SALTWATER IN SHALLOW AQUIFERS IN EAST-CENTRAL AND NORTHEASTERN LOUISIANA AND SOUTHEASTERN ARKANSAS

By G.F. Huff and J.P. Bonck

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows: °F = 1.8(°C) + 32.

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

Abbreviated water-quality units used in this report:

milligrams per kilogram (mg/kg)

milligrams per liter (mg/L)

milliequivalents per liter (meq/L)

liters per milligram (L/mg)

microsiemens per centimeter at 25 degrees Celsius (µS/cm)

micrograms per liter (µg/L)

kilogram (kg)

kilograms per liter (kg/L)

Saltwater in Shallow Aquifers in East-Central and Northeastern Louisiana and Southeastern Arkansas

By G.F. Huff and J.P. Bonck

Abstract

Analyses of water from irrigation and monitor wells in east-central Louisiana indicated the presence of saltwater in the Mississippi River alluvial aquifer and the uppermost part of the Jasper aquifer system. The salinity of this ground water makes it unsuitable for use in irrigation. Available geochemical data for bromide (Br) and chloride (Cl) ions and strontium (Sr) isotopes indicated that briny water from 5,800 to 6,800 ft below sea level within the Carrizo-Wilcox aquifer could be the source of saltwater in the alluvial aquifer and uppermost part of the Jasper aquifer system. However, in the absence of data on the concentrations of Br and Cl ions and the values of $^{87}Sr/^{86}Sr$ in water from the Catahoula, Cockfield, and Sparta aquifers within the study area, no conclusive statement can be made on the origin of saltwater in the alluvial aquifer and the uppermost part of the Jasper aquifer system.

Analyses of water from irrigation wells in northeastern Louisiana and southeastern Arkansas indicated the presence of saltwater in the Mississippi River alluvial aquifer. Saltwater probably moves from southern Chicot County, Arkansas, into northeastern Louisiana by flowing to the southwest along a fluvial channel eroded into the Cockfield Formation. Saltwater in the Mississippi River alluvial aquifer in northeastern Louisiana and southeastern Arkansas can be hazardous to salt-sensitive crops, such as rice, when used for irrigation.

The geochemistry of Br and Cl ions indicated that saltwater in the Mississippi River alluvial aquifer of southern Chicot County in southeastern Arkansas has two geochemically distinct sources. One source, which has Br/Cl ratios less than that of modern seawater, could be derived from saltwater present in aquifers of Tertiary age that enters the alluvial aquifer by upward flow from below as part of the natural regional ground-water flow pattern. The other source, which has Br/Cl ratios greater than that of modern seawater, could be derived, in part, from briny water present in the Smackover Formation at altitudes from 5,500 to 6,500 feet below sea level that enters the alluvial aquifer by upward migration along the reported intersection of two regional wrench faults, at least one of which penetrates from near land surface into the Smackover Formation.

INTRODUCTION

The Mississippi Alluvial Plain in Louisiana is a major area of ground-water withdrawal for agricultural irrigation (Williamson and others, 1990). The largest source of ground water in the Mississippi Alluvial Plain of northern Louisiana is the Mississippi River alluvial aquifer, referred to as the alluvial aquifer in this report. The alluvial aquifer is heavily used for crop irrigation. Irrigation with water containing elevated concentrations of dissolved solids can damage crops and soil. Rice, a major crop in the Mississippi River Alluvial Plain of Louisiana, is very sensitive to even slightly saline concentrations of dissolved solids in irrigation water during early stages of growth (J.C. Stevens, Louisiana Agricultural Extension Service, oral commun., 1989). Irrigation water with concentrations of dissolved solids as low as 1,700 mg/L was associated with reported failure of rice crops in 1988.

Long-term effects of irrigation with water containing high concentrations of dissolved solids include the build-up of salts in the soil. Damage to crops and soil has occurred where water from the alluvial aquifer has elevated concentrations of dissolved solids (J.C. Stevens, Louisiana Agricultural Extension Service, oral commun., 1989; Mark Walthall, Department of Agronomy, Louisiana State University, written commun., 1990).

Two areas with known crop damage due to elevated concentrations of dissolved solids in irrigation water were identified for study, one in east-central Louisiana and the other in northeastern Louisiana and southeastern Arkansas. In 1987, a study of the ground-water systems having elevated concentrations of dissolved solids in these two areas of the alluvial aquifer was undertaken as part of the cooperative program of water-resources investigations by the U.S. Geological Survey and the Louisiana Department of Transportation and Development.

Purpose and Scope

This report describes the occurrence and movement of saltwater in the Mississippi River alluvial aquifer and underlying shallow aquifers in east-central and northeastern Louisiana and southeastern Arkansas. Specifically determined are the areal and vertical distribution and geochemical characteristics of saltwater in the aquifers. A discussion of the possible origin of saltwater in the aquifers and a method that was developed to determine possible sources of saltwater in otherwise freshwater aquifers is included.

The report presents data collected from ground-water wells in the east-central and northeastern Louisiana and southeastern Arkansas and data collected on briny water from oil wells in east-central Louisiana. The report documents the methods used to collect data presented and presents interpretations of the data. All chemical data for cations and anions presented are for constituents in the dissolved state. The effects of ground-water salinity on farming practices are briefly discussed.

The scheme used for classification of the salinity of water by dissolved-solids concentration is from Robinove and others (1958) and is summarized as follows:

Classification	Dissolved solids, milligrams per liter
Slightly saline	1,000- 3,000.
Moderately saline	3,000-10,000
Very saline	10,000-35,000
Briny	More than 35,000

Lithologic and geophysical data used in this report were obtained from drilling and logging two test holes. Data for water-quality samples were collected from irrigation, monitor, and oil wells in 1989 and 1990.

Ground-Water Data Collection and Method of Study

Ground-water samples were collected from irrigation and observation wells in Concordia Parish in east-central Louisiana, Morehouse Parish in northeastern Louisiana, and Chicot County in southeastern Arkansas. Wells were pumped until field measurements of pH, temperature, and specific conductance of the produced water reached stable values. Temperature, pH, specific conductance, and alkalinity as calcium carbonate were determined on unfiltered samples. Water samples from irrigation and observation wells were analyzed for alkalinity as calcium carbonate by titrating to an endpoint pH of 4.5 with sulfuric acid. Water samples for determination of cations and anions were passed through a 0.45-micrometer filter and collected in pre-rinsed polyethylene bottles. Water samples for analysis of cations were preserved by acidification to a pH of about 1.5 using nitric acid (Wood, 1976). All quantitative elemental analyses not performed in the field were done in a U.S. Geological Survey laboratory. Analytical precisions of all measurements done in the laboratory are described by Fishman and Friedman (1989). Analyses of all water samples for values of $^{87}Sr/^{86}Sr$ were done at Geochron Laboratories, which reported the analytical precision of $^{87}Sr/^{86}Sr$ measurements to be ±0.00002.

Samples of briny water were collected from producing oil wells in Concordia, Tensas, and Catahoula Parishes in east-central Louisiana using methods described by Lico and others (1982). Only oil wells that had not been subjected to secondary recovery procedures such as steam or water injection, or injection of surfactant chemicals were chosen for sampling. Any addition of de-emulsifying chemicals added to the production stream at the wellhead was discontinued for at least 15 minutes prior to sampling.

Sampled oil wells typically produced a mixture of oil, natural gas, and briny water. Samples of this mixture were collected from valves near the wellhead into polyethylene carboys with spigots at the base. After the oil and natural gas gravitationally separated from the briny water in the carboy, samples of briny water were taken from the carboy spigot and passed through glass wool to further separate oil and briny water. Samples for determination of specific conductance, alkalinity as calcium carbonate, and $^{87}Sr/^{86}Sr$ values were collected following filtration through glass wool.

Specific conductance and alkalinity as calcium carbonate were determined in the field following sample collection. Because organic acid anions can contribute significantly to the titratable alkalinity of oil-field ground water (Willey and others, 1975), alkalinity of briny water samples was determined by incremental titration with sulfuric acid. Incremental titrations were carried to at least a pH of 3.5 to ensure titration of all organic species that could have contributed to titratable alkalinity. Following filtration through glass wool, briny water samples for analysis of cations and anions were filtered, preserved, and analyzed in the same manner as were samples from irrigation and observation wells.

Geochemical Tracers in Ground Water

Chloride ions are only rarely involved in sorption or exchange reactions in ground-water systems (Feth, 1981, p. 2) and are involved in precipitation reactions only for solutions saturated with halite or halide salts. Accordingly, any change in the concentration of chloride ions in ground water at less than halite or halide saturation that is not in contact with chloride salts can be assumed to be the result of mixing with other ground water that contains a different concentration of chloride ions. A chemical species that changes concentration only as a result of mixing is said to react conservatively. By this definition, chloride ions react conservatively in ground-water systems provided no dissolution or precipitation of chloride salts occurs.

Bromide ions are very similar in chemical characteristics to chloride ions and also are expected to react conservatively in ground-water systems. It is possible that some bromide ions could enter ground water from the decay of organic matter (Means and Hubbard, 1987; Whittemore, 1988).

Because bromide and chloride ions react conservatively, their concentrations, in a simple mixture of two reasonably homogenous end-member water masses, plot along a linear trend between the compositions of the end members provided the plots are made using linear axes. In addition, a unique relation of bromide to chloride exists for any given relative amount of the end members present. Plots of compositions caused by the mixing of two conservative species can appear as curved lines if the plot is made using logarithmic axes. Whether the plot is made on linear or logarithmic axes, it is referred to as a mixing curve.

Strontium ions do not necessarily react conservatively in the natural environment. Dissolution or alteration of common silicate minerals such as feldspars can add strontium to ground water. Dissolution or precipitation of common sulfate minerals such as gypsum or anhydrite can add or subtract strontium from ground water. Dissolution or precipitation of less common but more strontium-rich minerals like strontianite or celestite can have a substantial effect on strontium concentrations in ground water. Because of their small relative differences in atomic mass, the isotopes of strontium at atomic mass 87 (^{87}Sr) and at atomic mass 86 (^{86}Sr) are not preferentially incorporated into a precipitating mineral. Thus, precipitating gypsum, or other strontium-bearing minerals, can remove strontium from ground water; however, the ^{87}Sr/^{86}Sr ratio of the solution from which the gypsum precipitates will not be changed. Only dissolution of minerals with ^{87}Sr/^{86}Sr ratios different from that of ground water will change the ^{87}Sr/^{86}Sr ratio in ground water.

In a mixture of two reasonably homogenous end-member waters with differing concentrations of strontium ions, a plot of ^{87}Sr/^{86}Sr as a function of 1/Sr will yield a linear relation (Faure, 1977, p. 98-101). The relation of ^{87}Sr/^{86}Sr as a function of 1/Sr will be more complex if dissolution of strontium-bearing minerals having differing ^{87}Sr/^{86}Sr ratios than that of either end-member ground water takes place during mixing. By analogy, a plot of Br/Cl as a function of 1/Cl will also yield a linear relation on mixing of two reasonably homogenous end-member waters. It is often convenient to scale this type of relation by multiplying the values associated with the dependent axis of a plot by an arbitrary constant. In particular, BrX1,000/Cl values are used extensively in this report.

Acknowledgments

In addition to many private well owners who gave permission for their wells to be sampled, the following individuals aided the project with their expertise and cooperation: J.C. Stevens, Louisiana Agricultural Extension Service; Lee Bean; Bud Ricks; Ronald Routon; Anthony Ganey; E.D. Brown; and Benjamin Netherland. The following companies provided access to producing oil wells: BHP Petroleum Company, McGoldrick Oil Company, Crystal Oil and Land Company, Smith Operating, and Munoco Company.

GENERAL CHARACTERISTICS OF THE MISSISSIPPI RIVER ALLUVIAL AQUIFER

The uppermost 80 to 200 ft of clay, silt, sand, and gravel deposited by the Mississippi and smaller rivers within the Mississippi River valley collectively make up the Mississippi River valley alluvium (fig. 1). The alluvium generally thickens southward and toward the present position of the Mississippi River. The top, about 40 ft of the alluvium, is primarily silt and clay of Holocene age. Sand and gravel of Pleistocene age make up the remainder of the alluvium and form the alluvial aquifer. Deposits of Pleistocene age systematically coarsen with depth with gravel up to 3 in. in diameter common in basal deposits. The base of the Mississippi River alluvium is marked by the deepest occurrence of gravel of Pleistocene age (Whitfield, 1975).

Rainfall is the largest source of recharge to the alluvial aquifer (Whitfield, 1975). The alluvial aquifer also is recharged by upward flow from below (Ackerman, 1989). Lateral flow of water in the alluvial aquifer of northern Louisiana generally is southward to southeastward (Whitfield, 1975).

Calcium and bicarbonate generally are the dominant cation and anion, respectively, in alluvial water with concentrations of chloride ions less than about 250 mg/L. Sodium replaces calcium as the dominant cation in parts of Richland Parish, Louisiana. Whitfield (1975) and Smoot (1986) have mapped areas of the alluvial aquifer in Franklin, Richland, and Madison Parishes, Louisiana, that contain water with concentrations of chloride ions about 250 mg/L or greater. Whitfield (1975) has mapped additional areas of the alluvial aquifer in Ouachita and Morehouse Parishes, Louisiana, which contain water with concentrations of chloride ions about 250 mg/L or greater. Concentrations of chloride ions greater than 250 mg/L exceed the secondary maximum contaminant level[1] recommended for public water supply (U.S. Environmental Protection Agency, 1992).

Background values of dissolved solids and dissolved-chloride ion concentrations in water from the alluvial aquifer of northern Louisiana and southern Arkansas are approximately 500 mg/L and 100 mg/L or less, respectively, based on data from Whitfield (1975) and Boswell and others (1968). Whitfield (1975) identifies areas of chloride concentrations greater than 250 mg/l in all the parishes in Louisiana underlain by the alluvial aquifer except East and West Carroll Parishes (fig. 1).

An area of dissolved-solids concentrations greater than 1,000 mg/L in alluvial water exists in southern Chicot County (Boswell and others, 1968). Upward flow of saltwater from below has been suggested as the source of elevated concentrations of dissolved solids in alluvial water within the band of ground water having concentrations of dissolved solids and dissolved-chloride ion concentrations above background values (Boswell and others, 1968; Whitfield, 1975) and within the area containing dissolved-solids concentrations greater than 1,000 mg/L in southern Chicot County (Fitzpatrick, 1985).

EAST-CENTRAL LOUISIANA STUDY AREA

This section presents a brief description of the east-central Louisiana study area and describes the hydrogeology and water quality of aquifers in the area. The areal and vertical distribution, composition, geochemistry, and origin of saltwater are discussed.

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[1] Secondary maximum contaminant level: Contaminants that affect the aesthetic quality of drinking water. At high concentrations or values, health implications as well as aesthetic degradation may also exist. SMCLs are not Federally enforceble but are intended as guidelines for the States.

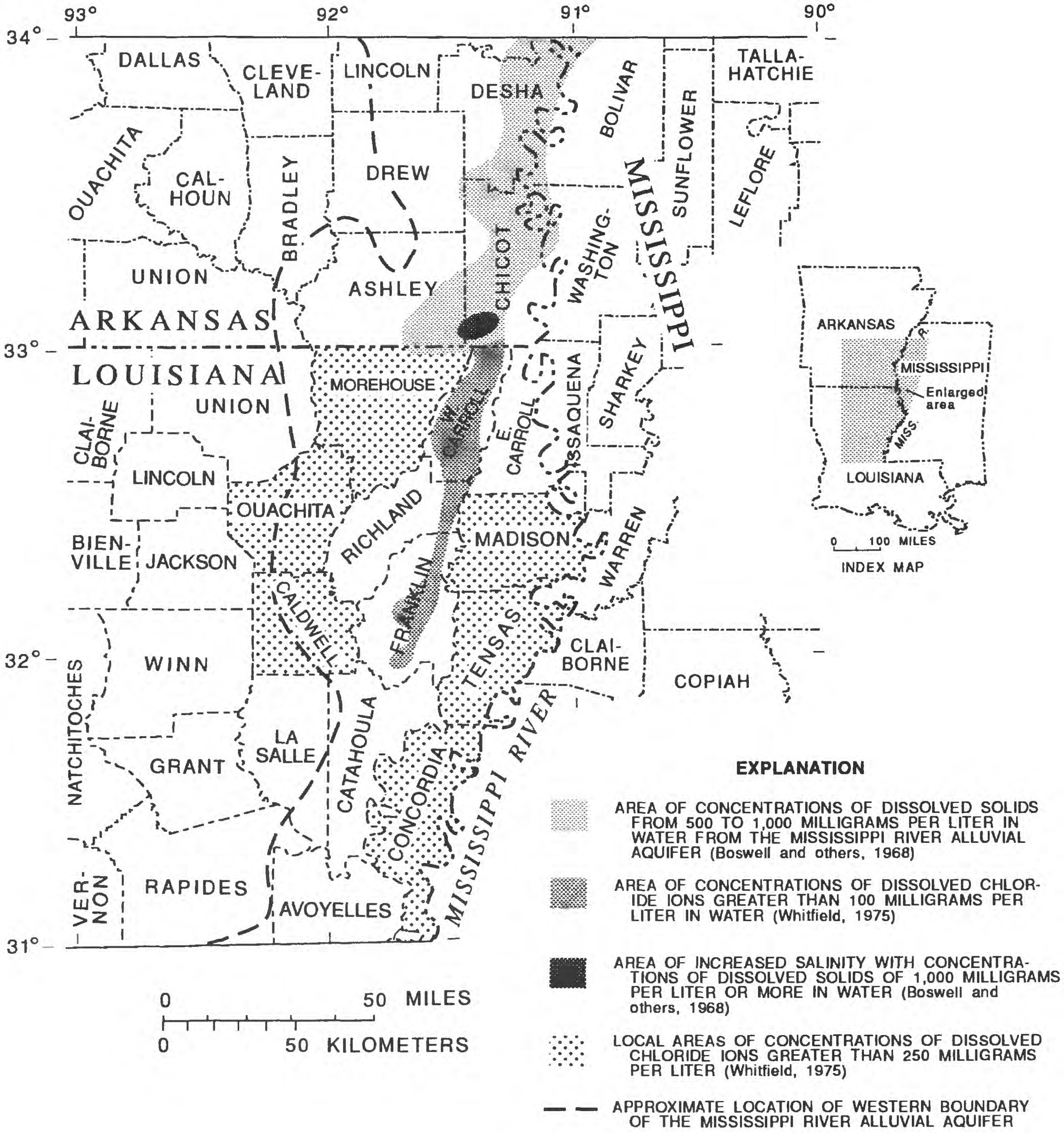


Figure 1. Areas of the Mississippi River alluvial aquifer in northeastern Louisiana and southeastern Arkansas that contain water having indicated concentrations of dissolved solids and dissolved chloride ions.

Description of the Study Area

The east-central Louisiana study area covers about 800 mi^2 (fig. 2). The land surface within the study area has very little local topographic relief and a mean altitude of 50 ft above sea level. No salt domes or diapirs (Beckman and Williamson, 1990) or deeply penetrating faults (Snead and McCulloh, 1984) are known to be present in the east-central Louisiana study area.

Hydrogeology and Water Quality of the Mississippi River Alluvial Aquifer and the Jasper Aquifer System

The stratigraphic units include the Wilcox Group of Tertiary age and younger formations, and the hydrogeologic units include the Carrizo-Wilcox and younger aquifers (fig. 3). The Mississippi River alluvium of Pleistocene age unconformably overlies sediments of the Carnahan Bayou Member of the Fleming Formation of Miocene age throughout the east-central Louisiana study area. The alluvium forms the alluvial aquifer, and Carnahan Bayou member forms the Jasper aquifer system within the study area.

The alluvial aquifer ranges in thickness from 120 ft in the northern part to 200 ft in the southern part of the study area. The base of the alluvial aquifer is marked by the deepest location of gravel of Pleistocene age (Whitfield, 1975). Within the study area, the Jasper aquifer system is about 800 ft thick, and the base of the Jasper aquifer system is marked by the clays of the Lena confining unit (fig. 3). No known salt domes or diapirs are located in or near the east-central Louisiana study area (Beckman and Williamson, 1990).

Water-level data were insufficient to evaluate directions of ground-water flow in the alluvial aquifer in Concordia Parish, Louisiana. However, ground water likely flows southward and discharges into major rivers and streams, as documented by Whitfield (1975) for the alluvial aquifer in Tensas Parish, Louisiana, which lies directly to the north of Concordia Parish.

Water in the alluvial aquifer of east-central Louisiana generally is a calcium-bicarbonate type. Background concentrations of hardness as calcium carbonate range from 200 to 400 mg/L and concentrations of chloride ions range from 10 to 20 mg/L in the study area.

Compilation of Data

Seven irrigation wells and six monitor wells screened in the alluvial aquifer or the uppermost part of the Jasper aquifer system were sampled between 1988 and 1989 (fig. 4). Selected physical properties and chemical analyses are listed in table 1. All monitor wells were screened in the uppermost part of the Jasper aquifer system with the exceptions of well Co-205, which was screened in the alluvial aquifer, and well Co-43, which was screened in the Catahoula aquifer. Well Co-43, located about 1 mi west of the western boundary of the study area, is not shown in figure 4.

Between 1988 and 1989, briny water samples were collected from oil wells in the east-central Louisiana study area (fig. 2). Specific conductance and selected chemical analyses of the briny water are listed in table 2. All sampled oil wells were screened within the Carrizo-Wilcox aquifer. Values of $^{87}Sr/^{86}Sr$ and 1/Sr for water from selected monitor wells and for briny water from oil wells in the study area are listed in table 3.

