association of Missouri Geologists Guidebook 24th annual field trip, 1977, 55 p.

McCracken, M.H., 1971, Structural features of Missouri: Rolla, Missouri Division of Geology and Land Survey Report of Investigations 49, 99 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 83-875, 528 p.

Miller, D.E., 1977, The land--Water, in The resources of St. Charles County, Missouri, land, water, and minerals: Rolla, Missouri Division of Geology and Land Survey, p. 31-82.

Miller, D.E., Emmett, L.F., Skelton, John, Jeffery, H.G., and Barks, J.H., 1974, Water resources of the St. Louis area, Missouri: Rolla, Missouri Division of Geology and Land Survey Water Resources Report 30, 114 p.

Missouri Department of Natural Resources, 1985, Census of Missouri public water supplies: Jefferson City, Missouri Division of Environmental Quality, 173 p.

_____ 1986, Missouri water atlas: Rolla, Missouri Division of Geology and Land Survey, 96 p. with appendix.

_____ 1991, Shallow ground water investigations at Weldon Spring, Missouri, final report for fiscal years 1988-1990: Rolla, Missouri Division of Geology and Land Survey, 36 p. with appendices and plates.

MK-Ferguson Company, 1987, Weldon Spring site remedial action project water quality phase I assessment report: U.S. Department of Energy, Oak Ridge Operations Office, 122 p. with appendices.

MK-Ferguson Company and Jacobs Engineering Group, 1989, Phase II ground water quality assessment for the Weldon Spring site, chemical plant, raffinate pits and surrounding vicinity properties: U.S. Department of Energy, Oak Ridge Operations Office, 81 p. with appendices.

_____ 1990a, Weldon Spring site remedial action project--Draft suitability of the Weldon Spring site for potential location of a disposal facility: U.S. Department of Energy, Oak Ridge Operations Office, revision A, 75 p.

_____ 1990b, Aquifer characteristics data report for the Weldon Spring site chemical plant/raffinate pits and vicinity property: U.S. Department of Energy, Oak Ridge Operations Office, revision O.

_____ 1991, Site suitability data on potential location of a disposal facility--Collapse potential and permeability: U.S. Department of Energy, Oak Ridge Operations Office, revision 2, 81 p.

National Oceanic and Atmospheric Administration, 1988, Climatological data annual summary, Missouri: Asheville, N.C., National Climatic Center, v. 92, no. 13.

Quinlan, J.F., and Ewers, R.O., 1986, Reliable monitoring in karst terranes--It can be done, but not by an EPA-approved method: Ground Water Monitoring Review, v. 6, no. 1, p. 4-6.

Roberts, C.M., 1951, Preliminary investigation of ground-water occurrences in the Weldon Spring area, St. Charles County, Missouri, <u>with further notes on problems of the Weldon Spring area, Missouri</u>, by C.V. Theis: U.S. Geological Survey Open-File Report 82-1008, 36 p.

Satterfield, I.R., 1977, The land--Rock, <u>in</u> The resources of St. Charles County, Missouri, land, water, and minerals: Rolla, Missouri Division of Geology and Land Survey, p. 108-145.

Schumacher, J.G., 1993, Geochemistry and migration of contaminants at the Weldon Spring chemical plant site, St. Charles County, Missouri--1989-91: U.S. Geological Survey Open-File Report 93-433, 102 p.

Schumacher, J.G., Sutley, S.J., and Cathcart, J.D., 1993, Geochemical data for the Weldon Spring training area and vicinity property, St. Charles County, Missouri--1990-92: U.S. Geological Survey Open-File Report 93-153, 84 p.

Toth, J., 1963, A theoretical analysis of groundwater flow in small drainage basins: Journal of Geophysical Research, v. 68, no. 16, p. 4,795-4,812.

U.S. Department of Interior, 1970, The national atlas of the United States of America: Washington, D.C., U.S. Geological Survey, 417 p.

Walton, W.C., 1960, Leaky artesian aquifer conditions in Illinois: Champaign, Illinois State Water Survey Report of Investigations 39, 27 p.

