BRINE CONTAMINATION OF GROUND WATER IN THE VICINITY OF THE BROOKHAVEN OIL FIELD, LINCOLN COUNTY, MISSISSIPPI

By Larry J. Slack, Charles G. O'Hara, and William T. Oakley

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CONVERSION FACTORS AND WATER-QUALITY INFORMATION

Multiply	By	To obtain
barrel	0.1590	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft	0.09290	cubic meter per day per square meter times meter of aquifer thickness
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
gallon per day (gal/d)	0.003785	cubic meter per day
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

To convert degrees Celsius (°C) to degrees Fahrenheit (°F), use the following:

$$°C = 5/9\ (°F-32)$$

Specific conductance is reported in microsiemens per centimeter at 25 °C (µS/cm); pH, in standard units. Chemical concentrations are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams and micrograms per liter are units expressing the weight of solute per volume of water. One thousand micrograms per liter is equivalent to 1 mg/L. For concentrations less than 7,000 mg/L, milligrams per liter are equivalent to parts per million.

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ABSTRACT

During 1993-94, chloride concentrations in ground water in the vicinity of the Brookhaven oil field in northwestern Lincoln County, Mississippi, ranged from 2.5 to 9,400 mg/L (milligrams per liter). Water from 89 (50 percent) of 177 wells was considered contaminated by brine--that is, had chloride concentrations greater than 20 mg/L. However, the chloride concentrations in water from only 12 of the wells (7 percent) sampled during this study were greater than the recommended secondary limit for drinking water (250 mg/L).

From 1981-84 to 1993-94, the chloride concentration increased significantly (was greater than 20 mg/L and increased at least 2.0 mg/L) at 23 of 81 sites. During the same period, the chloride concentration decreased significantly (was greater than 20 mg/L and decreased at least 2.0 mg/L) at 20 sites. The largest chloride increase (2,240 mg/L) and decrease (500 mg/L) were at shallow wells, 45 and 120 feet deep, respectively.

INTRODUCTION

Large quantities of brine are withdrawn in conjunction with the production of petroleum. Since 1939, when petroleum production began in Mississippi, disposal of brine has resulted in brine contamination of ground water and streams. In the early years of oil production in Mississippi, brine was discharged onto the ground or into nearby streams. Later, in an effort to avoid surface-water contamination, producers pumped brine into evaporation ponds or pits. These disposal practices led to the brine contamination of shallow ground water. In 1978, these disposal methods were prohibited in the State (Mississippi State Oil and Gas Board, 1985). Most of the brine produced in the Brookhaven oil field is reinjected into the deep (greater than 4,000 ft) oil producing formations (Smith and others, 1988).

Information about the extent and the movement of the brine contamination and the constituents that the brine contains is useful to residents in the vicinity of the Brookhaven oil field who use ground water and to water-resource planners and managers. From August 1993 to December 1994, the U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (EPA), collected water-quality data as part of a basic research study to determine the extent of brine contamination in the vicinity of the Brookhaven oil field in southwestern Mississippi.

Background

The Brookhaven oil field is west of Brookhaven in northwestern Lincoln County, Mississippi (fig. 1) . Oil production in the field began on March 10, 1943. Annual production exceeded 1 million barrels by 1946 and reached a maximum of 5.25 million barrels in 1949. Annual production gradually decreased to less than 1 million barrels in 1973 and to less than 200,000 barrels in 1983. Annual production has averaged about 124,000 barrels for the last 10 years (1985-94) and has averaged only about 114,000 barrels for the last 5 years (1990-94). In 1994, production was about 111,000 barrels. Cumulative production of the Brookhaven oil field through 1994 was about 72,976,000 barrels. (All oil and brine production data are from the Mississippi State Oil and Gas Board annual reports published in 1944-95.)

During the initial development of oil reservoirs in the Brookhaven oil field, relatively little brine in proportion to oil was brought to the surface. For example, the brine-to-oil ratio was less than 0.5 until 1957. As oil is removed, formation water (brine) fills the pore spaces vacated by the oil, and subsequent pumping produces brine with the oil. Consequently, the brine-to-oil ratio increased to 1.0 by 1964. In 1967, brine production reached a maximum of more than 6 million barrels and the brine-to-oil ratio increased to 5.6. By 1967, however, the brine-to-oil ratio decreased to about 1.5. For the last 10 years (1985-94), annual brine production has averaged about 550,000 barrels, and the brine-to-oil ratio has averaged about 4.4. For the last 5 years (1990-94), annual brine production has averaged about 444,000 barrels, and the brine-to-oil ratio has averaged about 3.9. In 1994, brine production was about 385,000 barrels, and the brine-to-oil ratio was about 3.5. From 1943 to the end of 1994, cumulative brine production was about 60,561,000 barrels, and the overall ratio of brine to oil produced was about 0.83.

Purpose and Scope

This report defines the extent of brine contamination in shallow ground water in the vicinity of the Brookhaven oil field. The report is based largely on chemical analyses of water samples collected from selected wells during the period August 1993 through December 1994. The water-quality data are listed and summarized, maps showing the extent of brine contamination are presented, and the chloride data are compared with chloride data from a previous study by Kalkhoff (1986).

Previous Investigations

Previous investigations of the water quality in the vicinity of the Brookhaven oil field, Lincoln County, or the region were conducted by Newcome and Thomson (1970), and Kalkhoff (1985, 1986). Water-quality data for six samples collected between 1951 and 1968 from municipal water-supply wells completed in the Citronelle aquifer in Brookhaven were reported by Newcome and Thomson (1970), who also describe the general geology of Lincoln County. The geology and hydrology of the Citronelle aquifers statewide were described by Boswell (1979). Water-quality samples were collected in 1981 and 1982 from 10 wells in the Brookhaven oil field as part of a reconnaissance of major oil producing areas in Mississippi by Kalkhoff (1985). Lastly, Kalkhoff (1986) discussed in detail brine contamination of ground water and streams in the study area during the period from October 1983 to September 1984.

DESCRIPTION OF THE STUDY AREA

Location and Topography

The 100-mi^2 study area is located in northwestern Lincoln County, Mississippi (figs. 1-4). The Brookhaven oil field (approximately 15 mi^2) lies entirely within the study area. The study area is in the Pine Hills physiographic district, which Cross and Wales (1974) characterized as having a high and rolling land surface with moderately high ridges forming divides between streams. However, streams in the western and northern parts of the study area have eroded the land surface into narrow steep-sloped ridges (Kalkhoff, 1986). Land in the study area is used primarily for crops and pastures or is wooded; most homes are in the southern one-half of the study area (Perry Brumfield, Lincoln County Cooperative Extension Service Agent, oral commun., 1994). Part of the land in Brookhaven oil field is used for roads, well sites, storage tanks, pipelines, and other facilities related to oil production.

Geology

The geologic units that crop out or are present in the shallow subsurface in the study area consist of unconsolidated sediments of sand, clay, and gravel deposits which range in age from Miocene to Holocene (Newcome and Thomson, 1970). The geologic units, from oldest to youngest, are the undifferentiated Hattiesburg Formation of the Miocene Series, the Citronelle Formation of the Pliocene Series, and the Quaternary deposits that consist of loess and alluvium (Kalkhoff, 1986).

Sediments of the undifferentiated Hattiesburg Formation form the upper part of the Miocene Series in this area and are the oldest and deepest units investigated in this study (Newcome, 1975). Although these units consist mainly of silty clay with minor amounts of sand, some extensive sand units are present in these sediments in the study area (Kalkhoff, 1986). In this report, the undifferentiated Hattiesburg Formation is considered one unit and is included in the Miocene Series. The undifferentiated strata consist of several distinct sand layers separated by clay and silt.

Generalized geologic sections A-A' and B-B' in the study area (fig. 5) were prepared by Kalkhoff (1986) "from drillers logs supplied by water-well drillers and from electric [resistivity] logs made in oil test holes." Kalkhoff (1986) also prepared a third geologic section, C-C', which is not shown in this report but which was referred to in his description of the geology of the study area (p. 9):

> Bicker (1969, p. 29) states that unweathered material from the Hattiesburg Formation contains clays that are gray, grayish brown, and blue. These weather rapidly to a greenish-gray color. On the basis of this description all sands deeper than the first reported blue or gray clay shown on drillers logs were assumed to be sands of the Hattiesburg Formation.
>
> The Hattiesburg Formation in the study area consists of discontinuous sands separated by confining layers. The sands are fine to coarse grained and the confining layers are made up of silt and clay. Three sands are identified as separate units (layers A, B, and C) * * * because the layers appear to be three discrete mapable units in the study area. They range in thickness from less than 10 to more than 90 ft and generally dip to the south at approximately 20 to 30 ft/mi. A westward dipping component to the sand layers is apparent as the corresponding sands in section B-B' are approximately 10 ft higher in altitude than in section C-C'.