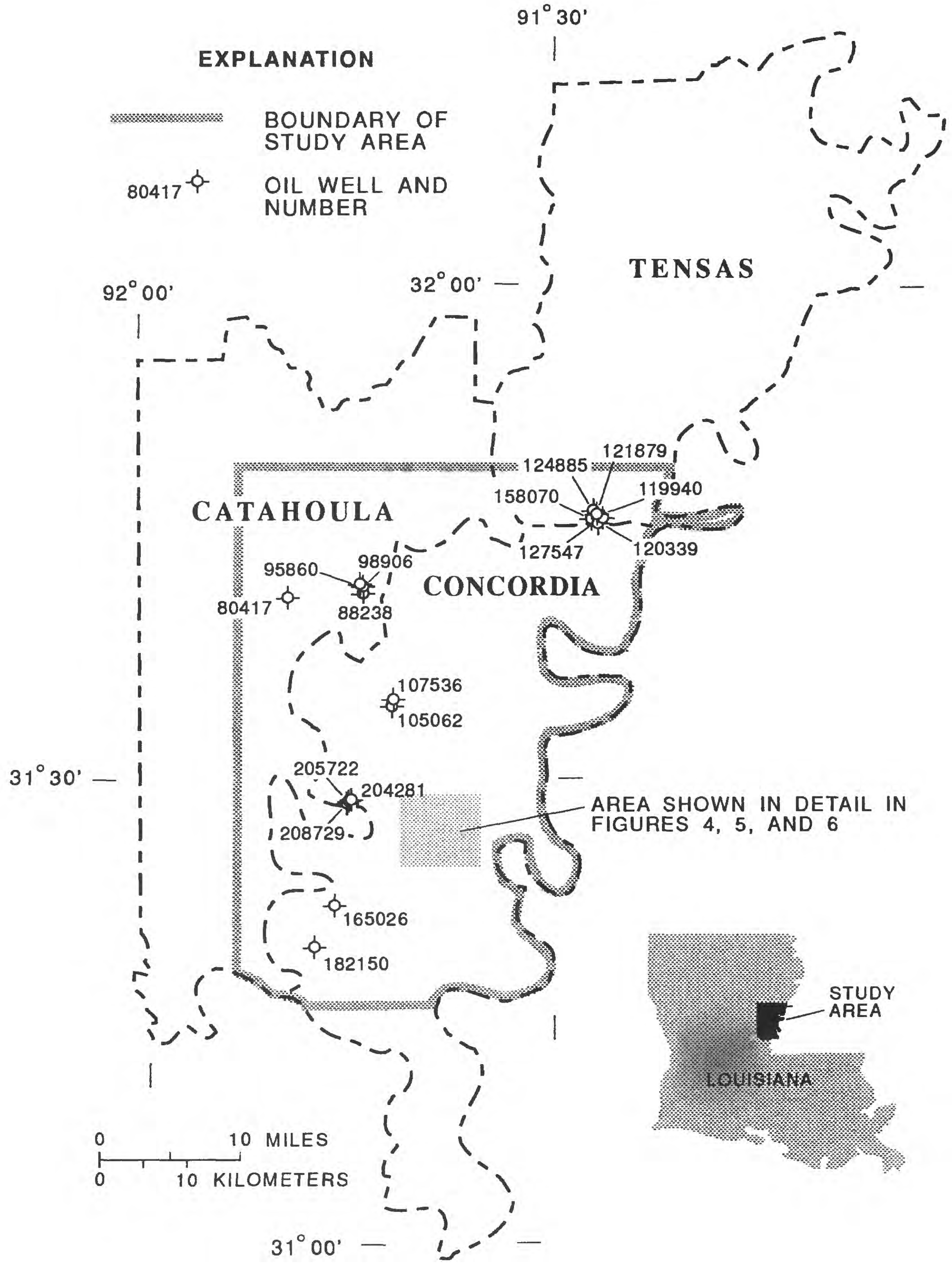


Figure 2. Location of the east-central Louisiana study area and oil wells sampled within the area.

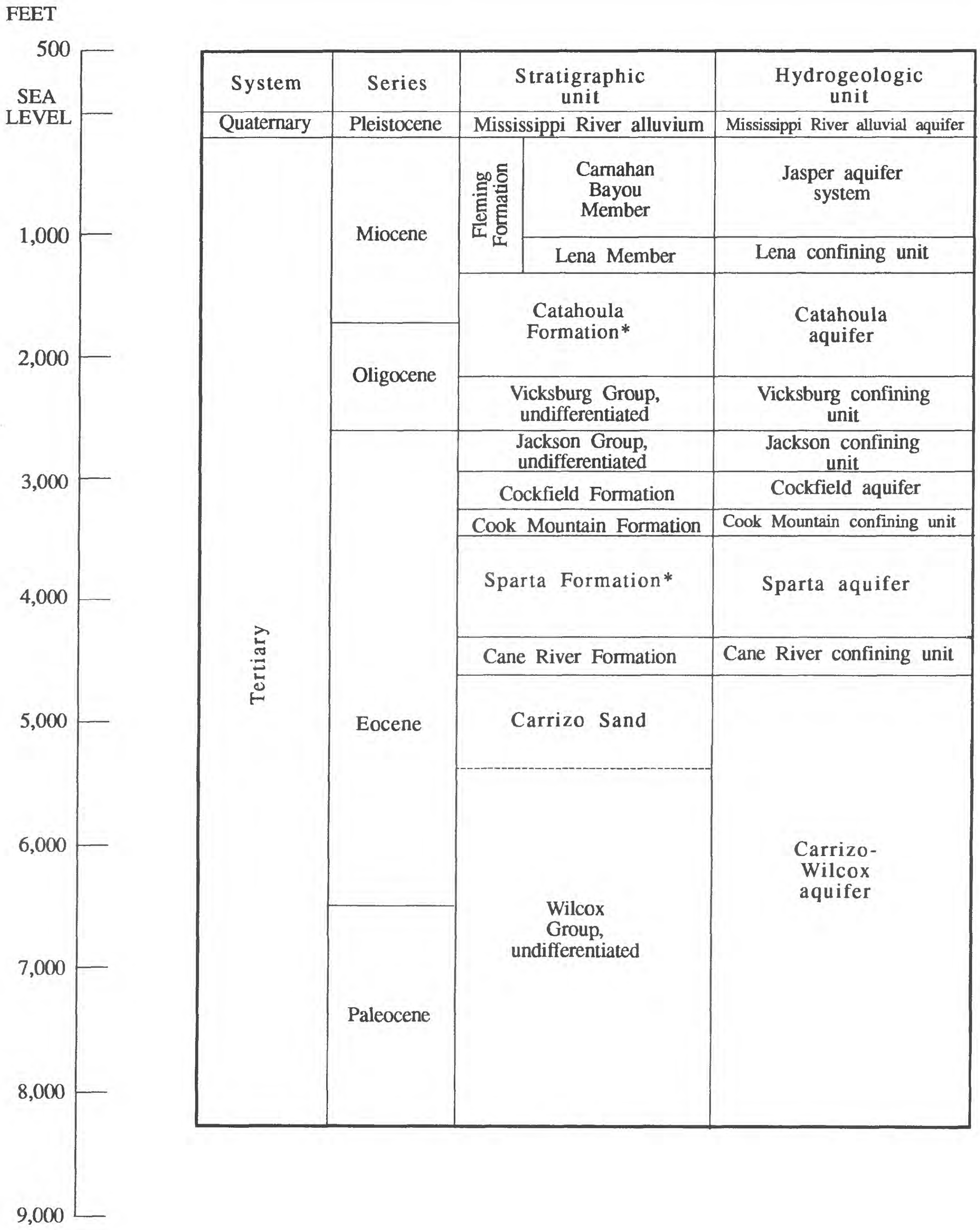


Figure 3. Stratigraphic and hydrogeologic units within the east-central Louisiana study area (modified from Eversull, 1984*).

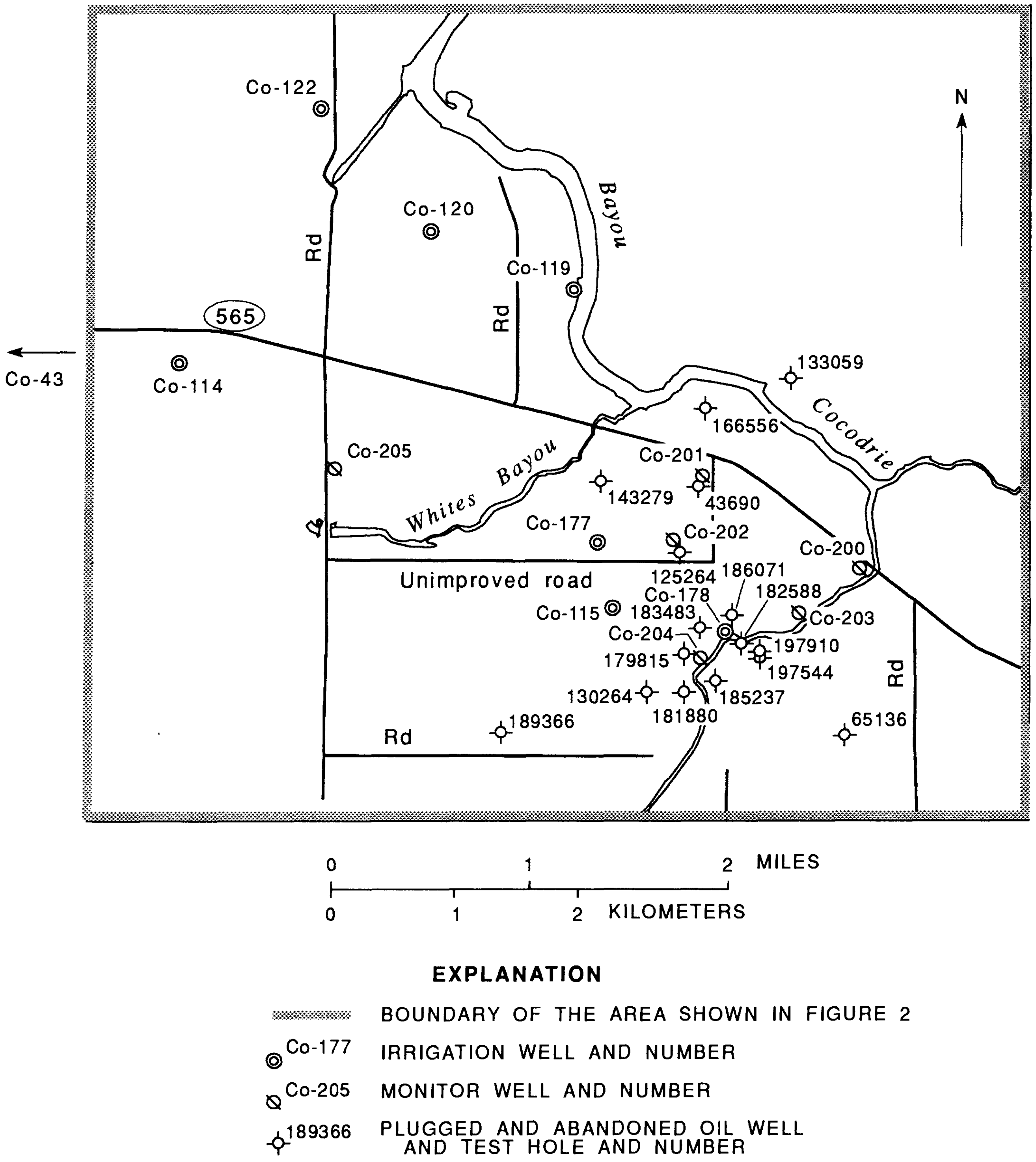


Figure 4. Locations of sampled irrigation and monitor wells and location of plugged and abandoned oil wells and test holes within the indicated area of the east-central Louisiana study area.

Table 1. Selected physical properties and chemical analyses of ground water from irrigation and monitor wells within the east-central Louisiana study area

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; deg. C, degrees Celsius; mg/L, milligrams per liter; FET, fixed end-point titration; --, no data available; <, less than; µg/L, micrograms per liter]

Well no.	Site no.	Date	Depth of well, total (feet)	Specific conductance (µS/cm)	pH	Temperature (deg. C)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)
Co- 43	312649091412101	9-26-67	689	2,720	7.4	23.5	16	3.7
Co-114	312643091404801	8-17-88	143	770	7.07	21.0	82	30
Co-115	312538091383001	9- 1-88	128	2,120	7.06	20.0	160	48
Co-119	312703091384301	9- 2-88	123	2,400	7.20	20.0	110	34
Co-120	312719091392801	8-18-88	123	1,180	7.07	20.0	120	44
Co-122	312751091400401	8-19-88	123	1,020	7.07	22.0	120	34
Co-177	312554091383401	8-18-88	125	1,530	7.28	21.0	140	46
Co-178	312532091375401	8-15-88	125	4,220	6.92	22.0	180	57
Co-200	312549091371201	7-25-89	192	11,000	7.25	21.0	180	46
Co-201	312613091380201	7-25-89	205	10,000	7.20	21.0	280	71
Co-202	312556091381101	7-25-89	232	14,000	7.11	21.0	310	75
Co-203	312537091373101	7-27-89	230	13,000	7.01	21.0	280	70
Co-204	312525091380201	7-27-89	220	10,000	7.00	22.0	240	62
Co-205	312614091400001	7-27-89	130	860	7.26	21.0	91	28

Table 1. Selected physical properties and chemical analyses of ground water from irrigation and monitor wells within the east-central Louisiana study area--Continued

Well no.	Site no.	Date	Sodium, dissolved (mg/L as Na)	Sodium (percent)	Sodium adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, total FET field (mg/L as $CaCO_3$)	Alkalinity, laboratory (mg/L as $CaCO_3$)	Alkalinity, carbonate, incremental titration (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)
Co- 43	312649091412101	9-26-67	570	95	33	4.7	--	--	--	<1.0
Co-114	312643091404801	8-17-88	36	19	.9	1.4	--	--	312	18
Co-115	312538091383001	9- 1-88	200	42	4	7.3	--	--	404	1.5
Co-119	312703091384301	9- 2-88	340	64	7	5.7	--	--	400	2.2
Co-120	312719091392801	8-18-88	74	25	1	3.7	--	--	440	97
Co-122	312751091400401	8-19-88	57	22	1	7.5	--	--	448	42
Co-177	312554091383401	8-18-88	110	30	2	6.6	--	--	472	1.7
Co-178	312532091375401	8-15-88	590	65	10	10	--	--	292	1.0
Co-200	312549091371201	7-25-89	1,800	86	31	17	302	292	--	<1.0
Co-201	312613091380201	7-25-89	1,600	77	22	16	285	279	--	<1.0
Co-202	312556091381101	7-25-89	2,500	83	33	24	266	262	--	<1.0
Co-203	312537091373101	7-27-89	2,100	82	29	18	280	279	--	<1.0
Co-204	312525091380201	7-27-89	1,700	81	25	17	356	355	--	<1.0
Co-205	312614091400001	7-27-89	44	22	1	4.6	396	399	--	21

Table 1. Selected physical properties and chemical analyses of ground water from irrigation and monitor wells within the east-central Louisiana study area--Continued

Well no.	Site no.	Date	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Silica, dissolved (mg/L as SiO_2)	Dissolved solids, residue at 180 deg. C (mg/L)	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Lithium, dissolved (µg/L as Li)	Strontium, dissolved (µg/L as Sr)
Co- 43	312649091412101	9-26-67	670	0.4	--	42	1,490	--	--	--	--
Co-114	312643091404801	8-17-88	52	.2	0.13	38	443	180	40	23	230
Co-115	312538091383001	9- 1-88	450	.2	.60	39	1,180	800	170	30	500
Co-119	312703091384301	9- 2-88	550	.2	1.3	33	1,310	600	300	20	520
Co-120	312719091392801	8-18-88	84	.2	.21	40	711	630	70	34	300
Co-122	312751091400401	8-19-88	50	.2	.13	43	606	450	120	31	580
Co-177	312554091383401	8-18-88	230	.2	.31	40	773	640	150	30	680
Co-178	312532091375401	8-15-88	1,100	.1	1.7	30	2,390	1,700	330	40	740
Co-200	312549091371201	7-25-89	3,100	.3	3.6	36	5,880	2,700	2,700	230	7,700
Co-201	312613091380201	7-25-89	3,000	.2	3.5	31	5,740	1,800	1,800	140	4,900
Co-202	312556091381101	7-25-89	4,400	.2	5.6	36	8,410	1,800	2,400	270	13,000
Co-203	312537091373101	7-27-89	3,900	.2	4.2	35	7,410	4,500	2,500	230	9,800
Co-204	312525091380201	7-27-89	2,700	.3	3.4	36	5,400	3,800	1,600	240	8,400
Co-205	312614091400001	7-27-89	17	.3	.06	35	439	680	90	23	510

Table 2. Specific conductance and selected chemical analyses of briny water from oil wells (Carrizo-Wilcox aquifer) within the east-central Louisiana study area

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; --, no data available; <, less than; deg. C, degrees Celsius; µg/L, micrograms per liter]

Well no.	Site no.	Date	Depth of well, total (feet)	Specific conductance (µS/cm)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Sodium (percent)	Sodium, adsorption ratio
				Catahoula Parish					
LA-080417	314016091502001	2-16-89	4,372	130,000	1,400	--	37,000	76	100
LA-088238	314031091444401	2-15-89	4,545	140,000	1,400	500	40,000	94	230
LA-095680	314041091445501	2-14-89	4,513	140,000	1,800	450	54,000	95	290
LA-095872	314041091445701	2-15-89	4,561	135,000	1,400	--	40,000	78	110
LA-098906	314051091445701	2-15-89	4,555	140,000	1,400	490	39,000	94	230
LA-204281	312725091455401	4-27-89	5,939	210,000	1,400	410	52,000	95	310
LA-205722	312731091454501	4-27-89	5,965	195,000	1,400	390	53,000	95	320
LA-208729	312726091455601	4-27-89	5,942	170,000	1,400	400	57,000	96	350
				Concordia Parish					
LA-105062	313330091424201	1-26-89	5,159	190,000	1,300	460	42,000	94	250
LA-107536	313344091423301	1-26-89	5,090	150,000	1,600	470	47,000	94	270
LA-119940	314453091271401	4-25-89	4,134	160,000	1,100	460	37,000	94	240
LA-120339	314433091265401	4-25-89	3,947	150,000	1,100	460	35,000	94	220
LA-121879	314504091272301	4-24-89	3,590	130,000	840	550	--	--	--
LA-124885	314505091272701	4-25-89	3,710	125,000	800	560	29,000	93	190
LA-127547	314440091270201	4-25-89	4,452	145,000	1,100	460	38,000	94	240
LA-158070	314452091272301	4-24-89	4,555	160,000	1,300	470	43,000	95	260
LA-165026	312107091465901	2-13-89	6,565	160,000	1,400	510	41,000	94	240
LA-182150	311833091483401	4-28-89	6,704	165,000	1,500	420	50,000	95	290

Table 2. Specific conductance and selected chemical analyses of briny water from oil wells (Carrizo-Wilcox aquifer) within the east-central Louisiana study area--Continued

Well no.	Site no.	Date	Potassium, dissolved (mg/L as K)	Alkalinity, total incremental field (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)
				Catahoula Parish				
LA-080417	314016091502001	2-16-89	120	196	<2.0	67,000	0.4	64
LA-088238	314031091444401	2-15-89	160	192	6.2	72,000	.3	67
LA-095680	314041091445501	2-14-89	260	192	92	93,000	.5	88
LA-095872	314041091445701	2-15-89	150	200	5.6	72,000	.3	67
LA-098906	314051091445701	2-15-89	110	200	8.3	--	.3	66
LA-204281	312725091455401	4-27-89	260	192	<1.0	90,000	.4	87
LA-205722	312731091454501	4-27-89	280	200	<1.0	88,000	.3	81
LA-208729	312726091455601	4-27-89	250	200	<1.0	87,000	.4	86
				Concordia Parish				
LA-105062	313330091424201	1-26-89	220	204	17	76,000	.3	70
LA-107536	313344091423301	1-26-89	190	220	<.20	77,000	.3	65
LA-119940	314453091271401	4-25-89	160	192	<1.0	65,000	.4	66
LA-120339	314433091265401	4-25-89	150	212	<1.0	61,000	.3	67
LA-121879	314504091272301	4-24-89	120	328	<1.0	65,000	.4	56
LA-124885	314505091272701	4-25-89	140	508	<1.0	51,000	.3	57
LA-127547	314440091270201	4-25-89	140	204	<1.0	63,000	.4	61
LA-158070	314452091272301	4-24-89	180	200	<1.0	71,000	.3	70
LA-165026	312107091465901	2-13-89	160	--	3.5	71,000	.3	66
LA-182150	311833091483401	4-28-89	270	--	43	86,000	.4	--

Table 2. Specific conductance and selected chemical analyses of briny water from oil wells (Carrizo-Wilcox aquifer) within the east-central Louisiana study area--Continued