Table 2–Statistical summary of selected water-quality data collected in the vicinity of the Weldon Spring chemical plant from September 1985 to August 1989 and used to determine background chemical constituent concentrations

[mg/L, milligrams per liter; <, less than; --, no data; µg/L, micrograms per liter; pCi/L, picocuries per liter]

Property or constituent	Type of site	Number of samples	Maximum	Minimum	Mean	Percentage of samples in which values were less than or equal to those shown: 95	75	50 (Median)	25	5
Specific conductance, microsiemens per centimeter at 25 degrees Celsius	Stream	20	659	297	462	659	543	438	392	298
	Spring	43	670	220	416	667	494	405	346	276
	Well	73	747	460	545	651	592	535	501	462
pH, standard units	Stream	20	8.2	7.5	[a]7.9	8.2	8.2	8.0	7.7	7.5
	Spring	41	8.4	6.3	[a]7.3	8.3	7.6	7.3	7.0	6.6
	Well	71	8.5	6.7	[a]7.5	8.1	7.7	7.5	7.3	7.0
Water temperature, degrees Celsius	Stream	19	23.0	4.0	12	23.0	17.0	12.0	6.0	4.0
	Spring	38	24.5	5.5	12	20.2	12.5	12.0	11.0	9.3
	Well	73	16.5	12	14	15.5	14.5	14.0	13.5	13.0
Hardness, total (mg/L as $CaCO_3$)	Stream	20	340	110	216	340	248	210	172	111
	Spring	48	370	100	208	346	250	200	152	109
	Well	66	370	220	284	336	300	290	260	240
Noncarbonate hardness (mg/L as $CaCO_3$)	Stream	19	67	8	29	67	33	27	19	8
	Spring	46	40	3	24	39	31	26	16	4
	Well	38	36	1	13	33	19	12	6	2
Calcium, dissolved (mg/L as Ca)	Stream	20	99	35	65	99	76	63	50	35
	Spring	48	120	30	63	97	73	62	48	34
	Well	66	83	39	62	82	65	60	58	44
Magnesium, dissolved (mg/L as Mg)	Stream	20	25	6	13	25	15	12	10	6
	Spring	48	26	6	12	24	16	12	8	6
	Well	66	51	12	32	47	36	32	25	2
Sodium, dissolved (mg/L as Na)	Stream	20	36	2	12	36	17	8	6	2
	Spring	48	20	3	8	17	9	6	5	3
	Well	66	32	5	11	30	13	9	7	5

Table 2–Statistical summary of selected water-quality data collected in the vicinity of the Weldon Spring chemical plant from September 1985 to August 1989 and used to determine background chemical constituent concentrations–Continued

Property or constituent	Type of site	Number of samples	Maximum	Minimum	Mean	Percentage of samples in which values were less than or equal to those shown				
						95	75	50 (Median)	25	5
Potassium,	Stream	20	5.6	1.2	2.5	5.5	3.0	2.4	1.5	1.2
dissolved	Spring	48	3.1	.6	1.7	2.8	2.2	1.7	1.2	0.7
(mg/L as K)	Well	66	23	.5	1.6	3.3	1.6	1.1	0.7	0.5
Bicarbonate,	Stream	16	390	160	265	390	288	265	222	160
(mg/L as HCO_3)	Spring	33	400	130	242	400	300	220	200	137
	Well	48	470	260	354	441	388	350	330	280
Alkalinity,	Stream	18	317	105	208	317	234	200	172	105
(mg/L as $CaCO_3$)	Spring	38	326	90	195	325	238	180	145	109
	Well	72	390	226	288	355	308	282	267	229
Sulfate,	Stream	20	77	13	33	76	42	30	26	13
dissolved	Spring	48	59	8	28	54	33	26	18	10
(mg/L as SO_4)	Well	66	35	2	17	32	21	17	11	5
Chloride,	Stream	20	43	2	13	42	15	10	7	2
dissolved	Spring	48	22	2	6	14	9	5	4	2
(mg/L as Cl)	Well	59	10.	.8	3	8	3	2	1	.8
Fluoride,	Stream	20	.3	.1	.2	.3	.3	.2	.1	.1
dissolved	Spring	48	.3	.1	.2	.3	.2	.1	.1	.1
(mg/L as F)	Well	66	1.0	.1	.3	.5	.3	.3	.2	.1
Bromide, dissolved	Stream	2	.06	<.01	--	--	--	--	--	--
(mg/L as Br)	Well	4	.03	.02	--	--	--	--	--	--
Silica,	Stream	20	15	6	11	15	13	10	9	6
dissolved	Spring	48	17	8	12	15	13	12	11	10
(mg/L as SiO_2)	Well	66	18	8	10	14	13	9	8	8
Dissolved solids,	Stream	20	385	151	263	384	304	246	231	153
residue at 180	Spring	48	401	149	241	386	266	234	194	152
degrees Celsius	Well	66	372	233	295	361	322	286	271	245
(mg/L)										