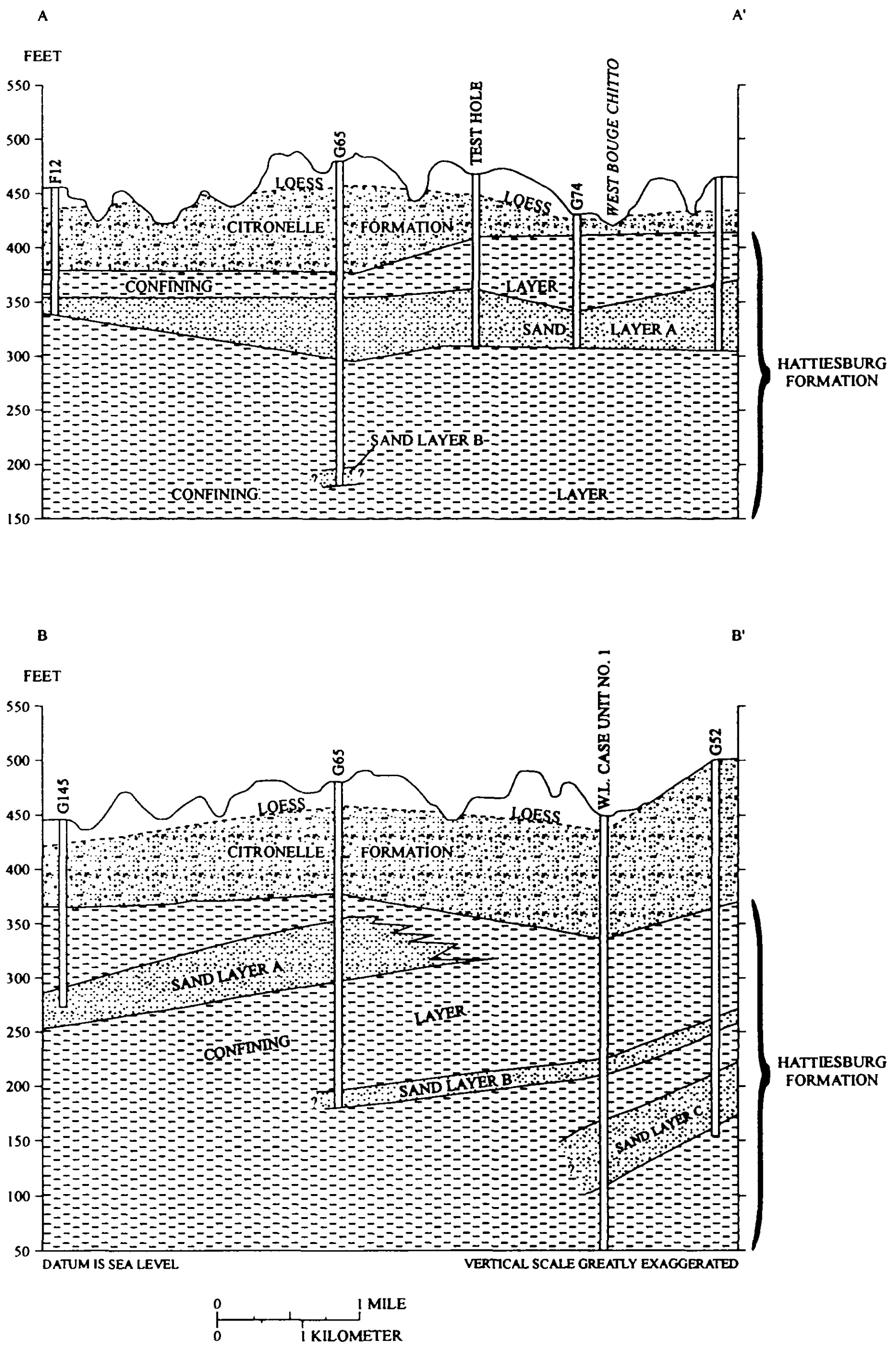

Figure 5. Generalized geologic sections A-A' and B-B' in the vicinity of the Brookhaven oil field in northwestern Lincoln County, Mississippi (from Kalkhoff, 1986).

In describing the Citronelle Formation, Kalkhoff (1986, p. 12) stated the following:

> Overlying the Hattiesburg Formation and exposed at places on the surface is the Citronelle Formation. The Citronelle Formation consists of discontinuous sand and gravel units separated by sandy clay lenses. Generally the thickest gravel layers are present in the basal part of the formation and the upper part is made up of sandy clay.
>
> The base of the Citronelle ranges from an altitude of 440 ft above sea level at the northern limit of the study area to an altitude of 370 ft at the southern boundary. Through the study area, the base of the Citronelle dips at a rate of approximately 9.5 ft/mi, slightly greater than the average regional dip of the formation reported by Boswell (1979). In the study area the Citronelle gradually thickens southward, ranging in thickness from approximately 40 ft in the north to over 100 ft in the central part of the oil field.

Hydrology

Two major sources of water in the study area are the Citronelle aquifer and the Miocene aquifer system. The Citronelle aquifer consists primarily of the sand and gravel units in the Citronelle Formation (Boswell, 1979) that contain sufficient saturated permeable material to yield significant quantities of water to wells. Similarly, the Miocene aquifer system consists primarily of the sand units in the Miocene Series (Newcome, 1975). The locations of wells for which water-quality data are used in this study are listed in table 1 and are shown in figures 1 and 3 (wells with depths of 120 ft or less) and in figures 2 and 4 (wells with depths greater than 120 ft).

Citronelle Aquifer

Water in the Citronelle aquifer in the study area originates from precipitation that percolates through the unsaturated soil to the water table. Water in the aquifer moves laterally and discharges into nearby streams or moves downward into the underlying Miocene aquifer system. Water-level data for the Citronelle aquifer were not collected during the 1993-94 study. However, water-level measurements made in May 1984 indicate that the water-table surface of the Citronelle aquifer in the Brookhaven oil field slopes generally to the south and southwest (Kalkhoff, 1986). The direction and rate of water movement are dependent on lithologic and hydraulic characteristics of the aquifer. Few data on the hydraulic properties of the Citronelle aquifer are available, but the results of aquifer tests on two shallow wells at Brookhaven indicate that the transmissivity of the aquifer is about 4,000 to 5,300 $[(ft^3/d)/ft^2]ft$. [The term $[(ft^3/d)/ft^2]ft$ is hereafter reduced to ft^2/d, or feet squared per day.] The hydraulic conductivity is about 82 to 200 ft/d (Slack and Darden, 1991).

Miocene Aquifer System

Water in the shallowest parts of the Miocene aquifer system originates as infiltration from the overlying Citronelle aquifer, as infiltration from terrace and alluvial deposits in the valleys outside the study area, and as direct infiltration from rainfall where Miocene sediments crop out. The potentiometric surface of sand layer A in the Hattiesburg Formation in the southern part of the study area, based on limited (nine) water-level measurements in May 1984, slopes generally to the south (Kalkhoff, 1986). Kalkhoff reported that the potentiometric surface of sand layer A "and the water-table surface of the Citronelle aquifer are at the same altitude" in the northern part of the study area. The similar potentiometric surfaces "may indicate that the two aquifers are hydraulically connected in this area." Southward, however, the potentiometric surface of sand layer A is lower than the water-table surface of the Citronelle aquifer, indicating the two aquifers are hydraulically separated.

Few data on the hydraulic properties of the Miocene aquifer system in the study area are available. However, the results of aquifer tests on three wells at Brookhaven, one well a few miles north of Brookhaven, and one well at Bogue Chitto (not shown) indicate that the transmissivity of the aquifer ranges from 620 to 7,200 ft^2/d (median transmissivity, 5,700 ft^2/d), and the hydraulic conductivity of the aquifer ranges from 20 to 140 ft/d (median conductivity, 71 ft/d) (Slack and Darden, 1991).