Well no.	Site no.	Date	Silica, dissolved (mg/L as SiO_2)	Dissolved solids, residue at 180 deg. C (mg/L)	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Lithium, dissolved (µg/L as Li)	Strontium, dissolved (mg/L as Sr)
				Catahoula Parish				
LA-080417	314016091502001	2-16-89	18	111,000	110,000	15,000	510	250,000
LA-088238	314031091444401	2-15-89	19	117,000	140,000	16,000	530	200,000
LA-095680	314041091445501	2-14-89	27	150,000	--	17,000	460	170,000
LA-095872	314041091445701	2-15-89	17	116,000	110,000	15,000	520	170,000
LA-098906	314051091445701	2-15-89	18	116,000	140,000	15,000	530	200,000
LA-204281	312725091455401	4-27-89	20	148,000	270,000	12,000	2,400	150,000
LA-205722	312731091454501	4-27-89	20	147,000	310,000	14,000	2,300	150,000
LA-208729	312726091455601	4-27-89	20	138,000	290,000	14,000	2,300	150,000
				Concordia Parish				
LA-105062	313330091424201	1-26-89	19	126,000	210,000	15,000	640	200,000
LA-107536	313344091423301	1-26-89	19	129,000	200,000	14,000	660	190,000
LA-119940	314453091271401	4-25-89	20	107,000	150,000	13,000	1,300	190,000
LA-120339	314433091265401	4-25-89	20	105,000	160,000	15,000	1,200	200,000
LA-121879	314504091272301	4-24-89	20	90,500	84,000	18,000	1,500	180,000
LA-124885	314505091272701	4-25-89	19	82,600	100,000	16,000	1,700	170,000
LA-127547	314440091270201	4-25-89	21	105,000	140,000	13,000	1,300	190,000
LA-158070	314452091272301	4-24-89	22	120,000	240,000	13,000	1,700	200,000
LA-165026	312107091465901	2-13-89	19	115,000	140,000	15,000	500	210,000
LA-182150	311833091483401	4-28-89	22	147,000	--	16,000	1,700	150,000

Table 3.--Values of ^{87}strontium/^{86}strontium and 1/dissolved strontium for ground water from selected monitor wells and briny water from oil wells in the east-central Louisiana study area

Well no.	Altitude of screen level (feet below sea level)	$^{87}Sr/^{86}Sr$	1/dissolved Sr (liters per milligram)
		Monitor Wells	
Co-200	146	0.70818	0.13
Co-201	160	.70831	.20
Co-202	187	.70814	.077
Co-203	185	.70820	.10
Co-204	175	.70820	.12
		Oil Wells	
LA-080417	4,312	.70772	.0040
LA-088238	4,486	.70767	.0050
LA-095680	4,458	.70772	.0059
LA-095872	4,506	.70788	.0059
LA-098906	4,500	.70769	.0050
LA-105062	5,103	.70763	.0050
LA-107536	5,036	.70770	.0053
LA-119940	3,886	.70728	.0053
LA-120339	3,880	.70725	.0050
LA-121879	3,531	.70728	.0056
LA-124885	3,652	.70732	.0059
LA-127547	4,392	.70726	.0053
LA-158070	4,496	.70749	.0050
LA-165026	6,517	.70805	.0048
LA-182150	6,660	.70797	.0067
LA-204281	5,893	.70807	.0067
LA-205722	5,918	.70797	.0067
LA-208729	5,895	.70800	.0067

Saltwater in Shallow Aquifers in East-central Louisiana

Areal and Vertical Distribution of Saltwater

Concentrations of dissolved solids (fig. 5) and chloride ions (fig. 6) in water samples from the alluvial aquifer and the upper part of the Jasper aquifer system were highest near the location of plugged and abandoned oil wells and test holes within the east-central Louisiana study area. North and northeast of the plugged and abandoned oil wells and test holes at wells Co-119 and Co-200, ground-water samples had elevated concentrations of dissolved solids and chloride ions. Possible sources of saltwater contamination in the shallow aquifers in the study area could be additional unknown abandoned oil well(s) and density-driven flow of saltwater controlled by paleotopography.

Salinity of ground water beneath the east-central Louisiana study area generally increases with depth. Winslow and others (1968) reported the location of ground water with a dissolved-solids concentration of 1,000 mg/L at an altitude about 500 ft below sea level (Catahoula aquifer), 3,000 mg/L at about 650 ft below sea level (Catahoula aquifer), and 10,000 mg/L at about 1,000 ft below sea level (Cockfield Aquifer). The general pattern of increasing ground-water salinity with depth reported by Winslow and others (1968) was supported by chemical analysis of a ground-water sample from well Co-43. This well was screened at an altitude about 640 ft below sea level (Catahoula aquifer) and yielded ground water with a dissolved-solids concentration of about 1,490 mg/L in 1967.

Ground-water salinity also apparently increases with depth within the alluvial aquifer and uppermost part of the Jasper aquifer system based on greater concentrations of dissolved solids and chloride ions in monitor wells screened within the uppermost part of the Jasper aquifer system than is present in water from irrigation wells screened in the alluvial aquifer. The greater concentrations of dissolved solids in monitor wells screened in the uppermost part of the Jasper aquifer system could result from the proximity to the known locations of plugged and abandoned oil wells rather than a general increase of salinity with depth.

Composition of Saltwater

Bromide-ion concentrations plotted as a function of chloride-ion concentrations in water from the alluvial aquifer, collected from irrigation and monitor wells within the east-central Louisiana study area (excluding well Co-43), and briny water from the Carrizo-Wilcox aquifer indicates a strong linear relation (r = 0.99, correlation coefficient, based on linear least-squares regression). The best agreement between all collected data and the best-fit line occurs when the chloride-ion concentration equals or exceeds 500 mg/L (fig. 7). The linear relation shown in figure 7 indicates that the source of saltwater having concentrations of chloride ions equal to or greater than 500 mg/L in the alluvial aquifer and the uppermost part of the Jasper aquifer system could be derived from the mixing of freshwater from the alluvial aquifer or from the uppermost part of the Jasper aquifer system with briny water from the Carrizo-Wilcox aquifer.

The values of $^{87}Sr/^{86}Sr$ in saltwater from the uppermost part of the Jasper aquifer system collected from monitor wells Co-200, -201, -202, -203, and -204 and briny water from the Carrizo-Wilcox aquifer are plotted against 1/Sr in liters per milligram in figure 8. The values of $^{87}Sr/^{86}Sr$ plotted against 1/Sr for samples of water from the uppermost part of the Jasper aquifer system follow a linear relation. The best-fit line through points representing analyses of these water samples was calculated using the least-squares linear regression technique (r = 0.94).

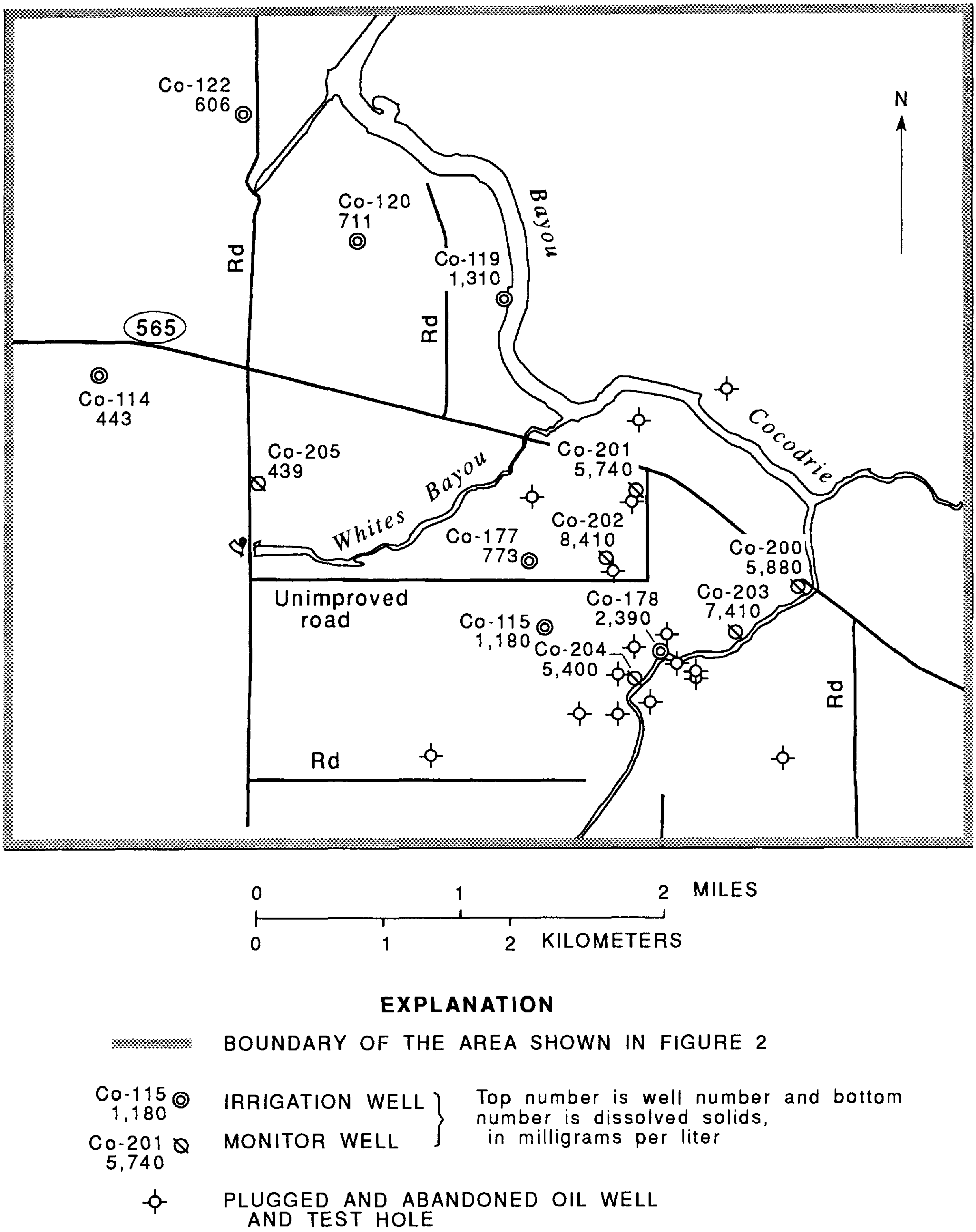


Figure 5. Concentrations of dissolved solids in water from irrigation and monitor wells within the indicated area of the east-central Louisiana study area.

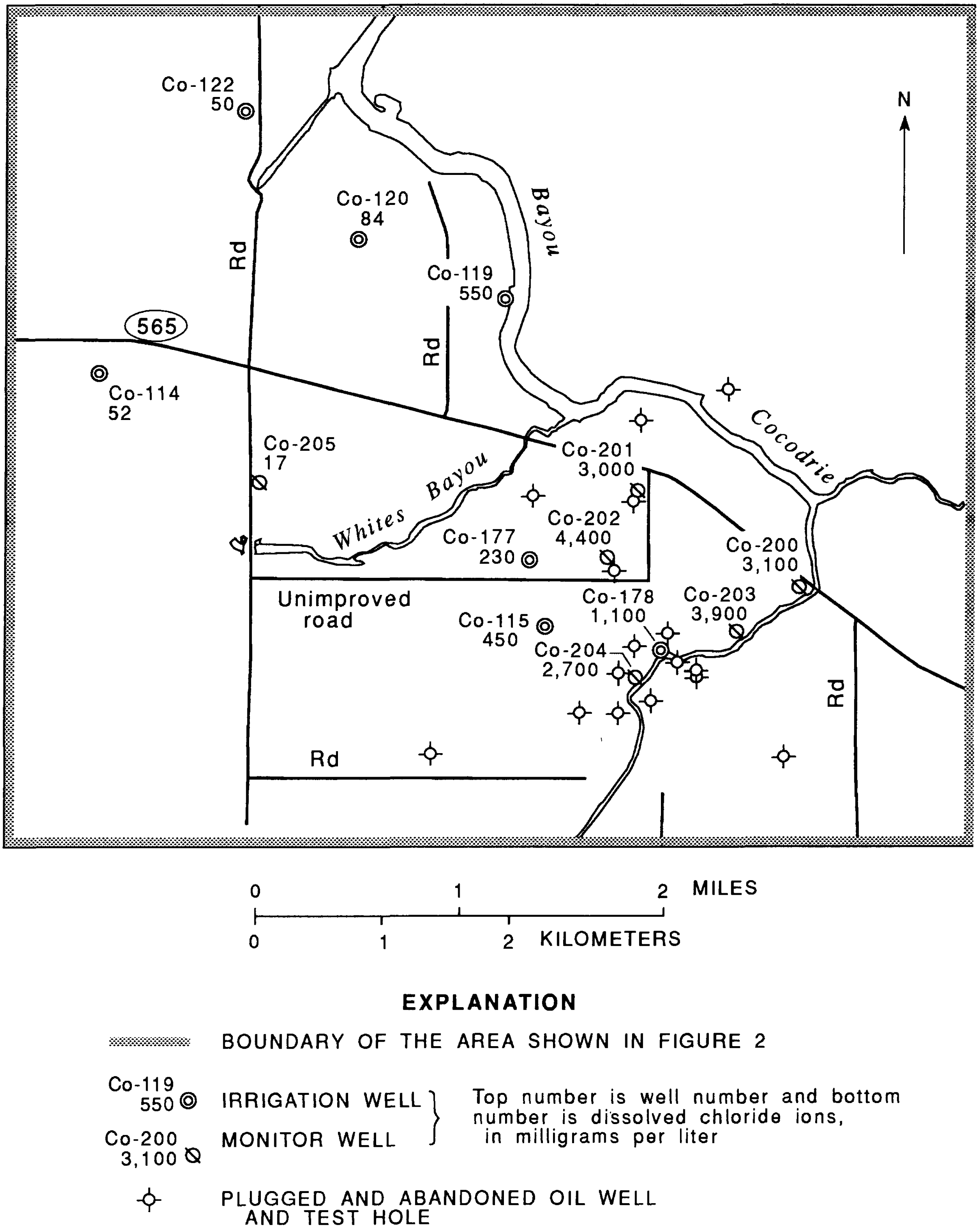


Figure 6. Concentrations of dissolved chloride ions in water from irrigation and monitor wells within the indicated area of the east-central Louisiana study area.

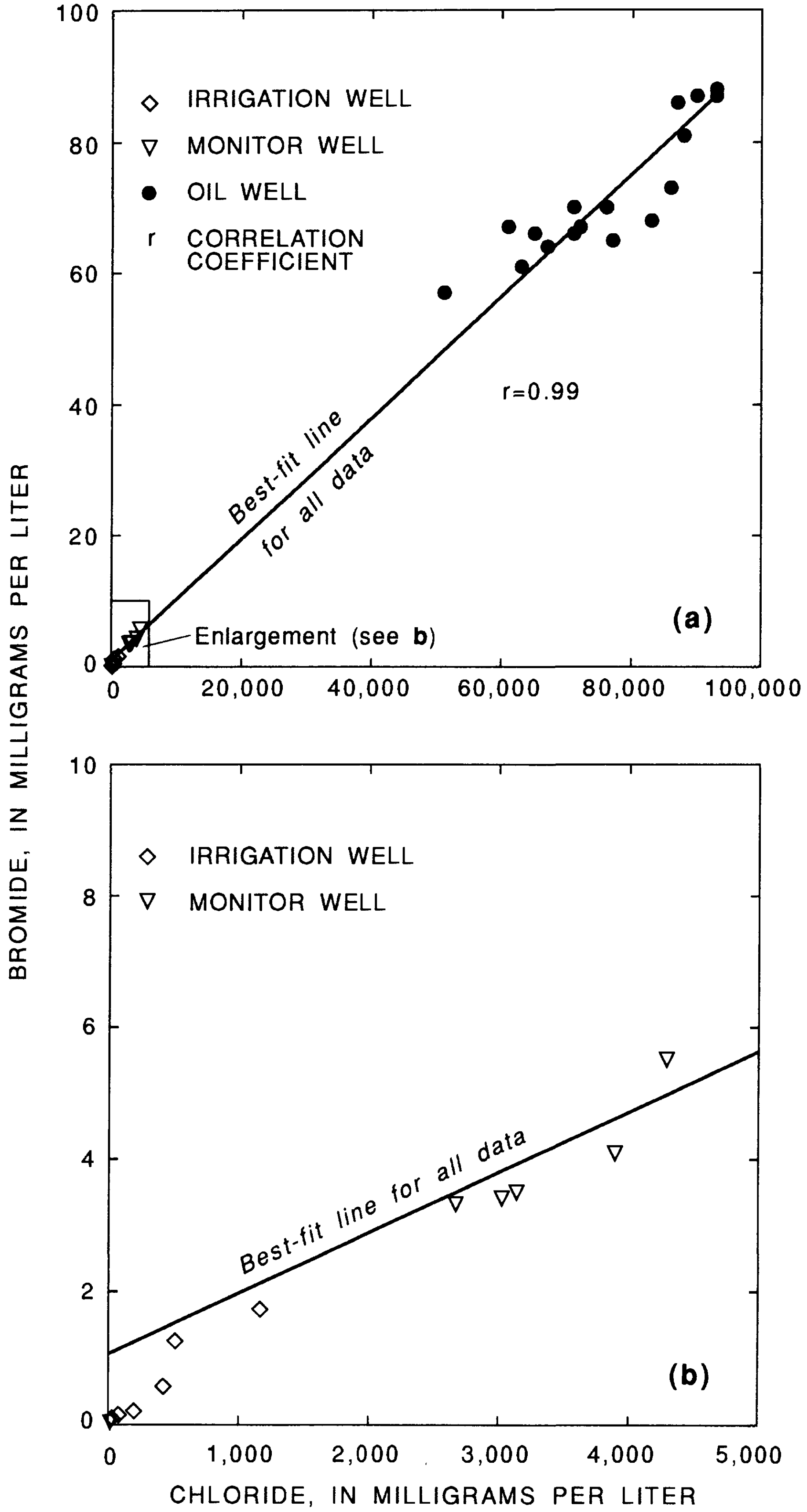


Figure 7. Concentrations of dissolved bromide ions as a function of the concentrations of dissolved chloride ions in water from irrigation and monitor wells completed in the Mississippi River alluvial aquifer and Jasper aquifer system and briny water from oil wells (Carrizo-Wilcox aquifer) within east-central Louisiana study area.

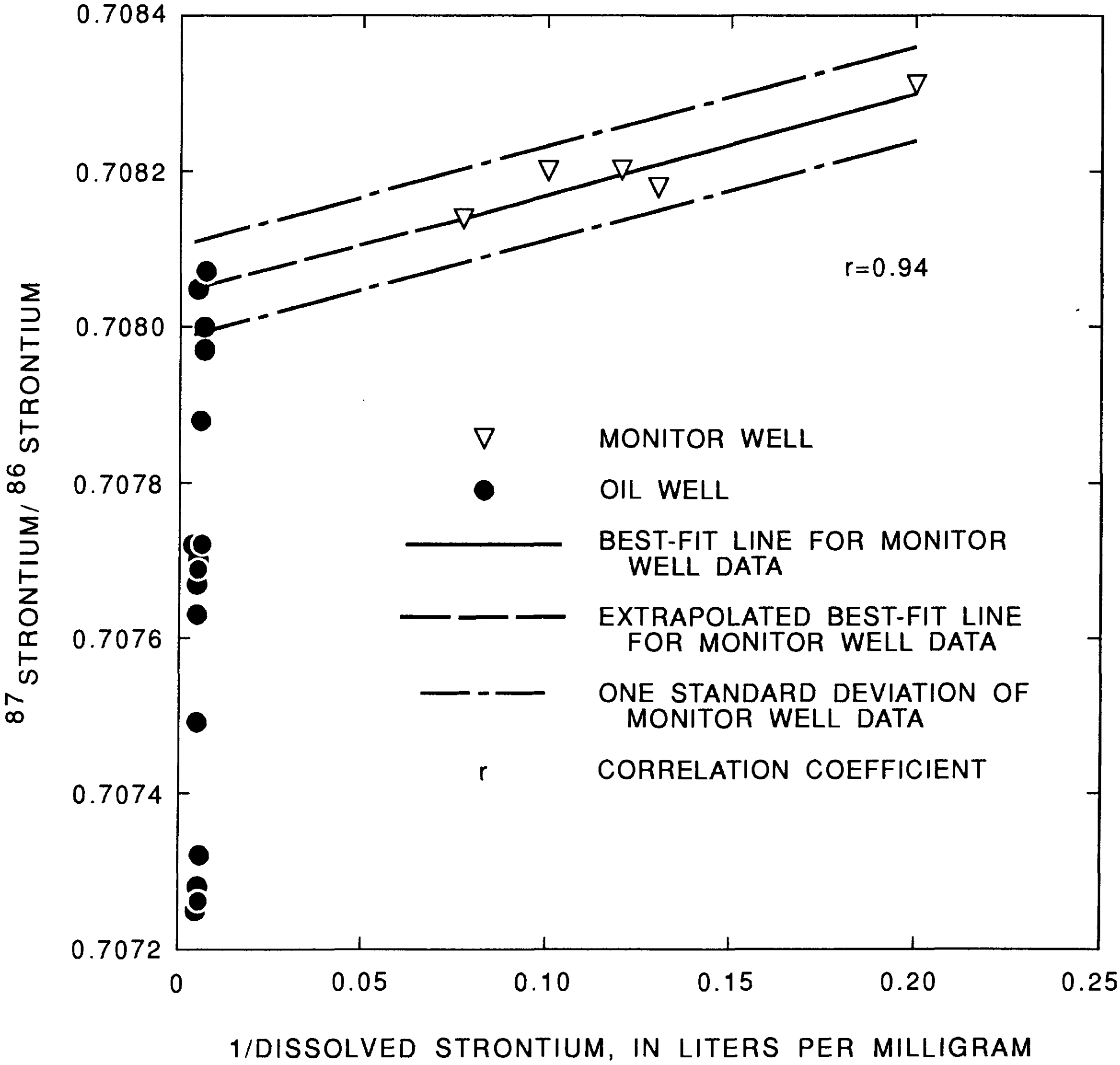


Figure 8. ^{87}Strontium/^{86}strontium as a function of 1/dissolved strontium in water from selected monitor wells and briny water from oil wells within east-central Louisiana study area.