Table 2–Statistical summary of selected water-quality data collected in the vicinity of the Weldon Spring chemical plant from September 1985 to August 1989 and used to determine background chemical constituent concentrations–Continued

Property or constituent	Type of site	Number of samples	Maximum	Minimum	Mean	Percentage of samples in which values were less than or equal to those shown: 95	75	50 (Median)	25	5
Nitrite,	Stream	22	0.01	<0.01	--	0.01	<0.01	<0.01	<0.01	<0.01
dissolved	Spring[b]	48	.02	<.01	--	--	--	--	--	--
(mg/L as N)	Well[b]	64	.05	<.01	[c]0.01	--	--	[c]0	--	--
Nitrite plus nitrate,	Stream	22	1.3	<.10	[c].37	1.3	.5	.2	.1	<.1
dissolved	Spring	48	1.7	<.10	[c].55	[c]1.2	[c].7	[c].6	[c].2	[c]<.1
(mg/L as N)	Well	64	2.4	<.10	[c].64	[c]1.6	[c]1.1	[c].5	[c].2	[c]<.1
Phosphorous, total (mg/L as P)	Well	5	.07	.01	--	--	--	--	--	--
Phosphorous,	Stream	3	.01	<.01	--	--	--	--	--	--
dissolved	Spring	1	.04	--	--	--	--	--	--	--
(mg/L as P)	Well	14	.05	.01	.02	.05	0	0	0	0
Orthophosphate, dissolved (mg/L as P)	Well	5	.04	.01	--	--	--	--	--	--
Aluminum,	Stream	2	<10	<10	--	--	--	--	--	--
dissolved (µg/L as Al)	Well	7	<10	<10	--	--	--	--	--	--
Arsenic, dissolved	Stream	2	<1	<1	--	--	--	--	--	--
(µg/L as As)	Well	7	2	<1	--	--	--	--	--	--
Barium, dissolved	Stream	2	130	100	--	--	--	--	--	--
(µg/L as Ba)	Well[d]	7	330	120	180	--	--	140	--	--
Beryllium, dissolved	Stream	2	<.5	<.5	--	--	--	--	--	--
(µg/L as Be)	Well	7	<.5	<.5	--	--	--	--	--	--
Boron,	Stream	8	40	20	26	40	30	25	20	20
dissolved	Spring	17	40	10	24	40	30	20	20	10
(µg/L as B)	Well	25	20	<10	[c]11	[c]20	[c]20	[c]10	[c]<10	[c]<10

Table 2--Statistical summary of selected water-quality data collected in the vicinity of the Weldon Spring chemical plant from September 1985 to August 1989 and used to determine background chemical constituent concentrations--Continued

Property or constituent	Type of site	Number of samples	Maximum	Minimum	Mean	Percentage of samples in which values were less than or equal to those shown: 95	75	50 (Median)	25	5
Cadmium, dissolved (µg/L as Cd)	Stream	2	<1	<1	--	--	--	--	--	--
	Well	7	2	<1	--	--	--	--	--	--
Chromium, dissolved (µg/L as Cr)	Stream	2	<1	<1	--	--	--	--	--	--
	Well	7	<1	<1	--	--	--	--	--	--
Cobalt, dissolved (µg/L as Co)	Stream	2	<3	<3	--	--	--	--	--	--
	Well	7	<3	<3	--	--	--	--	--	--
Copper, dissolved (µg/L as Cu)	Stream	2	<10	<1	--	--	--	--	--	--
	Well	7	20	<1	--	--	--	--	--	--
Iron, dissolved (µg/L as Fe)	Stream	2	11	10	--	--	--	--	--	--
	Well[d]	7	120	<3	[c]27	--	--	[c]14	--	--
Lead, dissolved (µg/L as Pb)	Stream	2	<10	<1	--	--	--	--	--	--
	Well	7	<5	<5	--	--	--	--	--	--
Lithium, dissolved (mg/L as Li)	Stream	20	10	<4	[c]5	9	6	4	<4	<4
	Spring	48	18	<4	[c]6	[c]11	[c]8	[c]5	[c]<4	[c]<4
	Well	66	16	<4	[c]7	[c]13	[c]9	[c]7	[c]5	[c]<4
Manganese, dissolved (µg/L as Mn)	Stream	2	250	96	--	--	--	--	--	--
	Well[d]	7	530	<1	[c]104	--	--	[c]17	--	--
Molybdenum, dissolved (µg/L as Mo)	Stream	2	<10	<10	--	--	--	--	--	--
	Well	12	10	1	[c]4	[c]10	[c]5	[c]3	[c]1	[c]<1