STUDY METHODS

Water samples were collected and analyzed to identify oil-field-brine contamination in shallow ground water in the vicinity of the Brookhaven oil field. First preference in site selection was wells included in the 1983-84 study by Kalkhoff (1986). Secondary preference was wells currently in use or wells recently in use. Analyses of water analyses collected during this study were compared to water-quality data collected during previous investigations.

Water samples were collected and analyzed from 177 wells (table 1; figs. 1-4). Water from 141 wells (80 percent) is used for domestic purposes. Water from the remaining 36 wells (20 percent) is unused.

Water samples were collected and analyzed to determine concentrations of sodium, chloride, barium, and strontium, which often occur in relatively large concentrations in oil-field brines. To obtain samples that closely represent ground water from the water-bearing unit, most of the wells were pumped prior to sampling long enough to withdraw at least twice the volume of water in the casing. Water from 26 wells was collected with a point sampler which was opened at the bottom of a 2-in.-diameter test hole. The test holes were punched by the Corps of Engineers using a cone

Table 1. Site information for selected wells in Lincoln County, Mississippi
[CRNL, Citronelle aquifer; MOCN, Miocene aquifer system]

Site number	Local number	Well owner or operator	Latitude	Longitude	Depth of well (feet)	Aquifer unit code
1	B37	Ronald Durr	31°37'31"	90°37'00"	152	MOCN
2	B48	Raymond Bowman	31°37'01"	90°33'07"	80	CRNL
3	C17	C L Dunn	31°36'53"	90°29'02"	50	CRNL
4	C18	Vicki Kinsey	31°36'52"	90°29'17"	65	CRNL
5	C19	T Smith	31°37'22"	90°29'58"	63	CRNL
6	C20	Odee Smith	31°37'55"	90°30'33"	100	CRNL
7	C21	Zeanni Hunt	31°38'58"	90°31'14"	40	CRNL
8	C22	J W Hunter	31°38'50"	90°31'25"	200	MOCN
9	C24	James E Smith	31°38'27"	90°30'33"	49	CRNL
10	C25	Claude Britt	31°37'48"	90°30'05"	60	CRNL
11	C28	Elmer Cockeram	31°38'24"	90°32'45"	200	MOCN
12	C29	Neil Lewis	31°37'05"	90°30'02"	80	CRNL
13	C31	Herman Smith	31°37'16"	90°30'11"	60	CRNL
14	C32	Kirby Humphreys	31°37'06"	90°31'22"	100	CRNL
15	C34	Evonne Maxwell	31°37'09"	90°31'37"	100	CRNL
16	C35	Jerry Bullock	31°37'14"	90°30'15"	70	CRNL
17	C36	Ed B Smith	31°37'00"	90°30'44"	30	CRNL
18	C37	Ricky Smith	31°37'09"	90°30'09"	75	CRNL
19	C45	Clarence Allen	31°37'33"	90°32'20"	28	CRNL
20	C49	J B Smith	31°37'18"	90°30'06"	87	CRNL
21	C51	J R Leming	31°37'32"	90°29'27"	115	MOCN
22	C52	Wayne Boyd	31°38'08"	90°30'38"	61	CRNL
23	C53	Howard Williams	31°38'46"	90°27'03"	90	CRNL
24	C55	Benjie Smith	31°37'12"	90°30'05"	87	CRNL
25	C58	Ford Crane	31°38'26"	90°28'02"	64	CRNL
26	C61	Henry Wallace	31°36'44"	90°26'53"	89	CRNL
27	C62	Roland Ross	31°37'27"	90°27'48"	60	CRNL
28	F20	Jack B Smith	31°35'50"	90°33'42"	85	MOCN
29	F21	Johnie Watts	31°33'19"	90°33'11"	80	CRNL
30	F24	R H Williams	31°36'29"	90°33'10"	87	CRNL
31	F27	Percy Wilson	31°34'19"	90°33'15"	98	CRNL
32	F28	Wessie C Wiltch	31°34'18"	90°33'17"	60	CRNL
33	F38	Jaudon Smith	31°32'58"	90°34'34"	72	CRNL
34	F39	Ruth Watts	31°32'05"	90°35'39"	80	CRNL
35	F40	Steve Case	31°31'27"	90°33'37"	120	CRNL

Table 1. Site information for selected wells in Lincoln County, Mississippi--Continued

Site number	Local number	Well owner or operator	Latitude	Longitude	Depth of well (feet)	Aquifer unit code
36	F41	Paul B Smith	31°35'04"	90°34'42"	80	CRNL
37	F44	Dykes A Britt	31°35'48"	90°32'56"	70	CRNL
38	F48	Annie B Case	31°36'14"	90°35'14"	67	CRNL
39	G25	Bryant Johnston	31°36'20"	90°29'56"	150	MOCN
40	G57	Steve McFadden	31°33'52"	90°31'39"	91	CRNL
41	G58	Harry Case	31°35'12"	90°31'47"	80	CRNL
42	G59	Elvin Smith	31°35'23"	90°31'16"	76	CRNL
43	G60	Cecil Case	31°35'36"	90°32'03"	100	CRNL
44	G61	Robert Falvey	31°35'42"	90°31'52"	85	CRNL
45	G62	Robert Falvey	31°35'41"	90°31'53"	45	CRNL
46	G63	Carol A Watts	31°34'32"	90°31'27"	65	CRNL
47	G66	Betty Warren	31°36'18"	90°32'10"	48	CRNL
48	G67	H R Owens	31°34'34"	90°31'55"	150	MOCN
49	G68	Aaron Achord	31°33'45"	90°31'22"	308	MOCN
50	G69	David Ballard	31°35'12"	90°31'51"	85	CRNL
51	G71	Rayburn Bowman	31°36'23"	90°32'11"	256	MOCN
52	G72	Dale Smith	31°36'29"	90°29'22"	80	CRNL
53	G73	S W Lee	31°36'21"	90°29'50"	120	CRNL
54	G74	Jack Hostetler	31°33'35"	90°29'56"	120	MOCN
55	G75	Gene Simmons	31°33'38"	90°29'55"	100	MOCN
56	G76	V Segars	31°36'14"	90°29'43"	100	CRNL
57	G77	Gary Norton	31°36'17"	90°29'38"	100	CRNL
58	G79	Marvin L Case	31°36'14"	90°29'01"	75	CRNL
59	G80	Vivian Smith	31°35'53"	90°29'28"	118	CRNL
60	G82	Clyde Norton	31°36'03"	90°29'33"	45	CRNL
61	G83	Jimmy D Smith	31°35'52"	90°29'25"	50	CRNL
62	G85	Steven R Sartin	31°36'28"	90°31'01"	100	CRNL
63	G86	M R Smith	31°36'25"	90°31'09"	65	CRNL
64	G87	Jimmie S Reeves	31°36'12"	90°31'11"	60	CRNL
65	G88	Willis Smith	31°35'58"	90°31'15"	80	CRNL
66	G89	Charles E Maxwell	31°36'29"	90°30'39"	50	CRNL
67	G91	Robert Watts	31°32'27"	90°32'27"	106	CRNL
68	G95	Glen Thompson	31°33'41"	90°30'31"	30	CRNL
69	G97	David Wilcher	31°33'45"	90°32'21"	175	MOCN
70	G99	Doug Warren	31°34'29"	90°31'31"	48	CRNL

Table 1. Site information for selected wells in Lincoln County, Mississippi--Continued