The concentrations of strontium in briny water sampled from the Carrizo-Wilcox aquifer in areas including and surrounding the east-central Louisiana study area ranged from 150 to 250 mg/L. The corresponding values of 1/Sr are about 0.0067 and 0.0040 L/mg. Values of 1/Sr in briny water from the Carrizo-Wilcox aquifer typically are approximately 0.005 L/mg in the study area. Extrapolation of the best-fit line through data from monitor wells in figure 8 to a value of 0.005 L/mg for 1/Sr yields a $^{87}Sr/^{86}Sr$ value of about 0.70805. The standard deviation of $^{87}Sr/^{86}Sr$ values along the best-fit line through data from monitor wells in figure 8 was calculated to be 0.00006. The lines parallel to the best-fit line in figure 8 graphically represent this value of the standard deviation. All data points representing water samples from monitor wells are within one standard deviation of the best-fit line (fig.8).

Extrapolation of the best-fit line and the lines representing one standard deviation to a 1/Sr value of 0.005 L/mg yields a value of 0.70805 ± 0.00006. This value represents the range of $^{87}Sr/^{86}Sr$ values in briny water that could be mixing with freshwater from the uppermost part of the Jasper aquifer system resulting in water with an elevated concentration of dissolved solids.

Hydrogeochemistry and Origin of Saltwater

Water from monitor well Co-202, which is completed in the uppermost part of the Jasper aquifer system, had a dissolved-solids concentration of about 8,410 mg/L, the highest concentration of dissolved solids from any sampled monitor well in the study area (table 1). Ground water with a dissolved-solids concentration of approximately 8,000 mg/L previously was detected at an altitude between 650 and 800 ft below sea level (Winslow and others, 1968), which corresponds to an altitude near the base of the Jasper aquifer system.

The relation between concentrations of bromide and chloride ions in ground water from irrigation and monitor wells within the east-central Louisiana study area is consistent with mixing of freshwater from the alluvial aquifer or the uppermost part of the Jasper aquifer system with briny water from the Carrizo-Wilcox aquifer (fig. 7). The $^{87}Sr/^{86}Sr$ value of briny water from the Carrizo-Wilcox aquifer systematically increases with depth (fig. 9). The range of $^{87}Sr/^{86}Sr$ values in the high-strontium end member, as defined by one standard deviation (fig. 8), coincides with the $^{87}Sr/^{86}Sr$ ratios in briny water from the Carrizo-Wilcox aquifer at altitudes from 5,800 to 6,800 ft below sea level (fig. 9).

Available geochemical data indicate that briny water from 5,800 to 6,800 ft below sea level within the Carrizo-Wilcox aquifer could be the source of saltwater in the alluvial aquifer and uppermost part of the Jasper aquifer system. However, in the absence of data on the concentrations of bromide and chloride ions and the values of $^{87}Sr/^{86}Sr$ in water from the Catahoula, Cockfield, and Sparta aquifers, no conclusive statement can be made on the origin of saltwater in the alluvial aquifer and the uppermost part of the Jasper aquifer system.

Of the 16 plugged and abandoned oil wells and test holes (fig. 4), 11 were completed at altitudes between 5,800 and 6,800 ft below sea level. These wells and test holes could provide an avenue for upward movement of saltwater from the Carrizo-Wilcox aquifer into the alluvial aquifer and the uppermost part of the Jasper aquifer system.

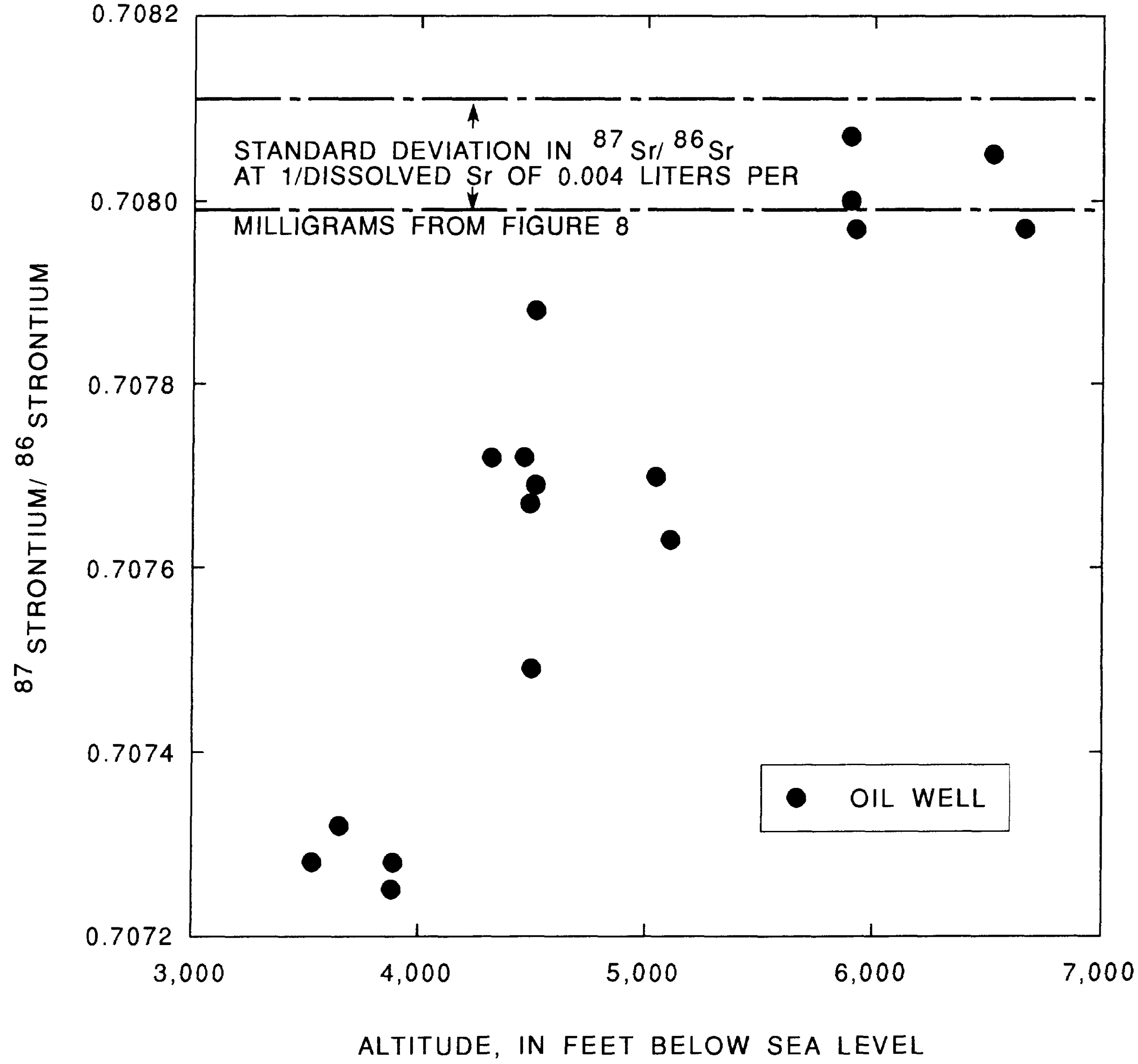


Figure 9. ^{87}Strontium/^{86}strontium as a function of altitude below sea level in briny water from oil wells (Carrizo-Wilcox aquifer) within the east-central Louisiana study area.

NORTHEASTERN LOUISIANA AND SOUTHEASTERN ARKANSAS STUDY AREA

This section presents a brief description of the northeastern Louisiana and southeastern Arkansas study area and describes the hydrogeology and water quality of aquifers in the area. The areal and vertical distribution, composition, geochemistry, and origin of saltwater are discussed.

Description of the Study Area

The study area includes northeastern and south-central Morehouse Parish, Louisiana, and adjoining areas of southern Chicot County, Arkansas (fig. 10). The land surface has very little local topographic relief and a mean altitude of about 90 ft above sea level.

Hydrogeology and Water Quality of the Mississippi River Alluvial Aquifer

The geologic column including the Louann Salt and younger formations, and the hydrogeologic column including the Carrizo-Wilcox and younger aquifers and confining units are shown in figure 11. The alluvium of Pleistocene age, which makes up the alluvial aquifer, unconformably overlies the Cockfield Formation of Tertiary age throughout the study area. Thickness of the alluvium ranges from 90 ft over paleotopographic highs on the Cockfield Formation to more than 150 ft over fluvial channels eroded into the Cockfield Formation (Saucier, 1967; Sanford, 1973). The alluvium that fills the fluvial channels contains a greater fraction of coarse sand and gravel than alluvium that covers paleotopographic highs (Sanford, 1973). No known salt domes or diapirs are located in or near the northeastern Louisiana and southeastern Arkansas study area (Beckman and Williamson, 1990).

Lateral ground-water flow in the alluvial aquifer generally is to the south. Locally, the presence of rivers and streams or large withdrawals of ground water can affect the direction of ground-water flow (Sanford, 1973).

Recharge through the top of the alluvial aquifer, excluding contributions from rivers and streams, was estimated to be between 0.51 and 1.5 in/yr over the study area. This recharge could result from direct infiltration of rainfall in areas where sandy sediments extend to the surface, or leakage from a perched water table in areas where clays and silts overlie the alluvial aquifer. A net recharge of as much as 0.5 in/yr flows upward from below through the base of the alluvial aquifer in the study area. (See Ackerman, 1989.)

Water in the alluvial aquifer generally is a calcium-magnesium bicarbonate type. Areas of the alluvial aquifer within the northeastern Louisiana study area contain water of higher chloride concentrations than elsewhere in the parish (Sanford, 1973).

Compilation of Data

Water samples from the alluvial aquifer were collected between 1988 and 1989 from irrigation and domestic wells (fig. 12). Two test holes were drilled in northeastern Morehouse Parish and examined using electric logs. The analyses of physical properties and chemical constituents of selected water samples collected from wells in the northeastern Louisiana and southeastern Arkansas study area are given in table 4.

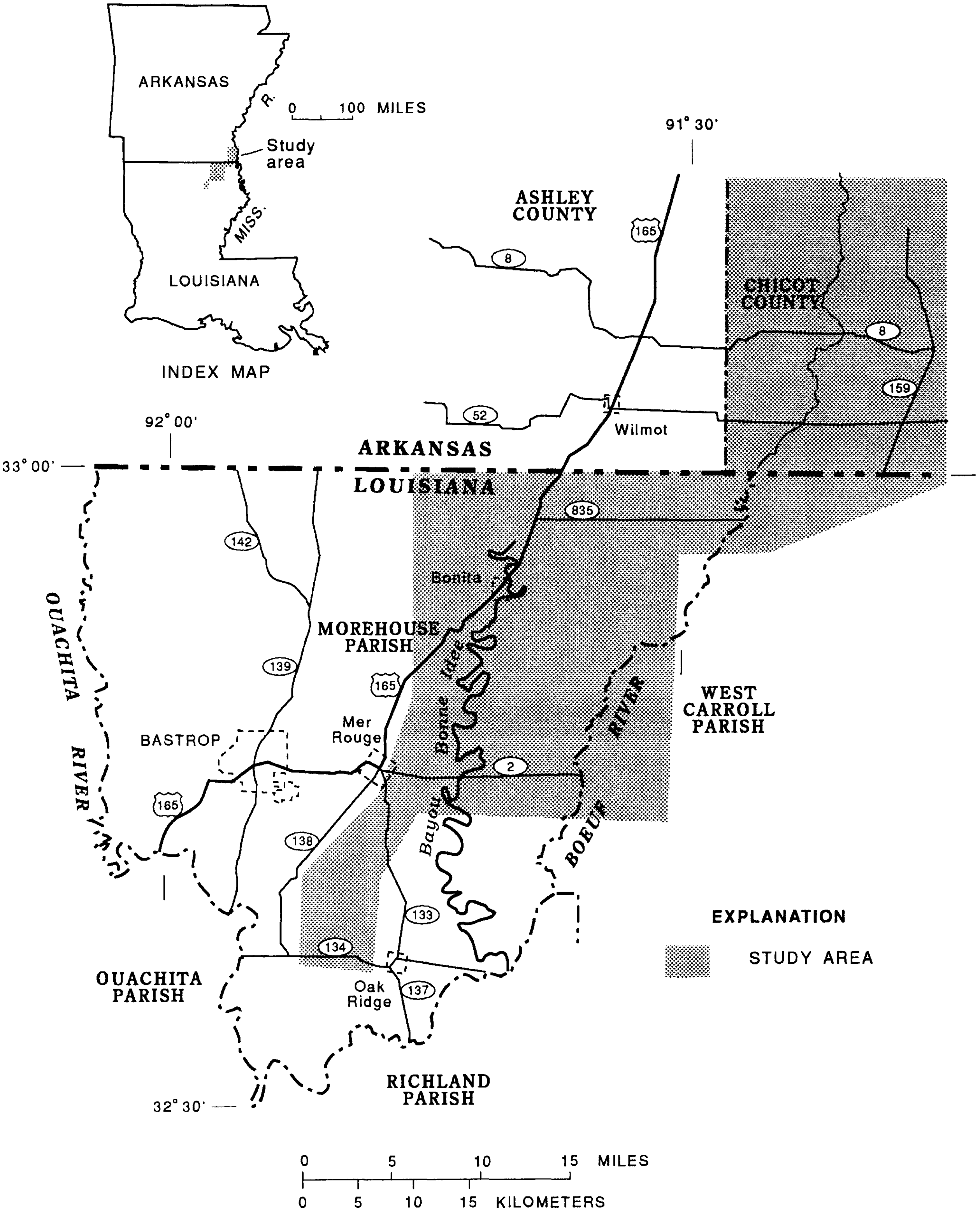
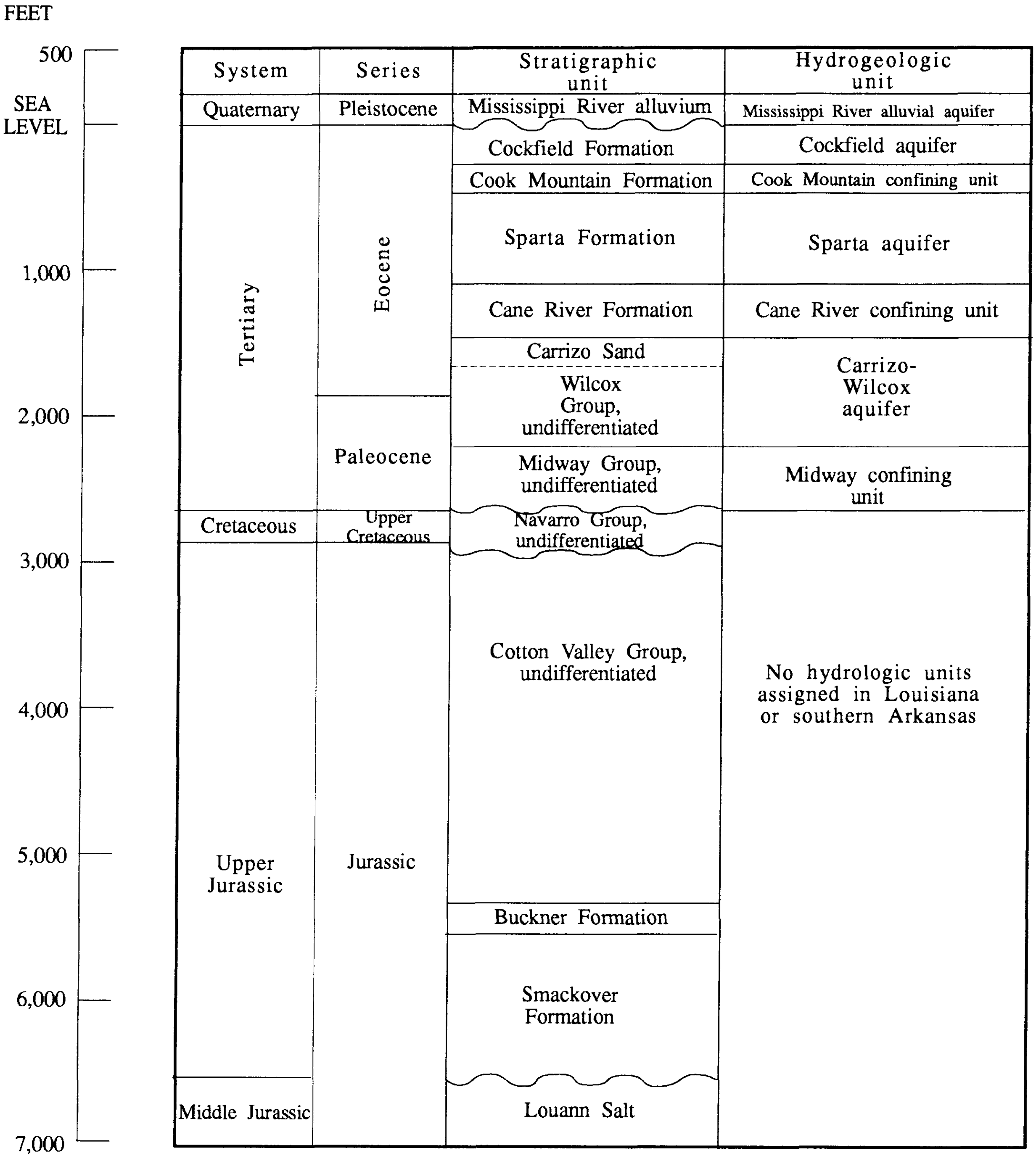


Figure 10. Location of the northeastern Louisiana and southeastern Arkansas study area.



System	Series	Stratigraphic unit	Hydrogeologic unit
Quaternary	Pleistocene	Mississippi River alluvium	Mississippi River alluvial aquifer
Tertiary	Eocene	Cockfield Formation	Cockfield aquifer
		Cook Mountain Formation	Cook Mountain confining unit
		Sparta Formation	Sparta aquifer
		Cane River Formation	Cane River confining unit
		Carrizo Sand	Carrizo-Wilcox aquifer
		Wilcox Group, undifferentiated	
	Paleocene	Midway Group, undifferentiated	Midway confining unit
Cretaceous	Upper Cretaceous	Navarro Group, undifferentiated	No hydrologic units assigned in Louisiana or southern Arkansas
Upper Jurassic	Jurassic	Cotton Valley Group, undifferentiated	
		Buckner Formation	
		Smackover Formation	
Middle Jurassic		Louann Salt	

Figure 11. Stratigraphic and hydrogeologic units within the northeastern Louisiana and southeastern Arkansas study area (modified from Eversull, 1984 and Smoot, 1989).

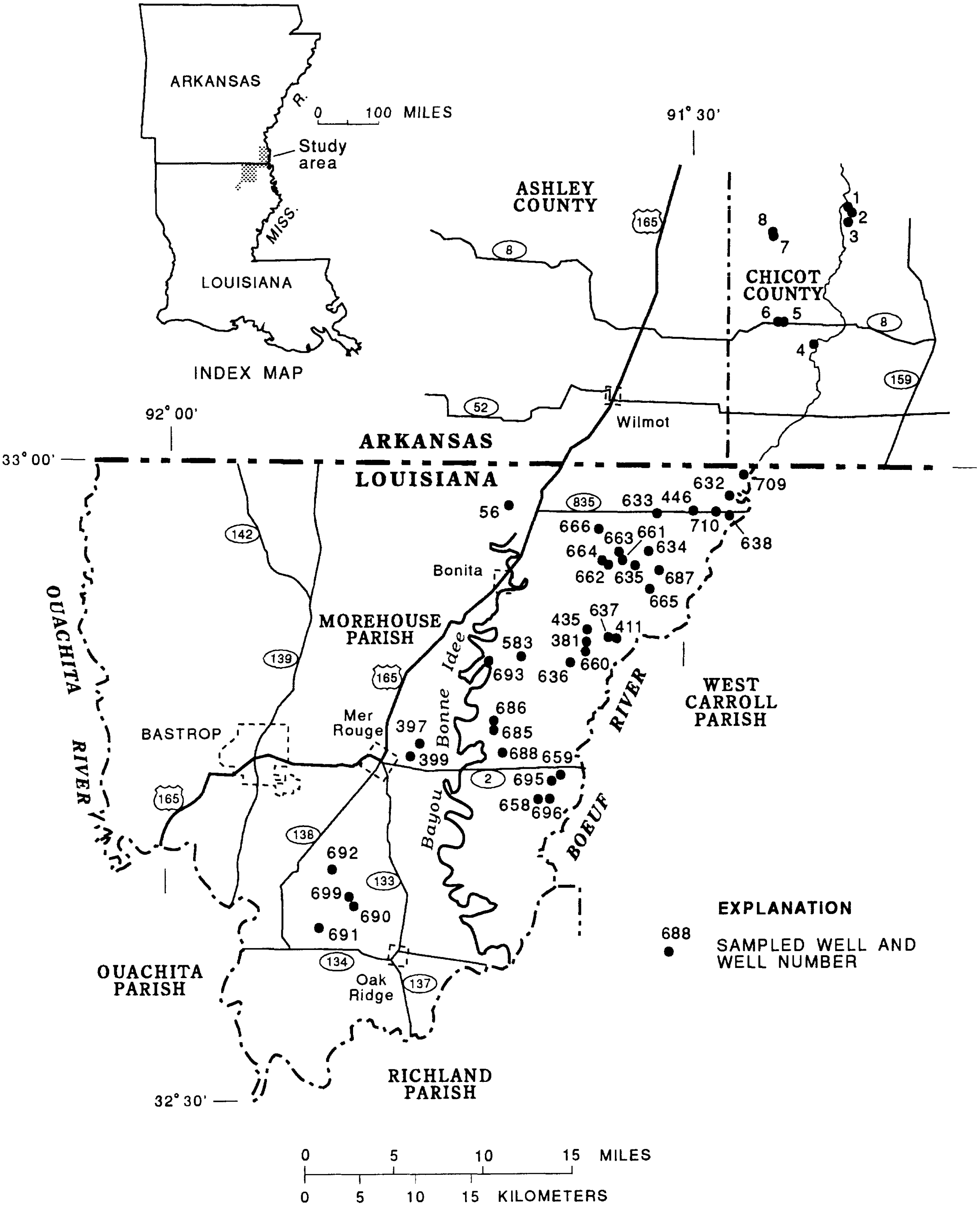


Figure 12. Location of sampled wells within the northeastern Louisiana and southeastern Arkansas study area.