Table 2–Statistical summary of selected water-quality data collected in the vicinity of the Weldon Spring chemical plant from September 1985 to August 1989 and used to determine background chemical constituent concentrations–Continued

Property or constituent	Type of site	Number of samples	Maximum	Minimum	Mean	Percentage of samples in which values were less than or equal to those shown				
						95	75	50 (Median)	25	5
Nickel, dissolved	Stream	2	2	<10	--	--	--	--	--	--
(µg/L as Ni)	Well[d]	7	3	<1	[c]2	--	--	[c]1	--	--
Selenium, dissolved	Stream	2	<1	<1	--	--	--	--	--	--
(µg/L as Se)	Well	7	<1	<1	--	--	--	--	--	--
Silver, dissolved	Stream	2	<1	<1	--	--	--	--	--	--
(µg/L as Ag)	Well	7	<1	<1	--	--	--	--	--	--
Strontium,	Stream	20	160	75	115	159	130	120	95	75
dissolved	Spring	46	150	58	94	140	110	91	82	61
(µg/L as Sr)	Well	65	250	71	156	220	190	150	135	73
Vanadium, dissolved	Stream	2	<6	<6	--	--	--	--	--	--
(µg/L as V)	Well	12	<6	<6	--	--	--	--	--	--
Zinc, dissolved	Stream	2	6	<3	--	--	--	--	--	--
(µg/L as Zn)	Well[d]	7	28	8	14	--	--	11	--	--
Radium-226,	Stream	13	.9	<.4	--	.9	<.4	<.4	<.4	<.4
dissolved	Spring	34	.6	<.4	--	--	--	--	--	--
(pCi/L)	Well	47	.6	<.4	[c].2	[c].4	[c]<.4	[c]<.4	[c]<.4	[c]<.4
Tritium, total	Spring	2	58	56	--	--	--	--	--	--
(pCi/L)	Well	5	30	<5.7	--	--	--	--	--	--
Uranium,	Stream	11	3.0	<1	[c]1.0	3.0	1.4	[c]<1	[c]<1	[c]<1
natural total	Spring	25	2.3	<1	[c]<1	[c]2.1	[c]1.0	[c]<1	[c]<1	[c]<1
(µg/L as U)	Well	29	5.5	<1	[c]1.3	[c]4.2	[c]1.6	[c]<1.1	[c]<1	[c]<1
Uranium,	Stream	10	2.7	.5	1.0	2.7	1.0	.8	.6	.5
natural dissolved	Spring	23	1.2	<.4	[c].7	[c]1.2	[c].8	[c].6	[c].5	[c]<.4
(µg/L as U)	Well	40	4.0	<.4	[c]1.1	[c]3.0	[c]1.6	[c].8	[c]<.4	[c]<.4

Table 2–Statistical summary of selected water-quality data collected in the vicinity of the Weldon Spring chemical plant from September 1985 to August 1989 and used to determine background chemical constituent concentrations–Continued

Property or constituent	Type of site	Number of samples	Maximum	Minimum	Mean	Percentage of samples in which values were less than or equal to those shown				
						95	75	50 (Median)	25	5
Carbon, total organic (mg/L as C)	Stream	19	14	1.7	4.0	14	4.8	3.4	2.2	1.7
	Spring	45	6.8	.4	2.7	5.6	3.6	2.5	1.6	.9
	Well	53	3.9	<.1	[c]1.0	[c]3.3	[c]1.3	[c].8	[c].3	[c]<.1
Carbon, dissolved organic (mg/L as C)	Well	4	.4	.2	--	--	--	--	--	--

[a] Mean pH will not satisfactorily summarize the typical hydrogen ion concentration if pH is not normally distributed.
[b] More than 80 percent of data less than detection limit; therefore, percentile estimates are considered unreliable.
[c] Value is estimated by using a log-probability regression to predict the values of data less than the detection limit as described by Gilliom and Helsel (1986) and Helsel and Cohn (1988).
[d] Because of small data set and the existence of one outlier, the percentile estimates are considered unreliable.