Site number	Local number	Well owner or operator	Latitude	Longitude	Depth of well (feet)	Aquifer unit code
71	G100	Earl Case	31°35'18"	90°31'42"	90	CRNL
72	G106	Jesse Warren	31°33'58"	90°31'55"	92	CRNL
73	G107	Billy Reed	31°34'46"	90°32'07"	120	CRNL
74	G109	Willie C Case	31°35'44"	90°31'21"	79	CRNL
75	G110	Charles W Smith	31°35'59"	90°30'46"	100	CRNL
76	G114	Charles Case	31°35'40"	90°32'05"	84	CRNL
77	G117	W Buddy Case	31°35'52"	90°32'49"	73	CRNL
78	G118	Eugene Case	31°34'08"	90°31'54"	69	CRNL
79	G119	Hosie Smith	31°35'45"	90°31'27"	98	CRNL
80	G120	Randy Britt	31°35'53"	90°31'24"	85	CRNL
81	G123	Case Grocery	31°35'23"	90°31'09"	75	CRNL
82	G127	Francis M Case	31°35'34"	90°32'21"	70	CRNL
83	G131	John Pounds	31°35'22"	90°30'13"	200	MOCN
84	G133	Rosy Reed	31°34'44"	90°31'46"	120	CRNL
85	G134	Sherry Spencer	31°34'53"	90°31'55"	50	CRNL
86	G135	W C Little	31°34'59"	90°31'50"	140	MOCN
87	G137	Maurice L Case	31°35'31"	90°32'23"	75	CRNL
88	G138	Dallas Anding	31°35'31"	90°32'44"	85	CRNL
89	G139	Curtis Nations	31°35'35"	90°32'25"	93	CRNL
90	G140	Winnie Smith	31°35'39"	90°32'44"	80	CRNL
91	G142	T Banks	31°34'37"	90°29'41"	40	CRNL
92	G143	Harold Case	31°33'40"	90°31'57"	80	CRNL
93	G144	Paul M Lewis	31°33'36"	90°30'59"	75	CRNL
94	G148	W B Eastley	31°32'40"	90°29'42"	68	CRNL
95	G151	Charlie Middleton	31°34'49"	90°29'13"	180	MOCN
96	G152	Mary Manning	31°33'37"	90°30'50"	165	MOCN
97	G161	John W Smith	31°33'34"	90°30'13"	62	CRNL
98	G162	Bolivar Coke	31°34'33"	90°31'52"	128	CRNL
99	G163	T S Webb	31°34'25"	90°28'50"	87	CRNL
100	G165	D R Herndon	31°35'03"	90°30'09"	114	MOCN
101	G169	Donald McCullough	31°36'25"	90°30'24"	115	CRNL
102	G175	Stanley Smith	31°32'17"	90°29'33"	70	CRNL
103	G177	Herman Smith	31°34'01"	90°31'15"	120	CRNL
104	G178	Sam C Smith	31°36'31"	90°31'21"	60	CRNL
105	G180	Aaron Achord	31°33'49"	90°31'22"	147	CRNL

Table 1. Site information for selected wells in Lincoln County, Mississippi--Continued

Site number	Local number	Well owner or operator	Latitude	Longitude	Depth of well (feet)	Aquifer unit code
106	G181	Bobby Moore	31°34'01"	90°31'09"	150	CRNL
107	G182	John Jordan	31°33'56"	90°31'19"	148	CRNL
108	G186	Buddy Price	31°33'55"	90°31'38"	150	MOCN
109	G208	V L Day	31°33'44"	90°31'23"	160	MOCN
110	G209	A C Lofton	31°33'57"	90°31'08"	120	MOCN
111	G210	A C Lofton	31°33'57"	90°31'08"	65	CRNL
112	G211	A C Lofton	31°33'58"	90°31'07"	125	MOCN
113	G212	Billy Reed	31°34'47"	90°32'01"	120	CRNL
114	G213	Leland Smith	31°33'49"	90°32'02"	80	CRNL
115	G214	Zetus Grocery	31°33'50"	90°31'44"	65	CRNL
116	G215	Clem B Smith	31°33'48"	90°31'55"	80	CRNL
117	G216	Truly Smith	31°35'44"	90°31'02"	68	CRNL
118	G217	Charles Cupit	31°33'41"	90°30'51"	60	CRNL
119	G218	Kenneth Williams	31°35'36"	90°30'41"	70	CRNL
120	G247	Joel Smith	31°34'25"	90°28'20"	160	MOCN
121	G258	Andy Cupit	31°33'57"	90°31'31"	145	CRNL
122	G262	Miss Highway Dept	31°32'45"	90°27'53"	160	MOCN
123	G267	John Allgood	31°33'43"	90°29'30"	113	MOCN
124	G268	Glynn C Smith	31°34'29"	90°32'03"	126	CRNL
125	G271	Andrew Sisung	31°35'28"	90°31'56"	66	CRNL
126	G272	Tommy Crum	31°33'52"	90°29'06"	58	CRNL
127	G275	Janice Thompson	31°35'27"	90°31'45"	84	CRNL
128	G276	Larry Warren	31°33'54"	90°32'07"	90	CRNL
129	G279	H S Woolley	31°35'12"	90°28'10"	85	CRNL
130	G283	Tony Lynn Smith	31°32'46"	90°32'50"	78	CRNL
131	G312	Larry McFadden	31°33'52"	90°31'36"	93	CRNL
132	G316	Randall Smith	31°33'47"	90°32'36"	160	CRNL
133	G324	Glynn C Smith	31°34'27"	90°31'57"	120	CRNL
134	G333	Dewayne Nevels	31°33'26"	90°30'13"	160	MOCN
135	G335	W G Sellers	31°33'04"	90°27'20"	180	MOCN
136	G337	Judy Patt	31°33'55"	90°31'57"	170	CRNL
137	G346	Clarence Hutson	31°33'34"	90°28'51"	170	MOCN
138	G354	Kenneth Smith	31°36'08"	90°31'06"	89	CRNL
139	G356	Richard Edwards	31°35'02"	90°32'04"	107	CRNL
140	G365	Margarite Smith	31°34'30"	90°31'40"	86	CRNL

Table 1. Site information for selected wells in Lincoln County, Mississippi--Continued

Site number	Local number	Well owner or operator	Latitude	Longitude	Depth of well (feet)	Aquifer unit code
141	G368	Bernice Smith	31°35'25"	90°31'33"	85	CRNL
142	G370	Bobby Reed	31°34'58"	90°31'52"	86	CRNL
143	G377	Ed Lambright	31°33'33"	90°30'16"	160	MOCN
144	G379	Donald Campbell	31°33'54"	90°28'50"	160	CRNL
145	G380	Betty Freeman	31°36'18"	90°32'11"	165	MOCN
146	G381	Roscoe Newton	31°33'47"	90°32'30"	93	CRNL
147	G382	Ed Lambright	31°33'33"	90°30'16"	58	CRNL
148	G383	Anna Littleton	31°35'57"	90°30'15"	57	CRNL
149	G403	Bailey Dunaway	31°35'24"	90°29'23"	110	CRNL
150	G404	Bailey Dunaway	31°35'48"	90°29'14"	40	CRNL
151	K35	John Newell	31°30'58"	90°34'50"	80	CRNL
152	C063	CP 27	31°37'12"	90°28'22"	30	CRNL
153	C064	CP 4	31°36'44"	90°28'18"	16	CRNL
154	C065	CP 28	31°38'11"	90°27'51"	57	CRNL
155	C066	CP 26	31°37'30"	90°28'19"	26	CRNL
156	C067	CP 22	31°39'05"	90°30'04"	45	CRNL
157	C068	CP 17	31°37'59"	90°31'12"	23	CRNL
158	C069	CP 66A	31°37'35"	90°31'05"	30	CRNL
159	C070	CP 30	31°38'31"	90°31'35"	67	CRNL
160	G385	CP C2	31°35'32"	90°29'29"	65	CRNL
161	G386	CP C4	31°35'32"	90°29'17"	65	CRNL
162	G387	CP C3	31°35'19"	90°29'28"	10	CRNL
163	G388	CP C5	31°35'11"	90°29'24"	73	CRNL
164	G389	CP G	31°35'42"	90°31'53"	45	CRNL
165	G390	CP A	31°35'36"	90°30'53"	52	CRNL
166	G391	CP B2	31°35'30"	90°30'44"	36	CRNL
167	G392	CP B3	31°35'19"	90°30'28"	50	CRNL
168	G393	CP 5	31°34'51"	90°30'28"	40	CRNL
169	G394	CP E	31°34'44"	90°30'30"	60	CRNL
170	G395	CP 41	31°34'29"	90°30'42"	65	CRNL
171	G396	CP 42	31°34'17"	90°30'41"	35	CRNL
172	G397	CP 7	31°34'46"	90°31'04"	57	CRNL
173	G398	CP 8	31°34'11"	90°31'30"	31	CRNL
174	G399	CP 67	31°33'52"	90°31'55"	80	CRNL
175	G400	CP 68B	31°34'02"	90°31'44"	77	CRNL
176	G401	CP 12	31°36'32"	90°31'36"	72	CRNL
177	G402	CP G	31°33'09"	90°31'53"	75	CRNL

penetrometer and a hydraulic press. The samples were analyzed at the USGS Water Resources Division Water-Quality Service Unit in Ocala, Florida.