Table 4. Selected physical properties and chemical analyses of selected ground-water samples from the northeastern Louisiana and southeastern Arkansas study area

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; deg. C, degrees Celsius; --, no data available; FET, fixed end-point titration; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than]

Well no.	Site no.	Date	Depth of well, total (feet)	Specific conductance (µS/cm)	pH	Temperature (deg. C)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)
				Morehouse Parish, Louisiana				
Mo-381	325217091354201	8-22-89	100.00	1,370	7.12	20.0	120	38
Mo-397	324728091452001	8-11-89	120.00	990	7.06	20.5	100	34
Mo-399	324649091455201	8-11-89	105.00	790	7.06	20.5	85	26
Mo-411	325229091335901	12- 1-88	130.00	3,300	7.14	18.0	290	86
Mo-435	325256091353901	12- 2-88	110.00	750	7.19	17.0	77	23
Mo-446	325836091293601	11-29-88	100.00	1,460	7.13	17.0	140	34
Mo-515	325849091401601	11-10-88	72.00	--	7.18	--	90	24
Mo-588	325138091392901	11-30-88	101.00	680	7.01	17.0	87	22
Mo-632	325920091273101	11- 9-88	--	3,360	6.79	20.0	260	94
Mo-633	325828091313901	11-11-88	--	1,230	7.42	17.0	62	17
Mo-634	325641091320901	11-29-88	--	1,550	7.36	18.0	92	26
Mo-635	325600091325601	11-30-88	--	2,010	7.29	18.0	130	38
Mo-636	325120091363601	12- 1-88	--	3,000	7.15	17.0	270	91
Mo-637	325233091342501	12- 1-88	--	2,180	7.17	19.0	190	63
Mo-638	325823091273001	12- 2-88	--	3,250	7.13	18.0	260	96
Mo-658	324449091382301	8-10-89	--	930	7.12	20.5	98	38
Mo-659	324601091370601	8-10-89	--	1,140	7.23	21.0	110	39
Mo-660	325151091354601	8-18-89	--	2,000	6.97	19.5	160	57
Mo-661	325616091334001	8-17-89	--	1,190	7.14	20.0	110	27
Mo-662	325559091343001	8-18-89	--	710	7.12	20.5	93	25
Mo-663	325639091335301	8-17-89	--	765	7.10	20.5	110	22
Mo-664	325613091344801	8-23-89	--	690	7.15	20.0	97	24
Mo-665	325455091320401	8-16-89	--	3,010	7.20	20.0	160	56
Mo-666	325741091350201	11-10-88	--	655	7.31	18.0	81	14
Mo-685	324807091410001	7- 5-89	--	560	5.98	22.0	--	--
Mo-686	324834091410101	7- 6-89	--	500	6.04	22.0	61	13

Table 4. Selected physical properties and chemical analyses of selected ground-water samples from the northeastern Louisiana and southeastern Arkansas study area -- Continued

Well no.	Site no.	Date	Depth of well, total (feet)	Specific conductance (µS/cm)	pH	Temperature (deg. C)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)
			Morehouse Parish, Louisiana--Continued					
Mo-687	325548091313401	7-18-89	--	2,850	7.37	20.0	190	59
Mo-688	324701091402901	7-18-89	--	520	7.10	20.5	73	17
Mo-689	324009091491701	8-23-89	--	600	7.11	20.0	73	18
Mo-690	323941091490101	8-22-89	255	550	7.24	20.5	73	18
Mo-691	323841091510401	8-22-89	313	600	6.93	21.0	69	17
Mo-692	324127091501801	8-22-89	334	610	6.97	20.5	78	14
Mo-693	325122091411901	8-10-89	335	635	6.88	19.5	72	18
Mo-695	324541091373801	8-10-89	576	1,060	9.22	19.5	110	38
Mo-696	324449091374301	8-10-89	712	1,360	7.23	20.5	130	54
			Chicot County, Arkansas					
Ch-1	331304091204501	10-25-89	--	1,580	6.79	18.5	110	40
Ch-2	331247091202901	10-25-89	--	1,610	6.97	19.0	110	40
Ch-3	331223091204501	10-25-89	--	1,890	7.00	19.0	100	40
Ch-4	330632091223801	10-25-89	--	1,510	7.15	19.0	160	40
Ch-5	330736091242501	10-24-89	--	4,620	6.71	19.0	370	140
Ch-6	330736091244601	10-24-89	--	5,150	6.80	19.5	380	140
Ch-7	331142091250201	10-24-89	--	3,540	6.96	19.0	240	74
Ch-8	331152091250301	10-24-89	--	1,900	6.97	19.0	170	34

Table 4. Selected physical properties and chemical analyses of selected ground-water samples from the northeastern Louisiana and southeastern Arkansas study area -- Continued

Well no.	Site no.	Date	Sodium, dissolved (mg/L as Na)	Sodium (percent)	Sodium, adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, total FET field (mg/L as $CaCO_3$)	Alkalinity, laboratory (mg/L as $CaCO_3$)	Alkalinity carbonate, incremental titration (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)
Morehouse Parish, Louisiana										
Mo-381	325217091354201	8-22-89	110	34	2	4.0	--	390	--	110
Mo-397	324728091452001	8-11-89	53	23	1	2.1	--	375	--	37
Mo-399	324649091455201	8-11-89	41	22	1	2.3	--	346	--	17
Mo-411	325229091335901	12- 1-88	270	35	4	5.9	--	--	464	200
Mo-435	325256091353901	12- 2-88	54	29	1	3.3	--	--	340	17
Mo-446	325836091293601	11-29-88	120	35	2	3.1	--	--	428	90
Mo-515	325849091401601	11-10-88	23	13	0.6	1.7	--	--	342	14
Mo-588	325138091392901	11-30-88	30	17	.7	2.3	320	--	--	42
Mo-632	325920091273101	11- 9-88	310	39	4	4.2	--	--	448	450
Mo-633	325828091313901	11-11-88	180	63	5	2.6	--	--	370	8.3
Mo-634	325641091320901	11-29-88	200	56	5	2.5	--	--	400	19
Mo-635	325600091325601	11-30-88	240	52	5	3.8	--	--	420	20
Mo-636	325120091363601	12- 1-88	270	36	4	4.6	--	--	500	390
Mo-637	325233091342501	12- 1-88	170	33	3	4.6	--	--	416	160
Mo-638	325823091273001	12- 2-88	300	38	4	4.0	--	--	432	360
Mo-658	324449091382301	8-10-89	43	19	.9	1.9	360	355	--	83
Mo-659	324601091370601	8-10-89	64	24	1	2.2	344	339	--	120
Mo-660	325151091354601	8-18-89	150	34	3	4.3	--	396	--	230
Mo-661	325616091334001	8-17-89	96	35	2	3.8	--	358	--	5.0
Mo-662	325559091343001	8-18-89	23	13	.5	2.3	--	342	--	20
Mo-663	325639091335301	8-17-89	26	13	.6	1.5	--	357	--	13
Mo-664	325613091344801	8-23-89	21	12	.5	1.8	--	333	--	20
Mo-665	325455091320401	8-16-89	380	57	7	4.1	--	456	--	120
Mo-666	325741091350201	11-10-88	17	12	.5	2.4	265	179	--	12
Mo-667	324807091410001	7- 5-89	--	--	--	--	222	--	--	1.0
Mo-685	324834091410101	7- 6-89	16	14	.5	.90	202	205	--	9.0

Table 4. Selected physical properties and chemical analyses of selected ground-water samples from the northeastern Louisiana and southeastern Arkansas study area -- Continued

Well no.	Site no.	Date	Sodium, dissolved (mg/L as Na)	Sodium (percent)	Sodium, adsorption ratio	Potassium, dissolved (mg/L as K)	Alkalinity, total FET field (mg/L as $CaCO_3$)	Alkalinity, laboratory (mg/L as $CaCO_3$)	Alkalinity carbonate, incremental titration (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)
					Morehouse Parish, Louisiana--Continued					
Mo-686	325548091313401	7-18-89	320	49	5	3.7	508	467	--	240
Mo-687	324701091402901	7-18-89	14	11	.4	1.1	237	239	--	12
Mo-688	324009091491701	8-23-89	33	22	.9	1.7	--	306	--	<1.0
Mo-689	323941091490101	8-22-89	16	12	.4	1.0	--	--	285	<1.0
Mo-690	323841091510401	8-22-89	32	22	.9	1.7	--	--	281	4.0
Mo-691	324127091501801	8-22-89	28	19	.8	1.6	--	--	290	3.0
Mo-693	325122091411901	8-10-89	34	22	.9	2.0	257	--	251	14
Mo-695	324541091373801	8-10-89	57	22	1	2.1	354	--	351	98
M0-696	324449091374301	8-10-89	57	26	2	2.8	--	--	397	190
					Chicot County, Arkansas					
Ch-1	331304091204501	10-25-89	150	42	3	2.5	--	--	--	130
Ch-2	331247091202901	10-25-89	160	44	3	2.2	--	--	--	160
Ch-3	331223091204501	10-25-89	220	53	5	2.2	--	--	--	160
Ch-4	330632091223801	10-25-89	160	38	3	3.7	--	--	--	84
Ch-5	330736091242501	10-24-89	380	35	4	5.2	--	--	--	290
Ch-6	330736091244601	10-24-89	440	38	5	6.5	--	--	--	320
Ch-7	331142091250201	10-24-89	350	46	5	4.7	--	--	--	200
Ch-8	331152091250301	10-24-89	82	24	2	3.8	--	--	--	190

Table 4. Selected physical properties and chemical analyses of selected ground-water samples from the northeastern Louisiana and southeastern Arkansas study area -- Continued

Well no.	Site no.	Date	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Silica, dissolved (mg/L as SiO_2)	Dissolved solids, residue at 180 deg. C (mg/L)	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Lithium, dissolved (µg/L as Li)	Strontium, dissolved (µg/L as Sr)
					Morehouse Parish, Louisiana						
Mo-381	325217091354201	8-22-89	140	0.30	0.35	32	734	360	150	21	950
Mo-397	324728091452001	8-11-89	65	.40	.23	27	454	420	70	14	780
Mo-399	324649091455201	8-11-89	28	.40	.09	27	414	400	60	12	490
Mo-411	325229091335901	12- 1-88	740	.20	1.6	28	1,910	400	90	20	2,400
Mo-435	325256091353901	12- 2-88	36	.30	.14	35	442	560	90	17	670
Mo-446	325836091293601	11-29-88	180	.30	.74	35	865	500	40	23	680
Mo-515	325849091401601	11-10-88	15	.40	.12	34	402	370	50	13	480
Mo-588	325138091392901	11-30-88	31	.20	.27	36	415	460	60	18	570
Mo-632	325920091273101	11- 9-88	620	.20	2.2	28	2,010	200	110	20	1,600
Mo-633	325828091313901	11-11-88	190	.30	.58	21	709	290	280	17	480
Mo-634	325641091320901	11-29-88	270	.20	.78	30	872	430	240	22	660
Mo-635	325600091325601	11-30-88	410	.30	1.1	32	1,100	660	200	24	890
Mo-636	325120091363601	12- 1-88	540	.20	1.3	28	1,840	100	110	20	1,600
Mo-637	325233091342501	12- 1-88	380	.20	.92	28	1,240	500	120	20	1,500
Mo-638	325823091273001	12- 2-88	610	.20	2.1	30	1,880	200	90	20	1,300
Mo-658	324449091382301	8-10-89	36	.20	.08	33	495	120	10	12	350
Mo-659	324601091370601	8-10-89	81	.20	.20	31	602	130	30	12	430
Mo-660	325151091354601	8-18-89	240	.20	.67	31	1,120	170	110	22	1,100
Mo-661	325616091334001	8-17-89	160	.30	.47	36	532	600	140	16	760
Mo-662	325559091343001	8-18-89	9.5	.40	.08	37	264	510	50	13	630
Mo-663	325639091335301	8-17-89	18	.30	.08	37	381	540	60	14	670
Mo-664	325613091344801	8-23-89	8.0	.40	.11	36	365	480	50	11	630
Mo-665	325455091320401	8-16-89	580	.30	1.7	29	1,570	1,000	310	20	950
Mo-666	325741091350201	11-10-88	9.4	.30	.05	34	224	300	40	8	430
Mo-667	324807091410001	7- 5-89	27	.20	.15	--	298	--	40	--	--
Mo-685	324834091410101	7- 6-89	18	.20	.12	42	256	130	30	13	200
Mo-686	325548091313401	7-18-89	450	.20	1.3	28	1,520	380	210	30	1,100
Mo-687	324701091402901	7-18-89	16	.20	.05	38	300	120	30	10	180

Table 4. Selected physical properties and chemical analyses of selected ground-water samples from the northeastern Louisiana and southeastern Arkansas study area -- Continued

Well no.	Site no.	Date	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Bromide, dissolved (mg/L as Br)	Silica, dissolved (mg/L as SiO_2)	Dissolved solids, residue at 180 deg. C (mg/L)	Barium, dissolved (µg/L as Ba)	Boron, dissolved (µg/L as B)	Lithium, dissolved (µg/L as Li)	Strontium, dissolved (µg/L as Sr)
					Morehouse Parish, Louisiana--Continued						
Mo-688	324009091491701	8-23-89	9.6	0.20	0.03	30	329	270	360	12	490
Mo-689	323941091490101	8-22-89	3.3	.30	9	32	350	190	32	30	190
Mo-690	323841091510401	8-22-89	12	.20	11	28	350	270	28	30	270
Mo-691	324127091501801	8-22-89	12	.20	10	30	430	390	30	30	390
Mo-693	325122091411901	8-10-89	38	.20	13	35	600	400	35	70	400
Mo-695	324541091373801	8-10-89	73	.20	14	35	470	170	35	40	170
M0-696	324449091374301	8-10-89	88	.20	15	32	490	130	32	20	130
					Chicot County, Arkansas						
Ch-1	331304091204501	10-25-89	240	.30	1.4	29	896	380	120	18	640
Ch-2	331247091202901	10-25-89	220	.40	.49	30	907	280	100	18	570
Ch-3	331223091204501	10-25-89	310	.40	1.6	29	1,070	190	120	17	550
Ch-4	330632091223801	10-25-89	360	.20	1.9	33	1,060	420	100	21	950
Ch-5	330736091242501	10-24-89	1,200	.20	5.8	28	3,030	<100	70	20	2,500
Ch-6	330736091244601	10-24-89	1,300	.20	6.5	26	3,300	400	80	20	2,600
Ch-7	331142091250201	10-24-89	810	.20	4.4	28	2,090	400	140	20	1,500
Ch-8	331152091250301	10-24-89	160	.10	.45	22	865	400	40	11	560

Suitability of Water for Irrigation

Replacement of calcium ions and magnesium ions sorbed onto clay particles in soil by dissolved sodium ions from irrigation water can cause undesirable soil characteristics such as decreased permeability and deflocculation. The sodium-adsorption ratio (SAR) is a measure of the replacement tendency and is defined by the following equation (U.S. Salinity Laboratory Staff, 1954):

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\frac{1}{2}\left[(\mathrm{Ca}^{2+}) + (\mathrm{Mg}^{2+})\right]}}, \tag{1}$$

where Na^{+}, Ca^{2+}, and Mg^{2+} represent the concentrations of sodium ions, calcium ions, and magnesium ions in irrigation water in milliequivalents per liter. As indicated by equation 1, the SAR depends on the concentrations of all three cations in the solution. Water with high concentrations of sodium ions can have low to moderate SAR's if the concentrations of calcium ions and magnesium ions also are high.

Specific conductance of water from the alluvial aquifer indicated a strong linear relation ($r = 0.99$) when plotted against the concentration of dissolved solids (fig. 13). The equation for the best-fit line shown in figure 13 is:

$$\text{dissolved solids (mg/L)} = \text{specific conductance } (\mu\text{S/cm at } 25^{\circ}\text{ C}) \times 0.631 - 107. \tag{2}$$

Equation 2 was generated using the least-squares linear regression technique.

Equation 2 can be used to estimate the dissolved-solids concentration of irrigation water sampled from a wellhead or discharge pipe based on a measurement of specific conductance. Because equation 2 was empirically derived from data collected during this study, it should be considered valid only for the northeastern Louisiana and southeastern Arkansas study area.

Irrigation water from the study area ranged from medium to very high in salinity hazard and low to medium in sodium hazard based on a classification scheme developed by the U.S. Salinity Laboratory Staff (1954) (fig. 14). The relatively low sodium hazard (associated with relatively low values of the sodium-adsorption ratio), even in alluvial water of high salinity hazard and high concentrations of sodium ions, is caused by elevated concentrations of calcium ions and magnesium ions. Leaching of the soil during the winter and spring months when rainfall is high has so far prevented substantial salt build-up in the soils of eastern Morehouse Parish (J.C. Stevens, Louisiana Agricultural Extension Service, oral commun., 1989).

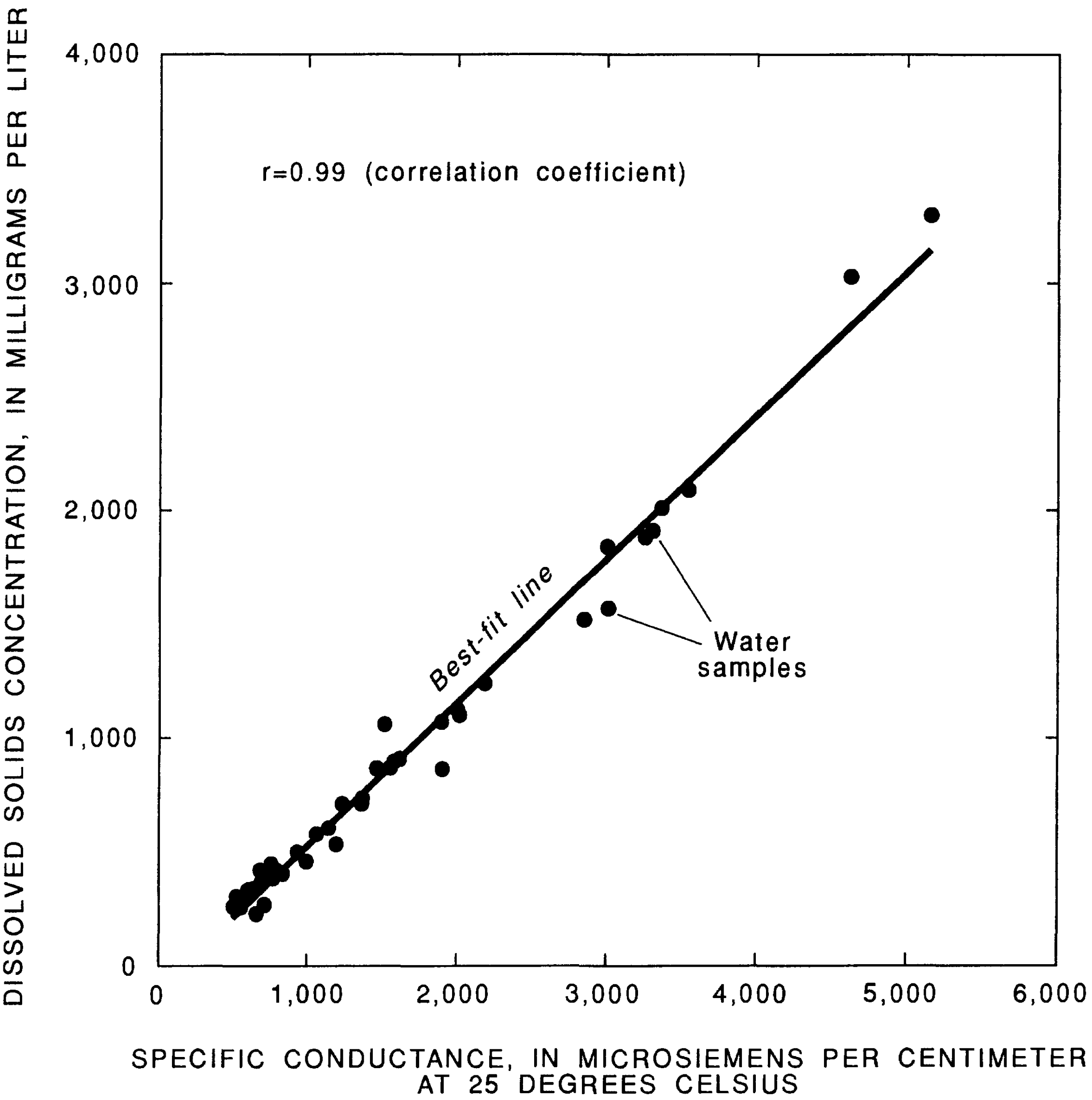


Figure 13. Dissolved solids as a function of specific conductance of water from the Mississippi River alluvial aquifer in northeastern Louisiana and southeastern Arkansas.