Laboratory procedures used to analyze the water samples for this study were similar to the procedures used in the previous study by Kalkhoff (1986). The Water-Quality Service Unit used methods described by Fishman and Friedman (1989). The detection limits of these techniques are listed below.

WATSTORE code	Property or constituent	Method number	Detection limit
90095	Specific conductance (lab)	I-1780-84	1.0 μS/cm
00403	pH (lab)	I-1586-84	0.1 standard pH unit
00930	Sodium, dissolved	I-1735-85	0.1 mg/L
00940	Chloride, dissolved	I-2057-84	0.1 mg/L
01005	Barium, dissolved	I-1472-87	5.0 μg/L
01080	Strontium, dissolved	I-1472-87	2.0 μg/L

All the water-quality data are stored in WATSTORE, the National Water Data Storage and Retrieval System of the U.S. Geological Survey. The system resides on the central computer facilities of the USGS at its National Center in Reston, Virginia.

CHEMICAL QUALITY OF BRINE AND UNCONTAMINATED GROUND WATER

Analyses of three brine samples from the major oil-producing formation (the lower part of the Tuscaloosa Formation) in the Brookhaven oil field are summarized in table 2. The brine samples represent water between a depth of 10,340 to 10,510 ft. Sodium is the predominant cation and chloride the predominant anion in the water. Sodium concentrations ranged from 46,700 to 48,700 mg/L with a mean concentration of 48,000 mg/L. Chloride concentrations ranged from 95,900 to 100,100 mg/L with a mean concentration of 98,500 mg/L. The mean dissolved-solids concentration of the brine was about 160,300 mg/L. The sodium to chloride ratio in the brine was about 0.49. The brine contains relatively large concentrations of barium plus strontium (mean of 1,220 mg/L), constituents that normally occur in very small concentrations in shallow and moderately deep ground water and in streams.

Sodium is the predominant cation and chloride and bicarbonate are the predominant anions in uncontaminated water in the Citronelle aquifer in northwestern Lincoln County (Kalkhoff, 1986). Sodium concentrations ranged from 2.7 to 14 mg/L (median, 4.5 mg/L) for 10 samples collected during August-September 1984 (table 3). Chloride concentrations ranged from 3.4 to 21 mg/L (median, 5.9 mg/L). The sodium to chloride ratio ranged

Table 2. Summary of analyses of brine samples from the Brookhaven oil field, Lincoln County, Mississippi

[From Hawkins and others, 1963. Dissolved solids, stoichiometrical analysis; mg/L, milligrams per liter. All constituents dissolved]

Lower part of the Tuscaloosa Formation (3 samples)			
	Minimum	Mean	Maximum
Depth, in feet	10,340	10,420	10,510
Dissolved solids (mg/L)	156,700	160,300	162,600
Calcium (mg/L)	12,100	12,600	12,900
Magnesium (mg/L)	780	990	1,100
Sodium (mg/L)	46,700	48,000	48,700
Bicarbonate (mg/L)	0	26	77
Sulfate (mg/L)	0	98	160
Chloride (mg/L)	95,900	98,500	100,100
Barium and strontium (mg/L)	34	1,220	2,073
Sodium to chloride ratio	0.49	0.49	0.49

Table 3. Summary of water-quality data for uncontaminated ground water in the Citronelle aquifer in northwestern Lincoln County, Mississippi

[From Kalkhoff, 1986; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter. All constituents dissolved]

(10 samples)			
	Minimum	Median	Maximum
Depth, in feet	40	80	120
Specific conductance, (µS/cm)	25	44	86
pH	4.9	5.2	5.4
Sodium (mg/L)	2.7	4.5	14
Chloride (mg/L)	3.4	5.9	21
Barium (µg/L)	20	31	50
Strontium (µg/L)	6	10	20
Sodium to chloride ratio	0.57	0.80	1.03

from 0.57 to 1.03 mg/L (median, 0.80). A chloride concentration of 20 mg/L or less is considered background level for water from the Citronelle aquifer for purposes of this study. Kalkhoff concluded that, for the study area, water with a chloride concentration exceeding 20 mg/L and a sodium to chloride ratio of less than 0.60 probably is contaminated. Additional indicators of probable brine contamination, according to Kalkhoff, are a barium concentration greater than 50 µg/L and a strontium concentration greater than 20 µg/L.

Uncontaminated water in the Miocene aquifer system in the study area is quite similar to uncontaminated water in the Citronelle aquifer. Consequently, Kalkhoff (1986) concluded that, for the study area, indicators of probable brine contamination are the same as those for the Citronelle aquifer.

BRINE CONTAMINATION OF GROUND WATER

Disposal of brine by injection into formations containing water with dissolved-solids concentrations greater than 10,000 mg/L can adversely affect shallow ground-water quality, even though this practice is environmentally more acceptable than surface disposal. Brine may leak directly into shallow aquifers or move upward through the annular space outside the well casing of improperly constructed and maintained or deteriorated injection wells. Brine may also leak through the deteriorated casing of deep abandoned wells into shallow freshwater aquifers.

Brine Contamination during August 1993-December 1994

Water-quality data for the selected 177 ground-water samples collected during this study (August 1993-December 1994) from wells in northwestern Lincoln County are listed in table 4 and summarized in table 5. Sodium concentrations ranged from 2.2 to 3,700 mg/L (median, 14 mg/L). Chloride concentrations ranged from 2.5 to 9,400 mg/L (median, 21 mg/L). Water from 89 wells (50 percent) was considered contaminated by brine--that is, had chloride concentrations greater than 20 mg/L.

The chloride concentrations in water from only 12 wells (7 percent) sampled during this study were greater than 250 mg/L, which is the recommended secondary limit for drinking water (U.S. Environmental Protection Agency, 1986a, b). [The recommended limit for chloride in public water supplies is based largely on aesthetic reasons.]

Water-quality data in the following sections are discussed on the basis of depth below land surface rather than on the basis of aquifer. The primary reason for this is that, although there is some uncertainty from which aquifer the water samples originated for a few wells, water-level data indicate that the Citronelle and Miocene aquifers may be hydraulically connected in part of the study area (Kalkhoff, 1986).

The areal extent of brine contamination (chloride concentration equal to or greater than 20 mg/L) in shallow ground water (depth 120 ft or less) in the vicinity of the Brookhaven oil field during August 1993-December 1994 is

Table 4. Water-quality data for selected wells in Lincoln County, Mississippi (August 1993-December 1994)

[ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter. All constituents dissolved]

Site number	Local number	Date	Depth (ft)	Specific conductance (lab, µS/cm)	pH (lab, standard units)	Sodium (mg/L)	Chloride (mg/L)	Barium (µg/L)	Strontium (µg/L)
1	B37	090293	152	40	5.7	4.7	5.1	27	5
2	B48	012694	80	61	5.5	6.8	10	38	14
3	C17	011894	50	134	5.6	15	40	69	18
4	C18	011894	65	160	6.0	18	34	110	23
5	C19	090893	63	720	6.0	81	200	260	95
6	C20	011894	100	43	5.6	4.8	8.3	34	8
7	C21	020394	40	396	6.8	52	30	99	88
8	C22	011994	200	116	5.3	15	18	81	35
9	C24	011994	49	106	5.8	18	16	21	6
10	C25	011994	60	124	5.3	14	29	46	19
11	C28	011894	200	77	6.5	5.5	3.0	60	63
12	C29	011294	80	352	5.7	25	99	450	120
13	C31	012094	60	412	5.8	40	110	260	75
14	C32	012094	100	55	5.4	7.1	7.5	21	8
15	C34	011994	100	62	5.9	8.2	8.4	19	7
16	C35	090893	70	476	5.4	54	140	410	74
17	C36	012094	30	161	5.0	12	21	170	83
18	C37	012194	75	420	5.3	39	120	400	85
19	C45	011894	28	66	5.8	3.6	3.9	64	42
20	C49	090893	87	55	5.6	5.9	11	52	5
21	C51	012194	115	29	6.1	3.4	3.0	21	7
22	C52	011294	61	95	5.6	14	21	42	8
23	C53	020294	90	48	5.5	6.0	8.9	26	9
24	C55	011194	87	80	5.6	8.8	18	62	12
25	C58	020394	64	103	5.8	16	19	35	10
26	C61	011194	89	37	5.8	3.7	4.8	28	11
27	C62	011194	60	66	6.2	9.2	11	17	8
28	F20	012594	85	39	5.6	3.8	5.7	32	10
29	F21	012694	80	88	5.6	10	18	59	19
30	F24	012594	87	43	5.8	4.4	6.2	24	10
31	F27	012594	98	49	5.5	6.0	8.2	26	7
32	F28	012594	60	55	5.6	7.7	9.3	23	7
33	F38	012694	72	38	5.6	5.1	6.7	20	6
34	F39	012594	80	27	5.8	3.1	3.4	20	8
35	F40	012794	120	51	5.8	7.0	7.1	28	12

Table 4. Water-quality data for selected wells in Lincoln County, Mississippi (August 1993-December 1994)--Continued

Site number	Local number	Date	Depth (ft)	Specific conductance (lab, µS/cm)	pH (lab, standard units)	Sodium (mg/L)	Chloride (mg/L)	Barium (µg/L)	Strontium (µg/L)
36	F41	012694	80	28	5.7	2.2	3.6	27	10
37	F44	013194	70	128	5.4	15	31	77	25
38	F48	020494	67	33	5.5	3.3	4.1	19	5
39	G25	082093	150	66	6.1	7.1	5.5	42	25
40	G57	082793	91	60	5.8	8.0	11	39	<1
41	G58	013194	80	326	6.1	38	80	110	51
42	G59	012694	76	854	5.7	110	240	410	140
43	G60	122993	100	1,260	5.5	160	400	710	230
44	G61	122993	85	649	5.5	59	190	440	170
45	G62	010494	45	7,200	6.1	1,200	2,500	2,100	7,500
46	G63	012694	65	64	5.5	9.0	11	43	11
47	G66	020494	48	141	5.5	21	33	18	68
48	G67	082593	150	69	6.2	7.0	10	60	33
49	G68	122193	308	231	6.0	25	58	210	120
50	G69	020294	85	272	5.3	32	74	160	42
51	G71	082693	256	85	6.4	10	3.4	53	56
52	G72	082093	80	54	6.1	5.9	8.3	41	<1
53	G73	081993	120	50	6.0	6.2	5.3	38	<1
54	G74	082693	120	43	6.1	4.0	3.5	38	5
55	G75	082693	100	42	6.1	3.9	3.5	29	16
56	G76	081993	100	52	6.0	7.3	5.2	32	<1
57	G77	082093	100	161	5.5	21	41	65	10
58	G79	082093	75	98	6.2	8.8	12	43	20
59	G80	081993	118	121	5.8	14	28	78	18
60	G82	081993	45	104	5.4	13	25	45	4
61	G83	010494	50	316	5.4	41	94	130	60
62	G85	082693	100	257	5.8	37	55	97	16
63	G86	082693	65	256	5.9	39	59	83	22
64	G87	020294	60	35	5.5	4.2	4.5	28	7
65	G88	082793	80	36	5.5	4.8	6.6	19	<1
66	G89	083193	50	196	5.9	13	32	130	72
67	G91	013194	106	37	5.7	5.0	5.9	25	5
68	G95	020194	30	37	5.6	5.1	5.8	23	7
69	G97	020194	175	54	5.9	5.4	6.4	65	19
70	G99	020394	48	994	5.9	110	280	1,100	370

Table 4. Water-quality data for selected wells in Lincoln County, Mississippi (August 1993-December 1994)--Continued

Site number	Local number	Date	Depth (ft)	Specific conductance (lab, µS/cm)	pH (lab, standard units)	Sodium (mg/L)	Chloride (mg/L)	Barium (µg/L)	Strontium (µg/L)
71	G100	020394	90	276	5.5	37	74	150	40
72	G106	020394	92	271	6.7	33	50	44	40
73	G107	122193	120	720	5.6	110	210	420	160
74	G109	020194	79	292	5.9	38	66	82	33
75	G110	020194	100	97	5.8	10	18	73	21
76	G114	122993	84	1,900	5.4	260	590	1,100	530
77	G117	013194	73	106	5.4	13	26	72	21
78	G118	020394	69	187	6.0	27	39	43	51
79	G119	090893	98	134	5.9	17	32	73	15
80	G120	090893	85	256	5.9	36	57	61	21
81	G123	090193	75	365	5.3	56	100	140	56
82	G127	013194	70	642	5.4	82	180	320	110
83	G131	020394	200	2,750	5.2	280	860	2,800	1,200
84	G133	082593	120	50	6.2	5.3	5.1	44	10
85	G134	122193	50	74	5.8	13	14	23	6
86	G135	082593	140	46	6.2	5.0	5.0	32	12
87	G137	082593	75	354	5.6	42	96	150	56
88	G138	082693	85	367	5.5	40	99	190	65
89	G139	122993	93	291	5.5	37	87	130	45
90	G140	090193	80	437	5.2	52	120	250	140
91	G142	090193	40	24	5.6	2.9	3.4	17	<1
92	G143	122193	80	100	6.2	8.1	14	44	42
93	G144	090193	75	58	5.8	6.6	6.2	23	8
94	G148	021794	68	40	5.6	5.4	6.7	23	9
95	G151	022894	180	36	5.9	4.0	3.3	26	14
96	G152	022894	165	475	5.1	54	140	330	130
97	G161	030194	62	56	5.5	7.8	10	29	9
98	G162	030294	128	56	6.0	5.2	6.3	68	24
99	G163	022894	87	188	5.6	19	50	230	57
100	G165	030194	114	698	5.5	67	210	660	260
101	G169	022894	115	137	5.8	15	31	86	19
102	G175	083193	70	90	5.4	12	20	36	11
103	G177	082593	120	28	5.8	2.6	2.6	31	<1
104	G178	082793	60	32	5.6	3.7	4.2	34	<1
105	G180	082493	147	327	5.8	36	89	260	76

Table 4. Water-quality data for selected wells in Lincoln County, Mississippi (August 1993-December 1994)--Continued

Site number	Local number	Date	Depth (ft)	Specific conductance (lab, µS/cm)	pH (lab, standard units)	Sodium (mg/L)	Chloride (mg/L)	Barium (µg/L)	Strontium (µg/L)
106	G181	122993	150	267	5.7	31	78	220	140
107	G182	082493	148	31	5.9	3.3	5.3	40	5
108	G186	090193	150	45	6.2	4.7	4.5	100	16
109	G208	083093	160	2,500	5.2	320	800	2,500	1,200
110	G209	083093	120	1,530	4.9	380	460	400	1,400
111	G210	083093	65	4,860	5.7	700	1,600	3,300	2,500
112	G211	083093	125	168	5.8	15	41	190	81
113	G212	083193	120	301	5.4	34	82	230	55
114	G213	090193	80	365	6.0	44	95	110	96
115	G214	090193	65	963	5.8	130	290	400	400
116	G215	090193	80	127	5.9	18	25	42	8
117	G216	090193	68	432	6.1	67	120	120	33
118	G217	090293	60	744	5.1	94	220	470	200
119	G218	090293	70	352	5.4	51	99	200	49
120	G247	021794	160	133	6.0	22	24	27	10
121	G258	021894	145	46	6.1	3.8	3.7	75	17
122	G262	021494	160	51	6.1	4.7	4.4	54	25
123	G267	021494	113	46	6.1	4.6	3.7	61	18
124	G268	021594	126	70	5.9	6.9	12	74	31
125	G271	021594	66	99	5.7	12	22	49	14
126	G272	021494	58	98	5.5	12	21	62	19
127	G275	021594	84	109	5.8	14	24	61	15
128	G276	021594	90	113	6.0	16	22	31	19
129	G279	021694	85	38	5.8	3.8	4.6	33	8
130	G283	021594	78	27	5.6	2.5	2.5	36	12
131	G312	021694	93	156	5.6	19	39	59	21
132	G316	021794	160	46	5.8	5.7	6.4	32	9
133	G324	021594	120	47	5.7	5.0	5.2	36	24
134	G333	021694	160	45	5.9	4.9	5.1	44	18
135	G335	021694	180	51	6.1	5.7	4.9	57	18
136	G337	021494	170	717	5.9	69	200	380	150
137	G346	021694	170	31	5.8	3.0	2.6	31	14
138	G354	021794	89	58	5.7	9.1	11	32	8
139	G356	021894	107	134	5.6	16	33	81	22
140	G365	021794	86	366	5.1	45	100	260	100