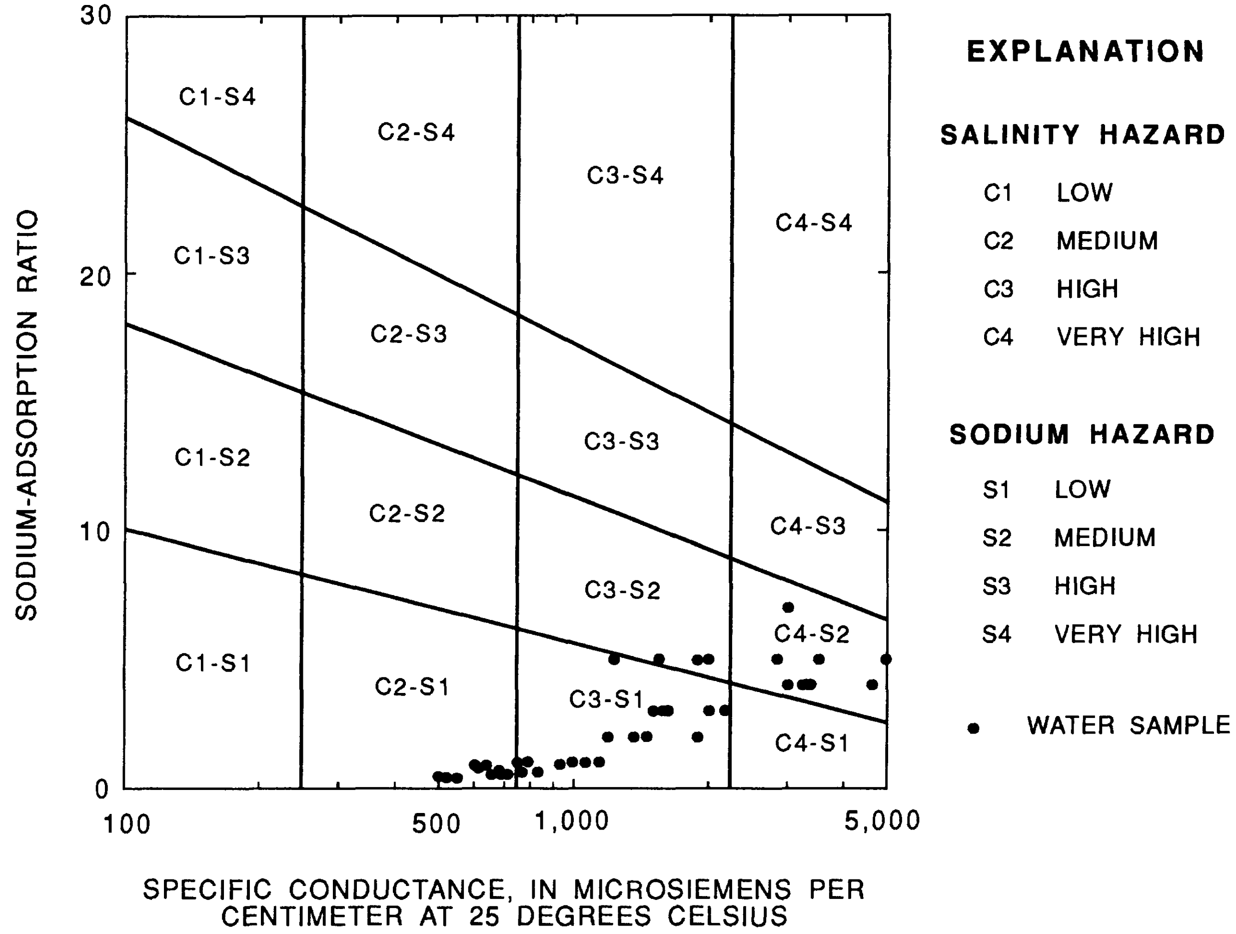


Figure 14. Classification scheme for evaluating the suitability of ground water for irrigation and sodium-adsorption ratio as a function of specific conductance of water from wells in the Mississippi River alluvial aquifer within the northeastern Louisiana and southeastern Arkansas study area.

Saltwater in the Mississippi River Alluvial Aquifer in Northeastern Louisiana and Southeastern Arkansas

Areal and Vertical Distribution of Saltwater

Concentrations of dissolved solids (fig. 15) and chloride ions (fig. 16) in water samples from the alluvial aquifer are plotted on the mapped altitude of the unconformable contact between the bottom of the alluvial deposits and the top of the underlying Cockfield Formation.

Paleotopographic features (Saucier, 1967) on the top of the Cockfield Formation indicate two roughly parallel northeast-southwest trending fluvial channels. In east Morehouse Parish wells producing water with concentrations of dissolved solids (fig. 15) greater than about 500 mg/L and concentrations of chloride ions (fig. 16) greater than about 100 mg/L are within or near the mapped location of the easternmost fluvial channel. Saltwater in the alluvial aquifer is present within, but is not limited to, the mapped location of this same fluvial channel in southern Chicot County.

Two test holes were drilled into the Cockfield aquifer. Test hole Mo-709 was drilled through the easternmost fluvial channel and test hole Mo-708 was drilled through an adjoining paleotopographic high on the Cockfield Formation (fig. 15). Wells Mo-709 and Mo-708 were completed in the locations of these test holes. The trace of electric logs in test holes Mo-708 and Mo-709 is shown in figure 17. Measured induction resistivity (dashed line) was lower in test hole Mo-709 than in test hole Mo-708 for the total thickness of the alluvial aquifer. Measured normal resistivity (solid line) shows the same pattern, except for the top 30 ft of test hole Mo-709, where normal resistivity could have been affected by invasion of drilling fluid into the alluvial aquifer. In the absence of large changes in subsurface temperature or lithology, changes in the measured resistivity between two points in an aquifer reflect changes in the concentration of dissolved solids in the water. Drillers' logs indicated lithology changes between test holes Mo-709 and Mo-708 were limited to a greater fraction of coarse sand and small gravel in about the lower 40 ft of the alluvial aquifer penetrated by test hole Mo-709 than was present in test hole Mo-708. Thus, the lower resistivity measured in the alluvial aquifer penetrated by test hole Mo-709 indicates the presence of alluvial water that had greater concentrations of dissolved solids than alluvial water in test hole Mo-708. Drillers' logs indicated that about 30 ft of clay and silty clay immediately underlie the base of the fluvial channel in test hole Mo-709. Where present, this layer of clay to silty clay obstructed vertical flow between the alluvial and Cockfield aquifers.

Paleotopographic Controls on the Areal Distribution of Saltwater

The trace of the electric log in test hole Mo-709 shows higher resistivities in the sandy interval of the Cockfield aquifer at an altitude from 145 to 165 ft below sea level than in the overlying alluvial aquifer. This indicated the presence of water with lower concentrations of dissolved solids in the Cockfield aquifer than in the overlying alluvial aquifer. Wells Mo-709 and Mo-710 were located about 100 ft apart near the site of test hole Mo-709 (fig. 12). Well Mo-709 was screened in the Cockfield aquifer at an altitude from 155 to 175 ft below sea level. Well Mo-710 was screened in the alluvial aquifer from 30 to 40 ft below sea level.

The dissolved-solids concentration of a water sample from well Mo-709 (895 mg/L), compared to a water sample from well Mo-710 (about 1,800 mg/L), confirmed that the alluvial aquifer within the easternmost fluvial channel had a greater concentration of dissolved solids than the underlying Cockfield aquifer. This indicated that upward flow from directly below the alluvial aquifer within the easternmost fluvial channel is not the source of saltwater to the aquifer.

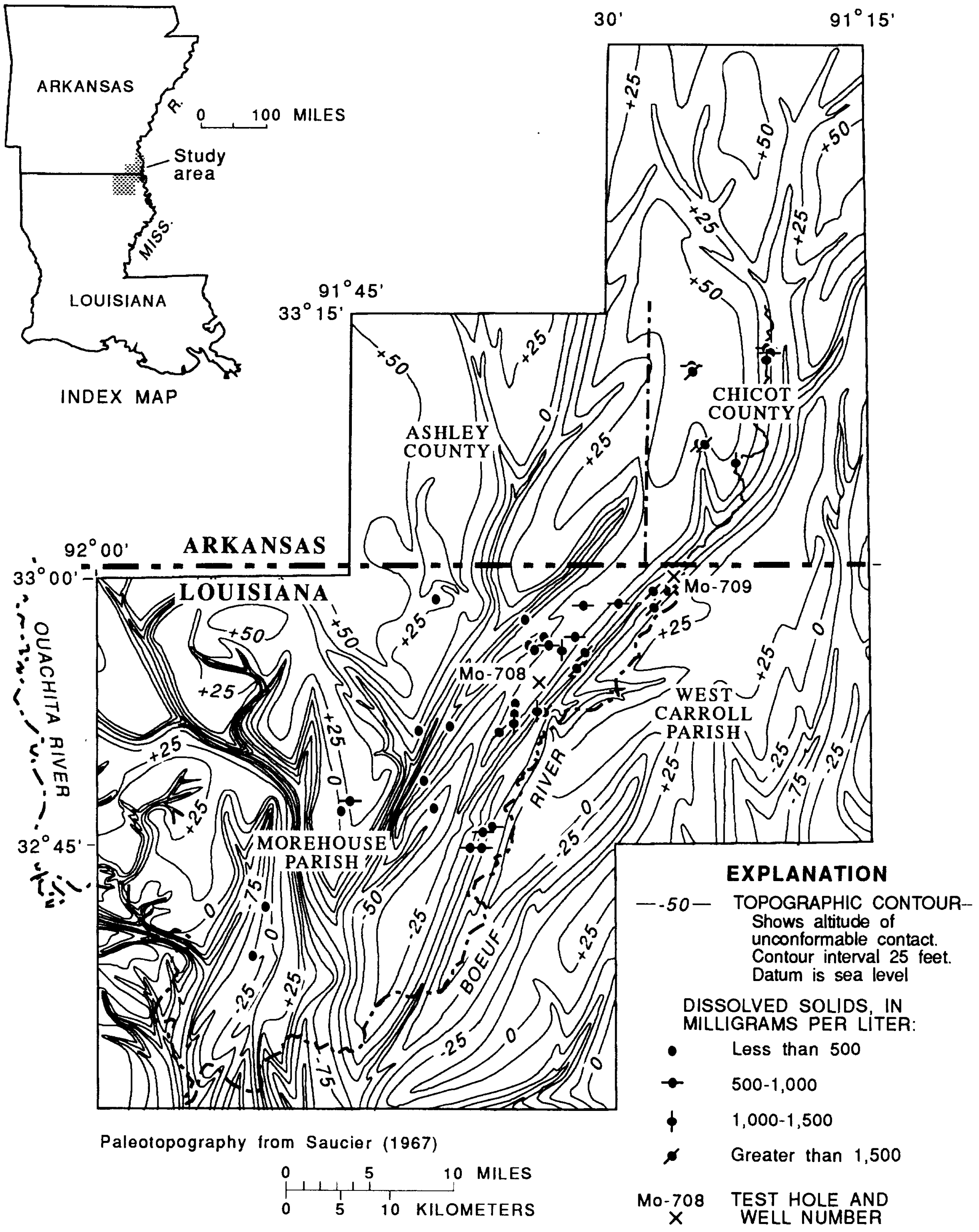
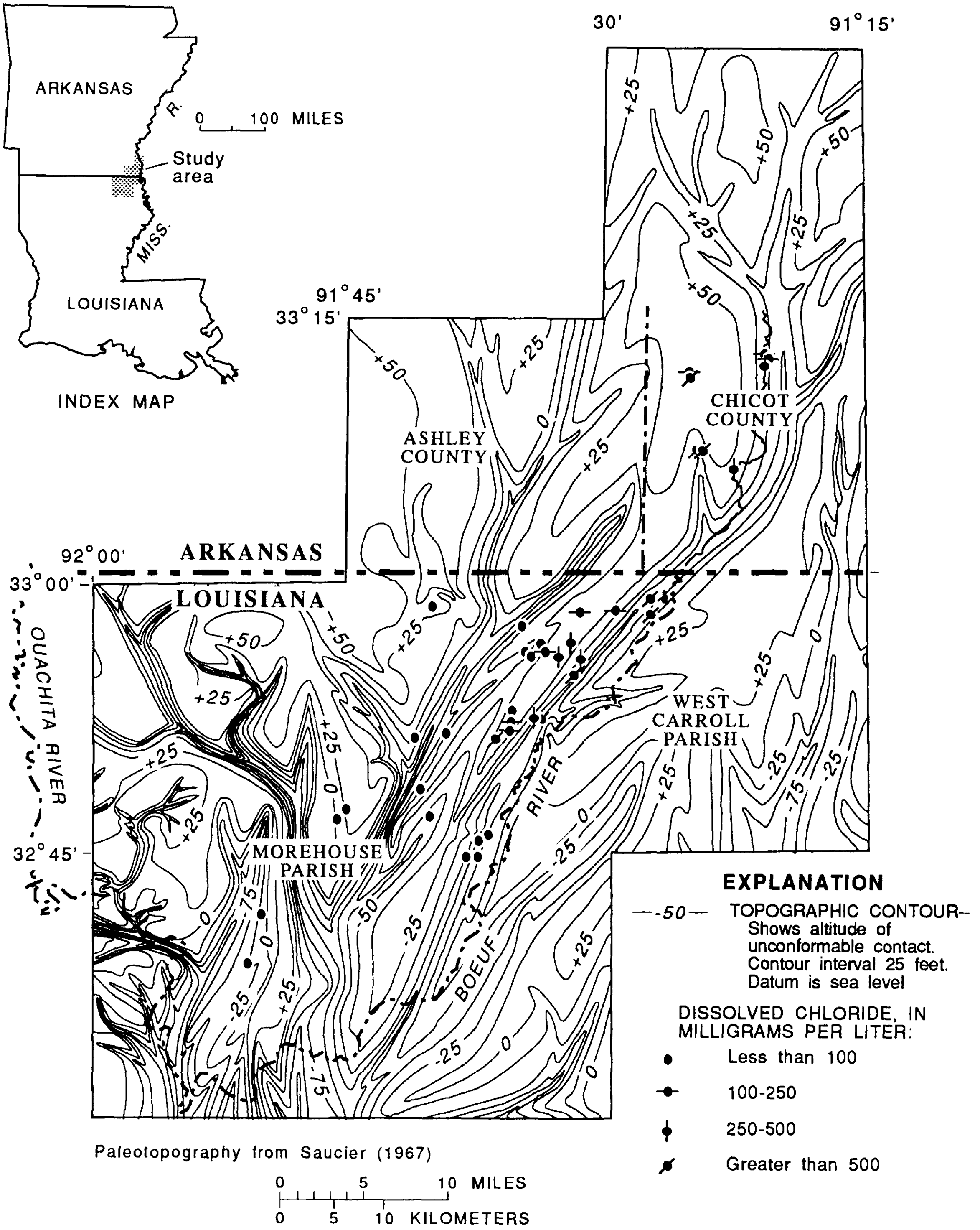
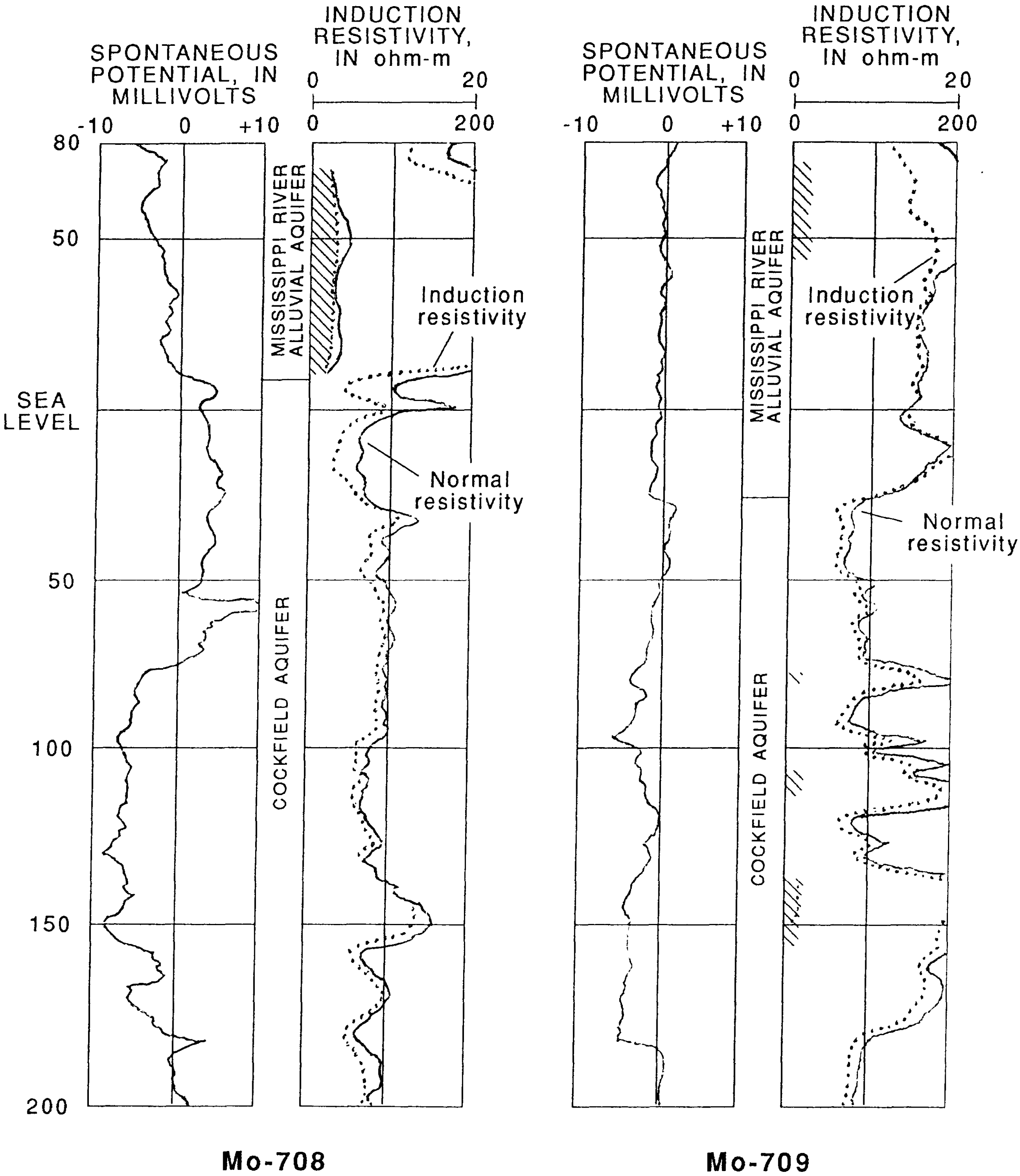


Figure 15. Concentrations of dissolved solids in water from the Mississippi River alluvial aquifer shown on the mapped altitude of the unconformable contact between the Mississippi River alluvial deposits and the underlying Cockfield Formation, northeastern Louisiana and southeastern Arkansas.



Paleotopography from Saucier (1967)

Figure 16. Concentrations of dissolved chloride ions in water from the Mississippi River alluvial aquifer shown on the mapped altitude of the unconformable contact between the Mississippi River alluvial deposits and the underlying Cockfield Formation, northeastern Louisiana and southeastern Arkansas.



EXPLANATION

▨ RESISTIVITY OF GREATER THAN 20 OHM-METERS READ ON BOTTOM SCALE

Figure 17. Trace of electric logs of test holes Mo-708 and Mo-709 within the northeastern Louisiana and southeastern Arkansas study area.

The easternmost fluvial channel in Morehouse Parish intersects a zone of saltwater in southern Chicot County. Because the density of saltwater is greater than that of freshwater, saltwater in the alluvial aquifer in southern Chicot County becomes trapped within the easternmost fluvial channel and flows to the southwest, even though water in the alluvial aquifer generally flows to the south or southeast. The layer of clay to silty clay present at the base of test hole Mo-709 could be laterally extensive in the channel and thus prevent downward flow from above of saltwater into the Cockfield aquifer.

Because bromide and chloride ions can be assumed to react conservatively in ground-water systems, their geochemistry can be interpreted in terms of mixing curves. Concentrations of bromide and chloride ions in water from the alluvial aquifer plotted against one another fall along two distinct trends (fig. 18). A best-fit line was drawn through each of the data trends using the least-squares linear regression technique. Each separate data trend in figure 18 represents the concentrations of bromide and chloride ions produced by mixing of fresh alluvial water with ground water having higher concentrations of bromide and chloride ions. Because the compositions of end members lie on or along an extension of a given mixing curve, the presence of two distinct trends in the data indicated the presence of two saline end members with distinct Br/Cl ratios.

The relation between concentration, in milligrams per liter, of bromide ions times 1,000 divided by the concentration, in milligrams per liter, of chloride ions as a function of the concentration of chloride ions in alluvial water samples is shown in figure 19. Hereafter, this relation will be referred to as the BrX1,000/Cl value.

For reference, calculated BrX1,000/Cl values as a function of chloride-ion concentrations on mixing of modern seawater with freshwater from the alluvial aquifer are shown in figure 19. The compositions used for freshwater alluvial aquifer end members in constructing the modern seawater mixing curves (fig. 19) are those which appear at the low chloride end of the mixing curves near the dependent (BrX1,000/Cl) axis. The BrX1,000/Cl value for modern seawater is 3.46 (Drever, 1982). The seawater mixing curve is used herein for reference only; its use for reference does not imply that Mississippi River alluvial saltwater in the northeastern Louisiana and southeastern Arkansas study area is formed by a mixture of seawater and fresh alluvial water.