Table 4. Water-quality data for selected wells in Lincoln County, Mississippi (August 1993-December 1994)--Continued

Site number	Local number	Date	Depth (ft)	Specific conductance (lab, µS/cm)	pH (lab, standard units)	Sodium (mg/L)	Chloride (mg/L)	Barium (µg/L)	Strontium (µg/L)
141	G368	030294	85	148	5.5	23	37	42	10
142	G370	021894	86	329	5.4	46	94	170	38
143	G377	021494	160	46	6.0	5.0	5.1	37	20
144	G379	011294	160	29	5.9	2.9	2.7	29	10
145	G380	020494	165	85	6.3	14	3.1	32	28
146	G381	030294	93	89	5.7	13	19	28	9
147	G382	030294	58	127	5.8	14	27	46	66
148	G383	030294	57	73	5.6	8.2	12	26	16
149	G403	120894	110	51	6.1	5.1	7.2	--	--
150	G404	120894	40	99	6.2	16	18	--	--
151	K35	010494	80	97	6.0	15	13	34	19
152	C63	101394	30	115	6.2	20	24	--	--
153	C64	102794	16	95	6.3	12	12	--	--
154	C65	101294	57	131	6.4	20	23	--	--
155	C66	102594	26	112	6.2	16	19	--	--
156	C67	102494	45	138	6.4	22	24	--	--
157	C68	102094	23	178	6.1	22	29	--	--
158	C69	102094	30	207	6.4	23	42	--	--
159	C70	110794	67	158	6.4	21	27	--	--
160	G385	101994	65	116	7.0	9.5	8.7	--	--
161	G386	101994	65	101	6.8	8.7	11	--	--
162	G387	101894	10	217	7.2	14	7.8	--	--
163	G388	101894	73	67	6.6	6.1	6.6	--	--
164	G389	110394	45	822	6.2	160	230	--	--
165	G390	110394	52	154	6.5	28	30	--	--
166	G391	102694	36	1,360	6.4	190	400	--	--
167	G392	102694	50	79	6.4	9.6	9.6	--	--
168	G393	103194	40	476	6.1	64	63	--	--
169	G394	110294	60	25,000	5.1	3,700	9,400	--	--
170	G395	110294	65	433	6.1	49	120	--	--
171	G396	110294	35	53	6.8	4.3	6.6	--	--
172	G397	110194	57	162	6.1	18	38	--	--
173	G398	110194	31	75	6.2	11	12	--	--
174	G399	101794	80	118	6.5	17	23	--	--
175	G400	110894	77	1,120	6.1	140	330	--	--
176	G401	110894	72	66	6.1	8.7	11	--	--
177	G402	110994	75	122	6.5	21	24	--	--

Table 5. Summary of water-quality data for selected wells in Lincoln County, Mississippi (August 1993-December 1994)

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter. All constituents dissolved]

	Minimum	Median	Maximum
Shallow wells (146 samples)			
Depth, in feet	10	75	120
Specific conductance, lab (µS/cm)	24	117	25,000
pH, lab	4.9	5.8	7.2
Sodium (mg/L)	2.2	15	3,700
Chloride (mg/L)	2.5	24	9,400
Barium (µg/L)	17	50	3,300
Strontium (µg/L)	<1	19	7,500
Deep wells (31 samples)			
Depth, in feet	125	160	308
Specific conductance, lab (µS/cm)	29	66	2,750
pH, lab	5.1	5.9	6.5
Sodium (mg/L)	2.9	5.7	320
Chloride (mg/L)	2.6	5.5	860
Barium (µg/L)	26	60	2,800
Strontium (µg/L)	5	25	1,200
All wells (177samples)			
Depth, in feet	10	80	308
Specific conductance, lab (µS/cm)	24	106	25,000
pH, lab	4.9	5.8	7.2
Sodium (mg/L)	2.2	14	3,700
Chloride (mg/L)	2.5	21	9,400
Barium (µg/L)	17	57	3,300
Strontium (µg/L)	<1	19	7,500

shown in figure 3. Although water from 80 (55 percent) of 146 shallow wells was contaminated, water from only 10 (7 percent) of the shallow wells had chloride concentrations greater than 250 mg/L.

The areal extent of brine contamination (chloride concentration equal to or greater than 20 mg/L) in deep ground water (depth greater than 120 ft) in the vicinity of the Brookhaven oil field during August 1993-December 1994 is shown in figure 4. Although water from 25 (81 percent) of 31 deep wells was contaminated, water from only 2 (6 percent) of the deep wells had chloride concentrations greater than 250 mg/L.

Change in Brine Contamination from 1981-84 to 1993-94

During 1993-94, ground-water-quality samples were collected at 81 sites that were sampled during 1981-84. The chloride concentrations for the 1981-84 and 1993-94 study periods and changes in chloride concentrations between the two periods are listed in table 6.

Analyses indicated that between 1981-84 and 1993-94, the chloride concentration increased at some sites and decreased at others due to the movement of brine in the area. Some of the decreases in chloride concentration likely reflect dilution by freshwater recharge by local rainfall. Furthermore, regionally, the total amount of brine in the shallow ground-water system is likely decreasing because of the regional discharge of the shallow ground water to streams. This conclusion is based on reports that significant quantities of brine are no longer being introduced into the ground-water system.

From 1981-84 to 1993-94, the largest chloride increase (2,240 mg/L) was at a shallow well (45 ft deep) completed in the Citronelle aquifer (in the western part of the oil field), but the next largest increase (851 mg/L) was at a moderately deep well (200 ft deep) completed in the Miocene aquifer system (in the eastern part of the oil field).

From 1981-84 to 1993-94, the chloride concentration increased significantly (was greater than 20 mg/L and increased at least 2.0 mg/L) at 23 (28 percent) of 81 sites. All but one well with significant increases in chloride concentration are within the Brookhaven oil field. The one exception (well 3) is located about 2 mi east of the oil field. Only three sections have two or more wells with large (greater than 20 mg/L) increases in chloride concentration. Two of these sections, T. 7 N., R. 7 E., sec. 7 and 8, are in the west-central part of the oil field. The other section, T. 8 N., R. 7 E., sec. 33, is in the northeastern part of the oil field.

From 1981-84 to 1993-94, the chloride concentration decreased significantly (was greater than 20 mg/L and decreased at least 2.0 mg/L) at 20 (25 percent) of 81 sites. Most wells with significant decreases in chloride concentration are in the southern two-thirds of the oil field or are southwest of the oil field. Nine wells had large (greater than 20 mg/L) decreases in chloride concentration; eight of these wells are in the oil field. The largest

Table 6. Change in chloride concentrations in ground water in the vicinity of the Brookhaven oil field, Lincoln County, Mississippi (1981-84 to 1993-94)
[CRNL, Citronelle aquifer; MOCN, Miocene aquifer system; ft, feet; mg/L, milligrams per liter. Bold data indicate sites with significant chloride changes--at least one chloride concentration exceeded 20 mg/L and the change was at least 2.0 mg/L]