In addition to providing a frame of reference, the modern seawater mixing curve indicates the rapid convergence of the BrX1,000/Cl value for a mixture of dilute and a more saline end member toward the BrX1,000/Cl value for the more saline end member. Most of the data points representing a concentration of chloride ion about 50 mg/L or greater are in two clearly defined groups (fig. 19). One group of data points represents alluvial water with BrX1,000/Cl values greater than that of modern seawater and the other group with values less than that of modern seawater. When the BrX1,000/Cl values of alluvial water are less than that of modern seawater they overlap the range of BrX1,000/Cl values of briny water in sediment of Tertiary age in southern (Hanor, 1984) and central (table 2) Louisiana.

Most of the data points representing alluvial water having BrX1,000/Cl values greater than that of modern seawater correspond to sampling locations in southern Chicot County, and values less than that of modern seawater correspond to sampling locations in Morehouse Parish.

Hydrogeochemistry and Origin of Saltwater

To understand the origin of these geochemically distinct sources of ground water having elevated concentrations of dissolved solids, the regional geochemistry of deep subsurface ground water and regional ground-water flow patterns in both deep and shallow aquifers must be considered. The following sections discuss aspects of geochemistry and regional ground-water flow in aquifers and formations that contain potential sources of elevated dissolved solids in alluvial water.

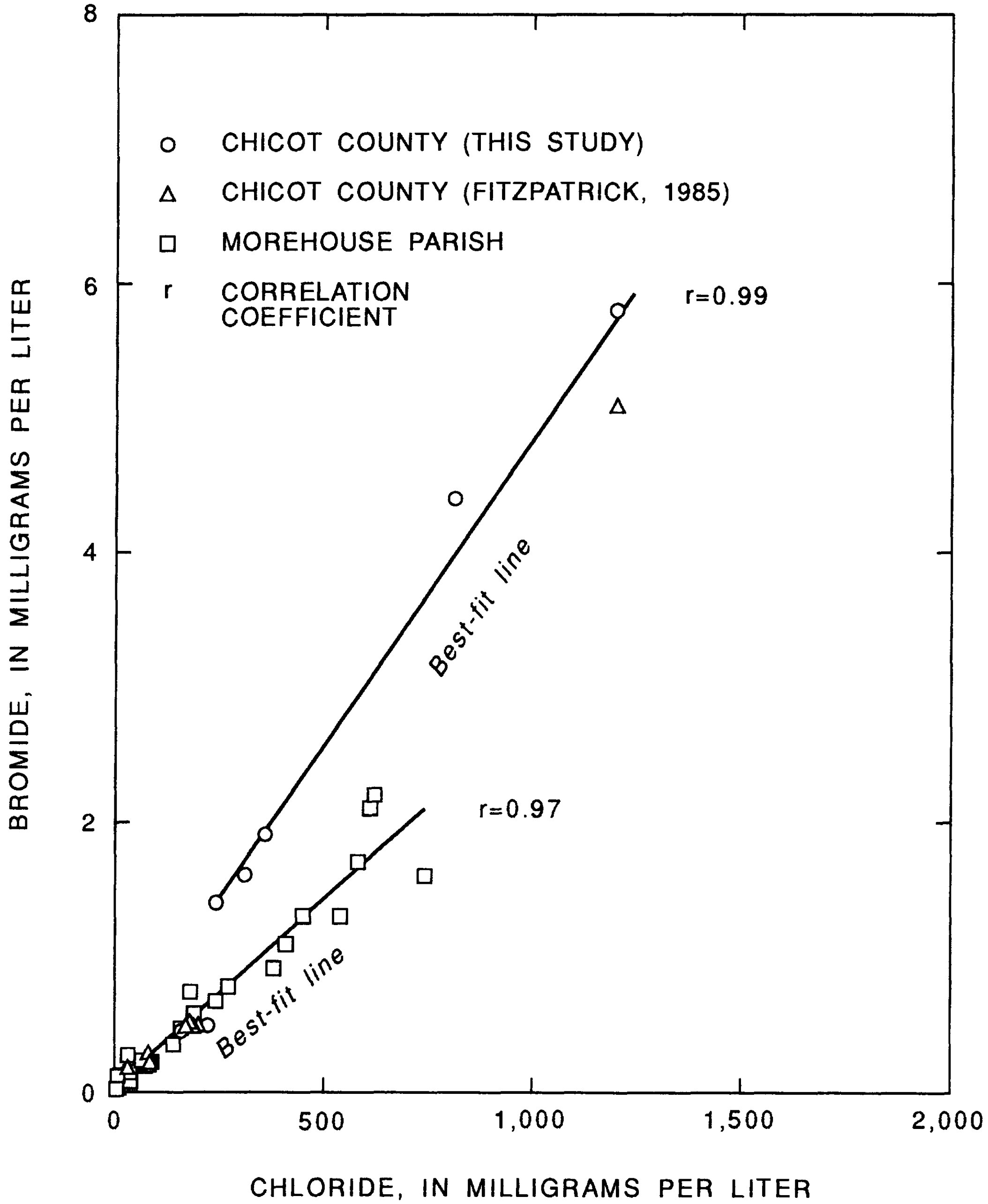


Figure 18. Concentrations of dissolved bromide ions as a function of the concentrations of dissolved chloride ions in water from the Mississippi River alluvial aquifer within the northeastern Louisiana and southeastern Arkansas study area.

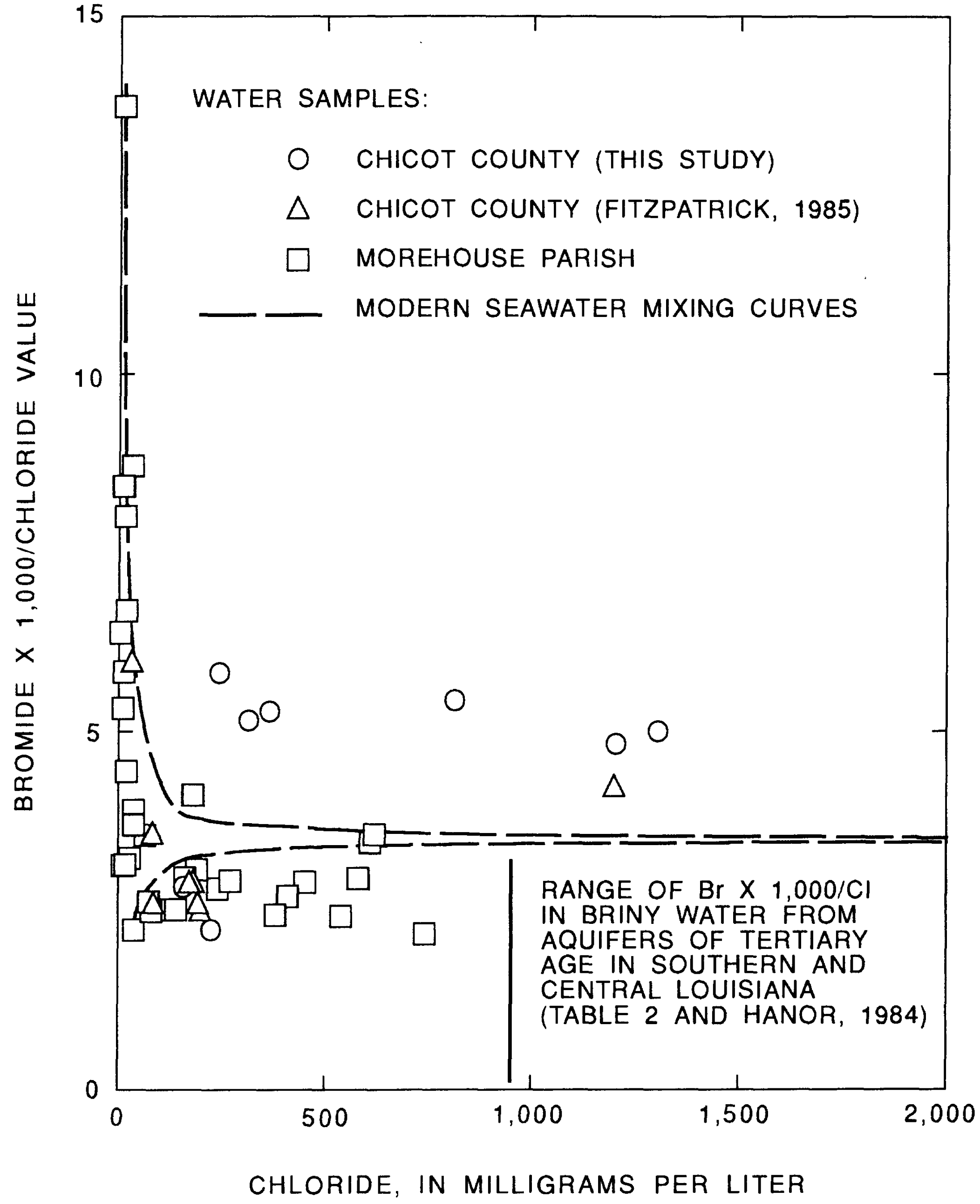


Figure 19. Bromide X 1,000/chloride value as a function of the concentrations of dissolved chloride ions in water from the Mississippi River alluvial aquifer within the northeastern Louisiana and southeastern Arkansas study area.

Aquifers of Tertiary Age

A part of the precipitation falling on the highlands to the west of the Mississippi Alluvial Plain flows downward and eastward into the Sparta aquifer or perhaps deeper into the Carrizo-Wilcox aquifer before circulating upward and entering the alluvial aquifer (fig. 20). Deeply circulating ground water is brought into contact with ground water having dissolved-solids concentrations ranging from 3,000 to greater than 10,000 mg/L. A similar circulation pattern exists on the eastern side of the Mississippi Alluvial Plain (Payne, 1968). Upward circulating ground water contains a greater concentration of dissolved solids, derived from mixing with more saline ground water at depth, than is present in fresh alluvial water. Upward flow from below of saltwater along the Mississippi Valley alluvium as shown in figure 20 could account for the zone of dissolved-solids and chloride ion concentrations in a part of the alluvial aquifer that are greater than background values shown in figure 1.

Hanor (1984; 1987, p. 81-82) proposed that briny water within aquifers of Tertiary age in southern Louisiana, which are sodium-chloride type water with BrX1,000/Cl values less than that of modern seawater, are created by subsurface dissolution of the mineral halite from salt domes. Halite usually contains about 100 mg of bromide per 1 kg of halite at initial halite saturation in evaporating seawater (Herrmann, 1980). Holser (1966) reported a concentration of 48 mg of bromide per 1 kg of halite in a coastal Louisiana salt dome. Congruent dissolution of halite having concentrations of 100 and 48 mg of bromide per 1 kg of halite into pure water would produce saltwater with BrX1,000/Cl values of about 0.17 and 0.08. These BrX1,000/Cl values are within the lower part of the range of BrX1,000/Cl values in briny water from aquifers in sediment of Tertiary age in southern and central Louisiana (fig. 19).

If saltwater present in the aquifers of Tertiary age in northern and central Louisiana had originated from dissolution of halite, it is likely that the associated BrX1,000/Cl values would be similar to briny water in southern Louisiana. Provided that saltwater within aquifers of Tertiary age in the study area has BrX1,000/Cl values less than that of modern seawater, upward circulating water having elevated concentrations of dissolved solids derived from mixing with saltwater at depth would represent the more saline end member required to produce alluvial saltwater with BrX1,000/Cl values less than that of modern seawater.

The Smackover Formation

Alluvial saltwater having BrX1,000/Cl values greater than that of modern seawater requires a source that also has a BrX1,000/Cl value greater than that of modern seawater. The Smackover Formation of Jurassic age is present at altitudes from 5,500 to 6,500 ft below sea level in the northeastern Louisiana and southeastern Arkansas study area (fig. 11). Briny water from the Smackover Formation in southwestern Arkansas contains BrX1,000/Cl values that are among the highest reported in the literature (Collins, 1974; Carpenter and Trout, 1978). This briny water represents a possible end member in a mixing scheme that could produce saltwater in the alluvial aquifer with BrX1,000/Cl values greater than that of modern seawater. Briny water having BrX1,000/Cl values greater than modern seawater is associated with an east-west trending, trough-shaped structure about 125 mi long and 25 mi wide (Carpenter, 1984). Briny water having high BrX1,000/Cl values within the Smackover Formation has not been confirmed to be present in Chicot County, possibly because of the lack of oil and gas development in the area. It is not unreasonable to assume, however, that briny water having high BrX1,000/Cl values that occur along an east-west trend in southwestern Arkansas could extend into Chicot County.

Figure 21 shows average concentrations of bromide and chloride ions in water from selected areas of ground water from southern and central Louisiana northward to southeastern Arkansas (table 2, this report; Collins, 1974; Carpenter and Trout, 1978; Hanor, 1984). The average composition of saltwater in the alluvial aquifer from the study area having a BrX1,000/Cl value less

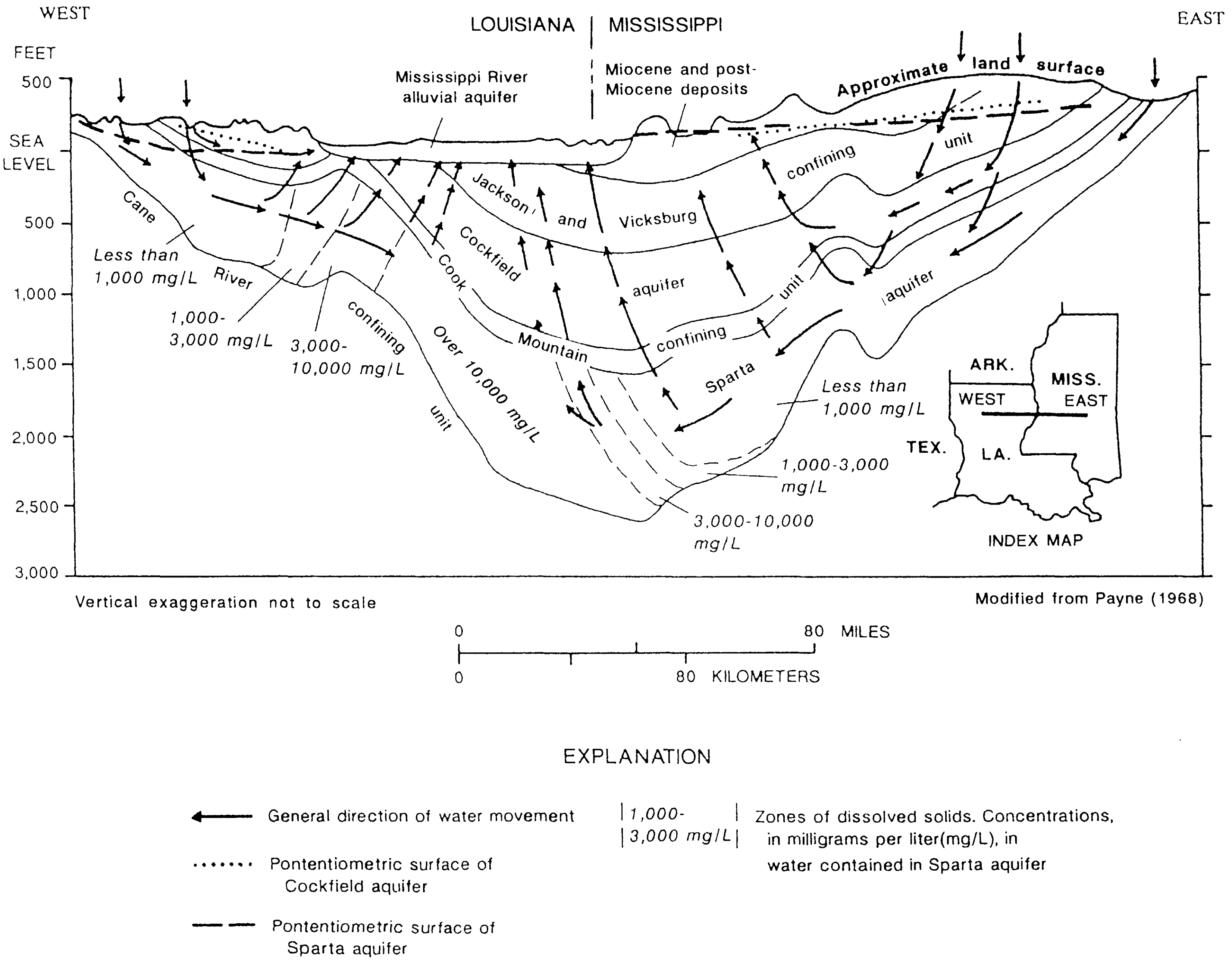


Figure 20. Generalized section showing regional geology and hydrology in the Mississippi Alluvial Plain.

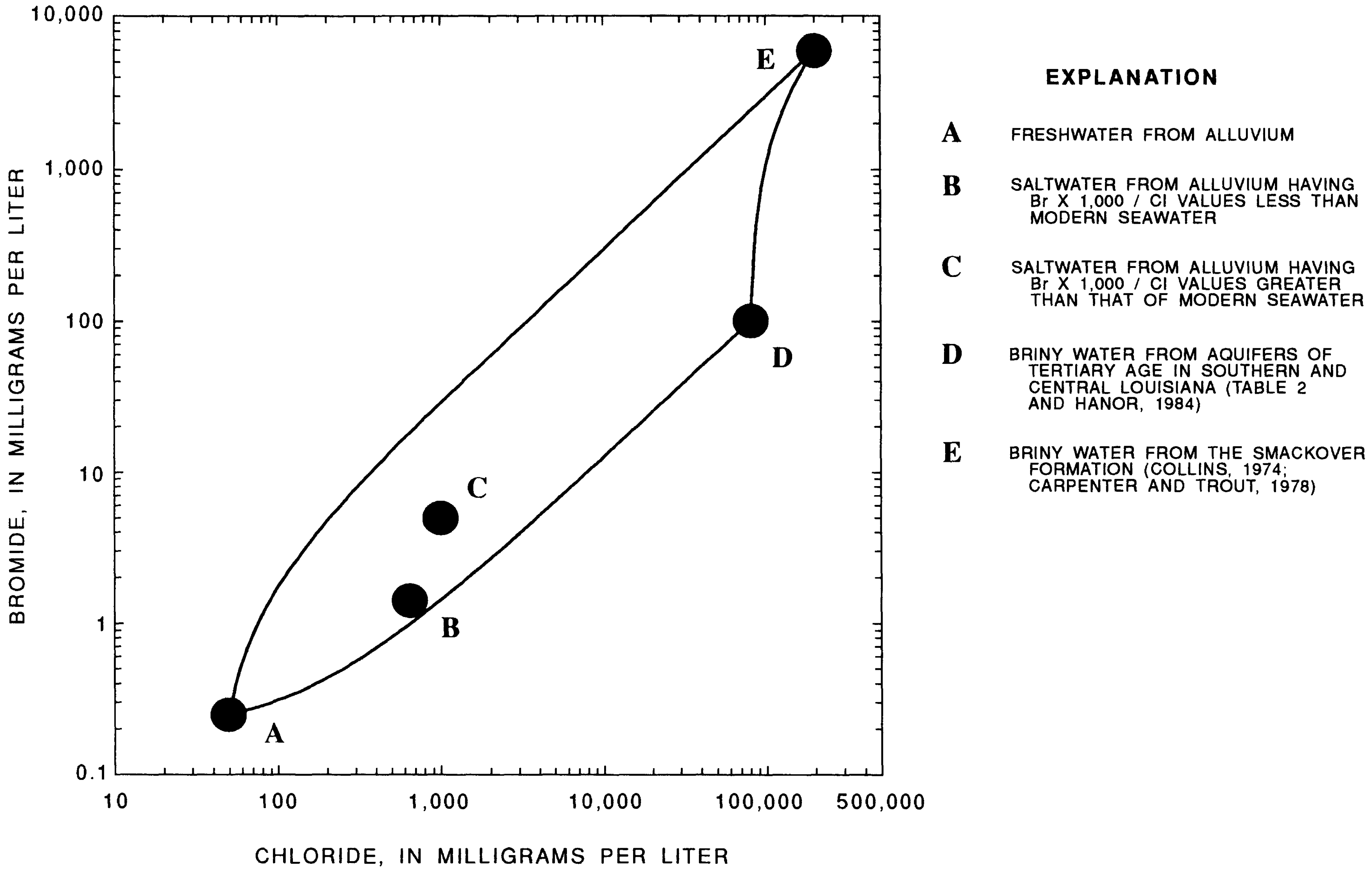


Figure 21. Average concentrations of dissolved bromide ions as a function of the average concentrations of dissolved chloride ions in selected areas of ground water within northern Louisiana and southern Arkansas.

than that of modern seawater (point B) is near a mixing curve between the average composition of fresh alluvial water (point A) and the average composition of briny water from aquifers of Tertiary age in southern and central Louisiana (point D). The relation of points A, B, and D indicates that saltwater in the alluvial aquifer in the study area having BrX1,000/Cl values less than that of modern seawater could be formed by a binary mixture of alluvial freshwater and briny water from aquifers of Tertiary age.

The average composition of saltwater in the alluvial aquifer with BrX1,000/Cl values greater than that of modern seawater is represented by point C (fig. 21). The average composition of briny water having high BrX1,000/Cl values from within the Smackover Formation is represented by point E (fig. 21). Because point C does not lie on a mixing curve between the average composition of fresh alluvial water (point A) and either known more saline end member (points D and E), the composition of saltwater in the alluvial aquifer with BrX1,000/Cl values greater than that of modern seawater (point C) cannot be explained as a binary mixture of fresh alluvial water with either known more saline end member. The composition of a hypothetical more saline end member required to generate saltwater in the alluvial aquifer with BrX1,000/Cl values greater than that of modern seawater is intermediate in composition between briny water having high BrX1,000/Cl values of the Smackover Formation and briny water from aquifers of Tertiary age in southern and central Louisiana.