Site number	Local number	Aquifer unit code	Depth (ft)	Year	Chloride (mg/L)	Year	Chloride (mg/L)	Chloride change (mg/L)
3	**C17**	**CRNL**	**50**	**1983**	**21**	**1994**	**40**	**19**
4	**C18**	**CRNL**	**65**	**1983**	**42**	**1994**	**34**	**-8.0**
5	**C19**	**CRNL**	**63**	**1983**	**170**	**1993**	**200**	**30**
6	C20	CRNL	100	1983	4.7	1994	8.3	3.6
7	**C21**	**CRNL**	**40**	**1983**	**7.5**	**1994**	**30**	**22**
8	C22	MOCN	200	1983	8.5	1994	18	9.5
9	C24	CRNL	49	1983	13	1994	16	3.0
10	**C25**	**CRNL**	**60**	**1983**	**57**	**1994**	**29**	**-28**
11	C28	MOCN	200	1983	3.0	1994	3.0	.0
12	**C29**	**CRNL**	**80**	**1983**	**23**	**1994**	**99**	**76**
13	**C31**	**CRNL**	**60**	**1983**	**95**	**1994**	**110**	**15**
14	C32	CRNL	100	1983	7.8	1994	7.5	-.3
15	C34	CRNL	100	1983	8.8	1994	8.4	-.4
16	**C35**	**CRNL**	**70**	**1983**	**100**	**1993**	**140**	**40**
17	**C36**	**CRNL**	**30**	**1983**	**<.2**	**1994**	**21**	**21**
18	**C37**	**CRNL**	**75**	**1983**	**17**	**1994**	**120**	**103**
19	C45	CRNL	28	1984	7.9	1994	3.9	-4.0
28	F20	MOCN	85	1983	3.4	1994	5.7	2.3
29	**F21**	**CRNL**	**80**	**1983**	**22**	**1994**	**18**	**-4.0**
30	F24	CRNL	87	1983	6.0	1994	6.2	.2
31	F27	CRNL	98	1983	9.2	1994	8.2	-1.0
32	F28	CRNL	60	1983	16	1994	9.3	-6.7
33	F38	CRNL	72	1984	5.0	1994	6.7	1.7
34	F39	CRNL	80	1984	3.5	1994	3.4	-.1
35	F40	CRNL	120	1984	6.5	1994	7.1	.6
36	F41	CRNL	80	1984	5.3	1994	3.6	-1.7
37	**F44**	**CRNL**	**70**	**1983**	**36**	**1994**	**31**	**-5.0**
39	G25	MOCN	150	1983	3.7	1993	5.5	1.8

Table 6. Change in chloride concentrations in ground water in the vicinity of the Brookhaven oil field, Lincoln County, Mississippi (1981-84 to 1993-94)--Continued

Site number	Local number	Aquifer unit code	Depth (ft)	Year	Chloride (mg/L)	Year	Chloride (mg/L)	Chloride change (mg/L)
40	G57	CRNL	91	1981	2.5	1993	11	8.5
41	G58	CRNL	80	1981	40	1994	80	40
42	G59	CRNL	76	1981	88	1994	240	152
43	G60	CRNL	100	1981	120	1993	400	280
44	G61	CRNL	85	1981	30	1993	190	160
45	G62	CRNL	45	1981	260	1994	2,500	2,240
46	G63	CRNL	65	1981	48	1994	11	-37
47	G66	CRNL	48	1981	50	1994	33	-17
48	G67	MOCN	150	1981	15	1993	10	-5.0
49	G68	MOCN	308	1982	20	1993	58	38
50	G69	CRNL	85	1982	21	1994	74	53
51	G71	MOCN	256	1981	2.7	1993	3.4	.7
52	G72	CRNL	80	1983	7.8	1993	8.3	.5
53	G73	CRNL	120	1983	6.5	1993	5.3	-1.2
54	G74	MOCN	120	1983	3.6	1993	3.5	-.1
55	G75	MOCN	100	1983	3.7	1993	3.5	-.2
56	G76	CRNL	100	1983	6.2	1993	5.2	-1.0
57	G77	CRNL	100	1983	47	1993	41	-6.0
59	G80	CRNL	118	1983	51	1993	28	-23
60	G82	CRNL	45	1983	29	1993	25	-4.0
61	G83	CRNL	50	1983	11	1994	94	83
62	G85	CRNL	100	1983	54	1993	55	1.0
63	G86	CRNL	65	1983	68	1993	59	-9.0
64	G87	CRNL	60	1983	9.1	1994	4.5	-4.6
65	G88	CRNL	80	1983	5.5	1993	6.6	1.1
66	G89	CRNL	50	1983	59	1993	32	-27
67	G91	CRNL	106	1983	44	1994	5.9	-38
68	G95	CRNL	30	1983	9.5	1994	5.8	-3.7

Table 6. Change in chloride concentrations in ground water in the vicinity of the Brookhaven oil field, Lincoln County, Mississippi (1981-84 to 1993-94)--Continued

Site number	Local number	Aquifer unit code	Depth (ft)	Year	Chloride (mg/L)	Year	Chloride (mg/L)	Chloride change (mg/L)
69	G97	MOCN	175	1983	8.0	1994	6.4	-1.6
71	**G100**	**CRNL**	**90**	**1983**	**49**	**1994**	**74**	**25**
72	**G106**	**CRNL**	**92**	**1983**	**63**	**1994**	**50**	**-13**
73	**G107**	**CRNL**	**120**	**1983**	**710**	**1993**	**210**	**-500**
74	**G109**	**CRNL**	**79**	**1983**	**56**	**1994**	**66**	**10**
75	G110	CRNL	100	1983	19	1994	18	-1.0
76	**G114**	**CRNL**	**84**	**1983**	**210**	**1993**	**590**	**380**
77	**G117**	**CRNL**	**73**	**1983**	**33**	**1994**	**26**	**-7.0**
78	**G118**	**CRNL**	**69**	**1983**	**120**	**1994**	**39**	**-81**
79	**G119**	**CRNL**	**98**	**1983**	**28**	**1993**	**32**	**4.0**
82	**G127**	**CRNL**	**70**	**1983**	**130**	**1994**	**180**	**50**
83	**G131**	**MOCN**	**200**	**1983**	**8.9**	**1994**	**860**	**851**
84	G133	CRNL	120	1983	6.4	1993	5.1	-1.3
89	**G139**	**CRNL**	**93**	**1983**	**160**	**1993**	**87**	**-73**
90	G140	CRNL	80	1983	120	1993	120	.0
91	G142	CRNL	40	1984	3.7	1993	3.4	-.3
92	**G143**	**CRNL**	**80**	**1984**	**26**	**1993**	**14**	**-12**
93	G144	CRNL	75	1984	9.2	1993	6.2	-3.0
102	G175	CRNL	70	1984	21	1993	20	-1.0
103	G177	CRNL	120	1984	3.0	1993	2.6	-.4
104	G178	CRNL	60	1984	5.1	1993	4.2	-.9
105	**G180**	**CRNL**	**147**	**1984**	**75**	**1993**	**89**	**14**
106	**G181**	**CRNL**	**150**	**1984**	**120**	**1993**	**78**	**-42**
107	G182	CRNL	148	1984	3.2	1993	5.3	2.1
151	**K35**	**CRNL**	**80**	**1984**	**29**	**1994**	**13**	**-16**

chloride decrease (500 mg/L) was in water from a shallow well (120 ft deep) in the southwestern part of the oil field.

SUMMARY

From August 1993 to December 1994, the U.S. Geological Survey, in cooperation with the U.S. Environmental Protection Agency, collected water-quality data to determine the extent of brine contamination of ground water in the vicinity of the Brookhaven oil field in northwestern Lincoln County, Mississippi. The geologic units of the Citronelle Formation and the Miocene Series that contain sufficient saturated permeable material to yield significant quantities of water serve as aquifers in the study area. These units are identified in this report as the Citronelle aquifer and the Miocene aquifer system. Data indicate that the two aquifers may be hydraulically connected in part of the study area.

Large quantities of brine are withdrawn in conjunction with the production of petroleum. For the last 10 years (1985-94) annual brine production in the Brookhaven oil field has averaged about 550,000 barrels, and the brine-to-oil ratio has averaged about 4.4. From 1943 to 1994, cumulative brine production was about 60,561,000 barrels. Sodium is the predominant cation (mean concentration, 48,000 mg/L) and chloride the predominant anion (mean concentration, 98,500 mg/L) in brine samples from the major oil-producing formation (the lower part of the Tuscaloosa Formation) in the Brookhaven oil field.

During 1993-94, sodium concentrations in ground water in the study area ranged from 2.2 to 3,700 mg/L (median, 14 mg/L); chloride, from 2.5 to 9,400 mg/L (median, 21 mg/L). Water from 89 (50 percent) of 177 wells was considered contaminated by brine--that is, had chloride concentrations greater than 20 mg/L. However, the chloride concentrations in only 12 (7 percent) of 177 wells were greater than the recommended secondary limit for drinking water (250 mg/L).

From 1981-84 to 1993-94, the chloride concentration increased significantly (was greater than 20 mg/L and increased at least 2.0 mg/L) at 23 sites and decreased significantly (was greater than 20 mg/L and decreased at least 2.0 mg/L) at 20 sites. The largest chloride increase (2,240 mg/L) was at a shallow well (45 ft deep) completed in the Citronelle aquifer, but the next largest increase (851 mg/L) was at a moderately deep well (200 ft deep) completed in the Miocene aquifer system. The largest chloride decrease (500 mg/L) was at a shallow well (45 ft deep).

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