The final concentrations of conservative constituents, such as bromide and chloride ions, in a mixture depend solely on the concentrations of conservative constituents present in the end members and the relative amounts of each end member present in the mixture. Thus, the composition represented by point C could be generated by mixing the appropriate amounts of water represented by points A, D, and E (fig. 21) in any order.

Mechanisms of Introduction of Saltwater

Saltwater in the alluvial aquifer with BrX1,000/Cl values less than that of modern seawater could be produced by mixing fresh alluvial water circulating to altitudes more than 2,500 ft below sea level with more saline water in aquifers of Tertiary age. This saltwater returns toward the surface and flows upward through the base of the alluvial aquifer as part of the regional ground-water flow pattern.

Saltwater in the alluvial aquifer with BrX1,000/Cl values greater than that of modern seawater could be derived, at least in part, from briny water within the Smackover Formation. For briny water from the Smackover Formation to affect the geochemistry of saltwater, a mechanism must exist for transporting briny water from the Smackover Formation, or water derived from briny water within the Smackover Formation, upward through the base of the alluvial aquifer.

Geochemical data on the abundance of bromide and chloride ions reported by Broom and others (1984) indicated that locally occurring saltwater in the upper part of the Sparta aquifer in Union County, Arkansas (fig. 1), could have been derived from briny water within the Smackover Formation. This area is associated with the location of a graben. The depth of penetration of the faults bounding the graben was not reported by Broom and others (1984). The presence of graben-bounding faults in the proximity of local maximum salinity indicates that graben-bounding faults could function as conduits along which dissolved ions migrate upward from depth.

The areal distribution of concentrations of chloride ions greater than about 100 mg/L in water from the alluvial aquifer of southern Chicot County occurs along a roughly north-south trend in an area about 17 mi long and 3 mi wide (Fitzpatrick, 1985) and coincides with the area of concentrations of dissolved solids greater than 1,000 mg/L mapped by Boswell and others (1968) (fig. 1). The areal distribution of concentrations of chloride ions greater than about 100 mg/L in water from the alluvial aquifer of southern Chicot County is not consistent with a point source of saltwater contamination. Fitzpatrick (1985) has suggested that saltwater could migrate into the alluvial aquifer by upward flow along a fault or through a thin or missing section of the regional confining layer (Jackson Formation) which underlies the Cockfield aquifer in southern Arkansas. Less restricted upward flow of saltwater from below in an area where the Jackson Formation is thin or missing could explain a local increase in the salinity of alluvial water. However, upward flow of saltwater from below in an area where the Jackson Formation is thin or missing does not account for the geochemically distinct BrX1,000/Cl values observed in alluvial water within the area of chloride concentrations greater than 100 mg/L in southern Chicot County, Arkansas.

The location of two regional wrench faults in northern Louisiana and southern Arkansas was reported by Zimmerman (1992). The reported intersection of these two faults coincides with the area of maximum chloride and dissolved-solids concentrations in the alluvial aquifer of southern Chicot County (fig. 22). At least one of these faults extends into the Smackover Formation and has been active as late as Pleistocene or Holocene time Zimmerman (1992). Upward movement of dissolved ions, derived at least in part from briny water within the Smackover Formation, along the intersection of these faults in southern Chicot County could introduce saltwater having BrX1,000/Cl values greater than that of modern seawater into the alluvial aquifer. Increased vertical hydraulic conductivity along the intersection of these faults also could explain the locally-elevated salinity in southern Chicot County, Arkansas.

The present delineation of the zone of high to very high salinity hazard in eastern Morehouse Parish (fig. 23) is based on the southernmost location of alluvial water samples from within the easternmost fluvial channel which fall into the C3 or C4 category (fig. 14). Because the saltwater appears to be largely confined within the fluvial channel, lateral spreading is unlikely. It is possible, however, that saltwater within the easternmost fluvial channel could migrate southwestward along the fluvial channel in the future.

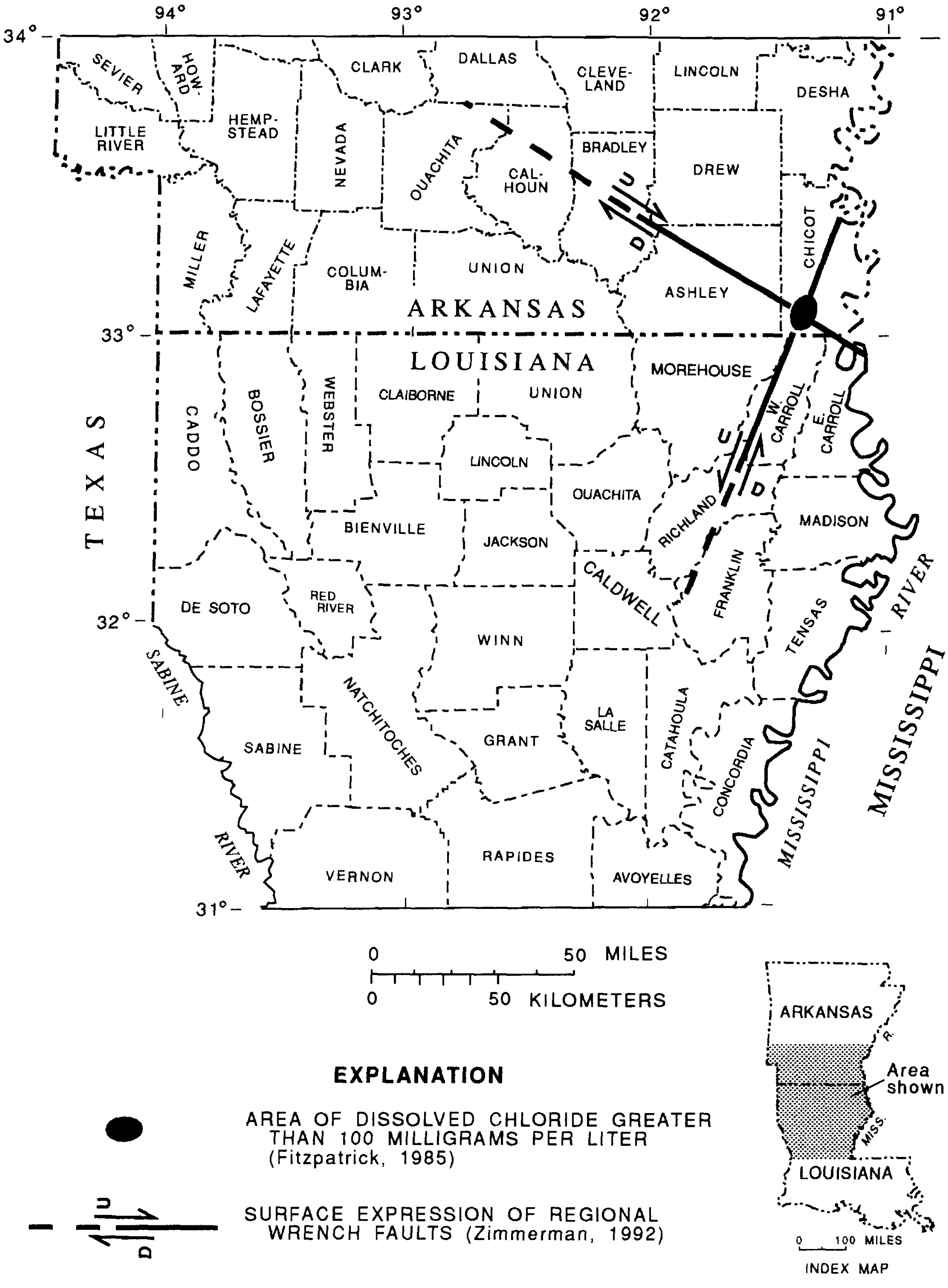


Figure 22. The surface expression of regional wrench faults in northern Louisiana and southern Arkansas and the area of dissolved chloride ion concentrations greater than 100 milligrams per liter in the Mississippi River alluvial aquifer of southern Chicot County, Arkansas.

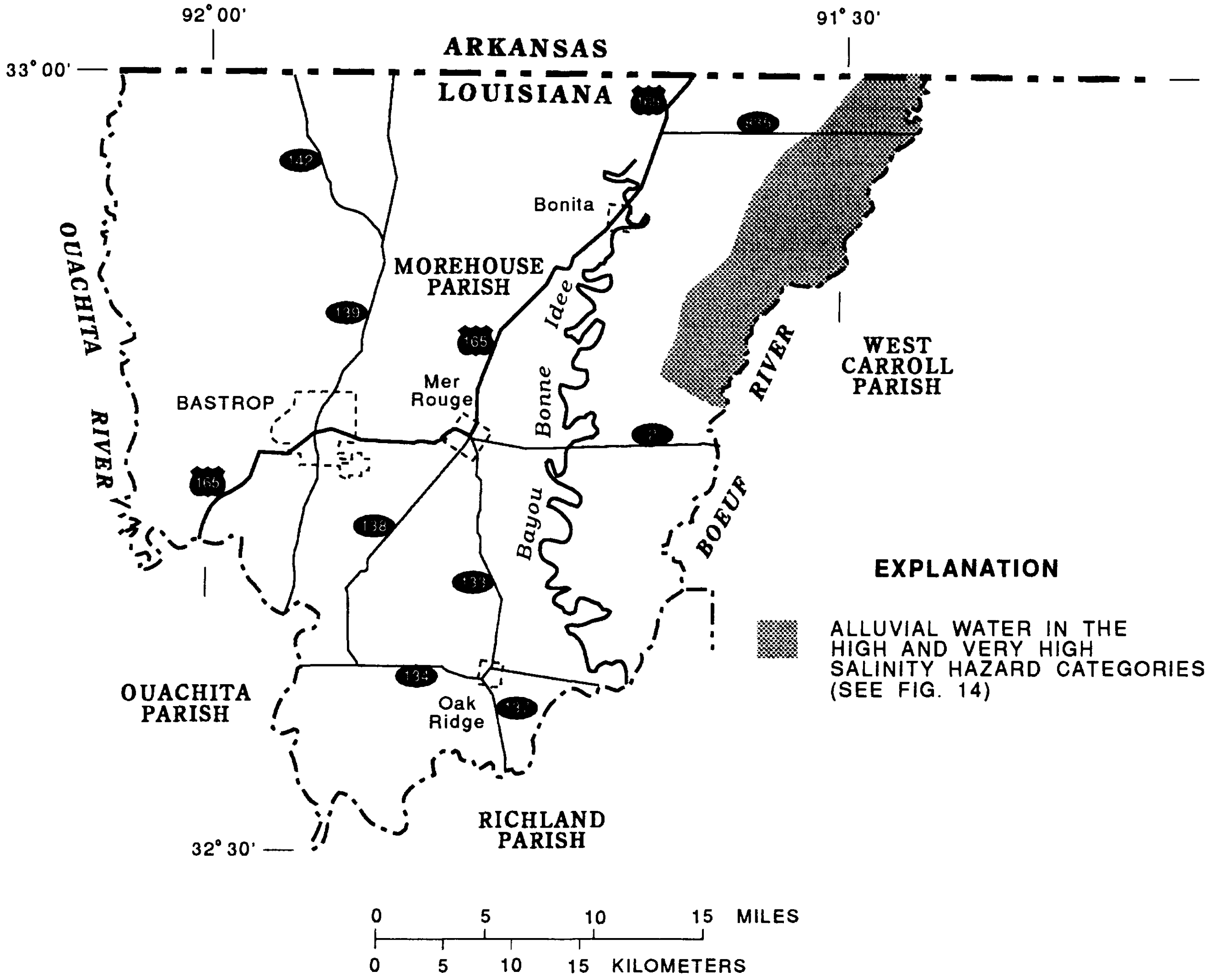


Figure 23. Zone of water having a high-salinity hazard in the Mississippi River alluvial aquifer in northeastern Louisiana.

SUMMARY AND CONCLUSIONS

Analyses of water from irrigation and monitor wells in east-central Louisiana, indicated the presence of saltwater in the Mississippi River alluvial aquifer and the uppermost part of the Jasper aquifer system. The salinity of this ground water makes it unsuitable for use in irrigation. Available geochemical data for bromide (Br) and chloride (Cl) ions and strontium (Sr) isotopes indicated that briny water from 5,800 to 6,800 ft below sea level within the Carrizo-Wilcox aquifer could be the source of saltwater in the alluvial aquifer and uppermost part of the Jasper aquifer system. However, in the absence of data on the concentrations of Br and Cl ions and the values of $^{87}Sr/^{86}Sr$ in water from the Catahoula, Cockfield, and Sparta aquifers within the study area, no conclusive statement can be made on the origin of saltwater in the alluvial aquifer and the uppermost part of the Jasper aquifer system.

Analyses of water from irrigation wells in northeastern Louisiana and southeastern Arkansas indicated the presence of saltwater in the Mississippi River alluvial aquifer. Saltwater in the Mississippi River alluvial aquifer in these areas can be hazardous to salt-sensitive crops, such as rice, when used for irrigation. The location of saltwater in the alluvial aquifer in eastern Morehouse Parish is controlled by the paleotopography of the unconformable contact between the alluvium of Pleistocene age and sediments of the Cockfield Formation of Tertiary age. Saltwater could move into the alluvial aquifer in southern Chicot County, Arkansas, by upward flow from below as part of the natural regional ground-water flow pattern and by movement along a fault that penetrates into the Smackover Formation. Because the density of saltwater in southern Chicot County is greater than that of the surrounding fresh ground water, the saltwater probably becomes trapped within a northeast-southwest trending fluvial channel eroded into Cockfield Formation and flows along the fluvial channel to the southwest into Morehouse Parish.

Water from the alluvial aquifer with concentrations of Cl ions greater than about 50 mg/L can be divided into two groups on the basis of BrX1,000/Cl values. One group has a BrX1,000/Cl value less than that of modern seawater and the other group has a BrX1,000/Cl value greater than that of modern seawater.

The geochemistry of Br and Cl ions in saltwater from the alluvial aquifer with BrX1,000/Cl values less than that of modern seawater could be explained as a binary mixture of fresh alluvial water with more saline water derived from aquifers of Tertiary age. Saltwater with BrX1,000/Cl values less than that of modern seawater could be introduced into the alluvial aquifer of southern Chicot County by upward flow from below as part of the natural regional ground-water flow system.

The geochemistry of Br and Cl ions in saltwater from the alluvial aquifer with BrX1,000/Cl values greater than that of modern seawater could be explained as a ternary mixture of fresh alluvial water, saltwater from aquifers in sediments of Tertiary age, and saltwater from the Smackover Formation of Jurassic age at altitudes from 5,500 to 6,500 feet below sea level. Saltwater could be derived from the Smackover Formation by upward migration of briny water along the intersection of two regional wrench faults, at least one of which penetrates from near land surface into the Smackover Formation.

SELECTED REFERENCES

Ackerman, D.J., 1989, Hydrology of the Mississippi River Valley alluvial aquifer, south-central United States -- A preliminary assessment of the regional flow system: U.S. Geological Survey Water-Resources Investigations Report 88-4028, 74 p.

Beckman, J.D., and Williamson, A.K., 1990, Salt-dome locations in the Gulf Coastal Plain, south-central United States: U.S. Geological Survey Water-Resources Investigations Report 90-4060, 44 p.

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

Broom, M.E., Kramer, T.F., and Bush, W.V., 1984, A reconnaissance study of saltwater contamination in the El Dorado aquifer, Union County, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 84-4012, 47 p.

Carpenter, A.B., 1984, Chemical constraints and origins of four groups of Gulf Coast fluids: Discussion, *in* Origin of Gulf Coast Brines, A Continuing Dialog: Applied Carbonate Research Program Technical Series Contribution No. 23, Louisiana State University, Baton Rouge, Louisiana.

Carpenter, A.B., and Trout, M.L., 1978, Geochemistry of bromide-rich brines of the Dead Sea and southern Arkansas: Oklahoma Geological Survey Circular 79, p. 78-88.

Collins, A.G., 1974, Geochemistry of liquids, gases, and rocks from the Smackover Formation: U.S. Bureau of Mines Report of Investigations 7897, 84 p.

Drever, J.I., 1982, The Geochemistry of Natural Waters: Prentice-Hall, Englewood Cliffs, New Jersey, 388 p.

Eversull, L.G., 1984, Regional cross sections, north Louisiana: Louisiana Geological Survey Folio Series No. 7, 11 p.

Faure, Gunter, 1977, Principles of Isotope Geology: John Wiley and Sons, New York, New York, 464 p.

Feth, J.H., 1981, Chloride in natural continental water - A review: U.S. Geological Survey Water-Supply Paper 2176, 30 p.

Fishman, M.J., and Friedman, L.C., eds., 1989 (revised), Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations book 5, chap. A1, 545 p.

Fitzpatrick, D.J., 1985, Occurrence of saltwater in the alluvial aquifer in the Boeuf-Tensas Basin, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 85-4029, 1 sheet.

Hanor, J.S., 1984, Salinity and geochemistry of subsurface brines in south Louisiana and their potential for reacting with injected geothermal waste waters: U.S. Department of Energy Report DOE/NV/10174-3, p. 277-346.

-----1987, Origin and Migration of Subsurface Sedimentary Brines: Society of Economic Paleontologists and Mineralogists Short Course No. 21, 247 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water, third edition: U.S. Geological Survey Water-Supply Paper 2254, p. 157.

Herrmann, A.G., 1980, Bromide distribution between halite and NaCl-saturated seawater: Chemical Geology, v. 28, p. 171-177.

Holser, W.T., 1966, Bromide geochemistry in salt rocks, *in* J.L. Rau, ed., Second Symposium on Salt: Northern Ohio Geological Society, v. 1, p. 248-275.

Lico, M.S., Kharaka, Y.K., Carothers, W.W., and Wright, V.A., 1982, Methods for collection and analysis of geopressured geothermal and oil field waters: U.S. Geological Survey Water-Supply Paper 2194, 21 p.

Means, J.L., and Hubbard, N., 1987, Short-chain aliphatic acid anions in deep subsurface brines: A review of their origin, occurrence, properties, and importance, and new data on their distribution and geological implications in the Palo Duro Basin, Texas: Organic Geochemistry, v. 11, no. 3, p. 177-191.

Payne, J.N., 1968, Hydrologic significance of the lithofacies of the Sparta sand in Arkansas, Louisiana, Mississippi, and Texas: U.S. Geological Survey Professional Paper 569-A, 17 p.

Robinove, C.J., Langford, R.H., and Brookhart, J.W., 1958, Saline-water resources of North Dakota: U.S. Geological Survey Water-Supply Paper 1428, 72 p.

Sanford, T.H., Jr., 1973, Ground-water resources of Morehouse Parish, Louisiana: Department of Conservation, Louisiana Geological Survey, and Louisiana Department of Public Works Water Resources Bulletin No. 19, 90 p.

Saucier, R.T., 1967, Geological investigation of the Boeuf-Tensas Basin lower Mississippi Valley: U.S. Army Corps of Engineers Waterways Experiment Station Technical Report No. 3-757.

Smoot, C.W., 1986, Louisiana hydrologic atlas map no. 2: Areal extent of freshwater in major aquifers of Louisiana: U.S. Geological Survey Water-Resources Investigations Report 86-4150, map (1 sheet).

-----1989, Louisiana hydrologic atlas map no. 4: Geohydrologic sections of Louisiana: U.S. Geological Survey Water-Resources Investigations Report 87-4288, map (1 sheet).

Snead, J.I., and McCulloh, R.P., 1984, Geologic map of Louisiana: Louisiana Geological Survey, map (1 sheet).

U.S. Environmental Protection Agency, 1992, Final rule, National primary and secondary drinking water regulations--Synthetic organic chemicals and inorganic chemicals (sections 141.12, 141.32, 141.50, 141.51, 141.61, 141.62 of part 141, and 143.3 of part 143) U.S. Federal Register, v. 57, no. 138, July 17, 1992, p. 31, 776-31, 849.

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

Whitfield, M.S., Jr., 1975, Geohydrology and water quality of the Mississippi River alluvial aquifer, northeastern Louisiana: Louisiana Department of Public Works Water Resources Technical Report No. 10, 29 p.

Whittemore, D.O., 1988, Bromide as a tracer in ground water studies: Geochemistry and analytical determination, *in* Proceedings of the Ground Water Geochemistry Conference, Denver, Colorado: National Water Well Association, Dublin, Ohio, p. 339-360.

Willey, L.M., Kharaka, Y.K., Presser, T.S., Rapp, J.B., and Barnes, Ivan, 1975, Short chain aliphatic acid anions in oil field waters and their contribution to the measured alkalinity: Geochimica et Cosmochimica Acta, v. 39, no. 12, p. 1707-1711.

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

Winslow, A.G., Hillier, D.E., and Turcan, A.N., Jr., 1968, Saline ground water in Louisiana: U.S. Geological Survey Hydrologic Investigations Atlas HA-310, 4 sheets.

Wood, W.W., 1976, Guidelines for collection and field analysis of ground-water samples for selected unstable constituents: U.S. Geological Survey Techniques of Water-Resources Investigations, book 1, chap. D2, 24 p.

Zimmerman, R.K., 1992, Fractured Smackover limestone in northeast Louisiana; implications for hydrocarbon exploitation: Gulf Coast Association of Geological Societies Transactions, v. 42, p. 401-412.

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