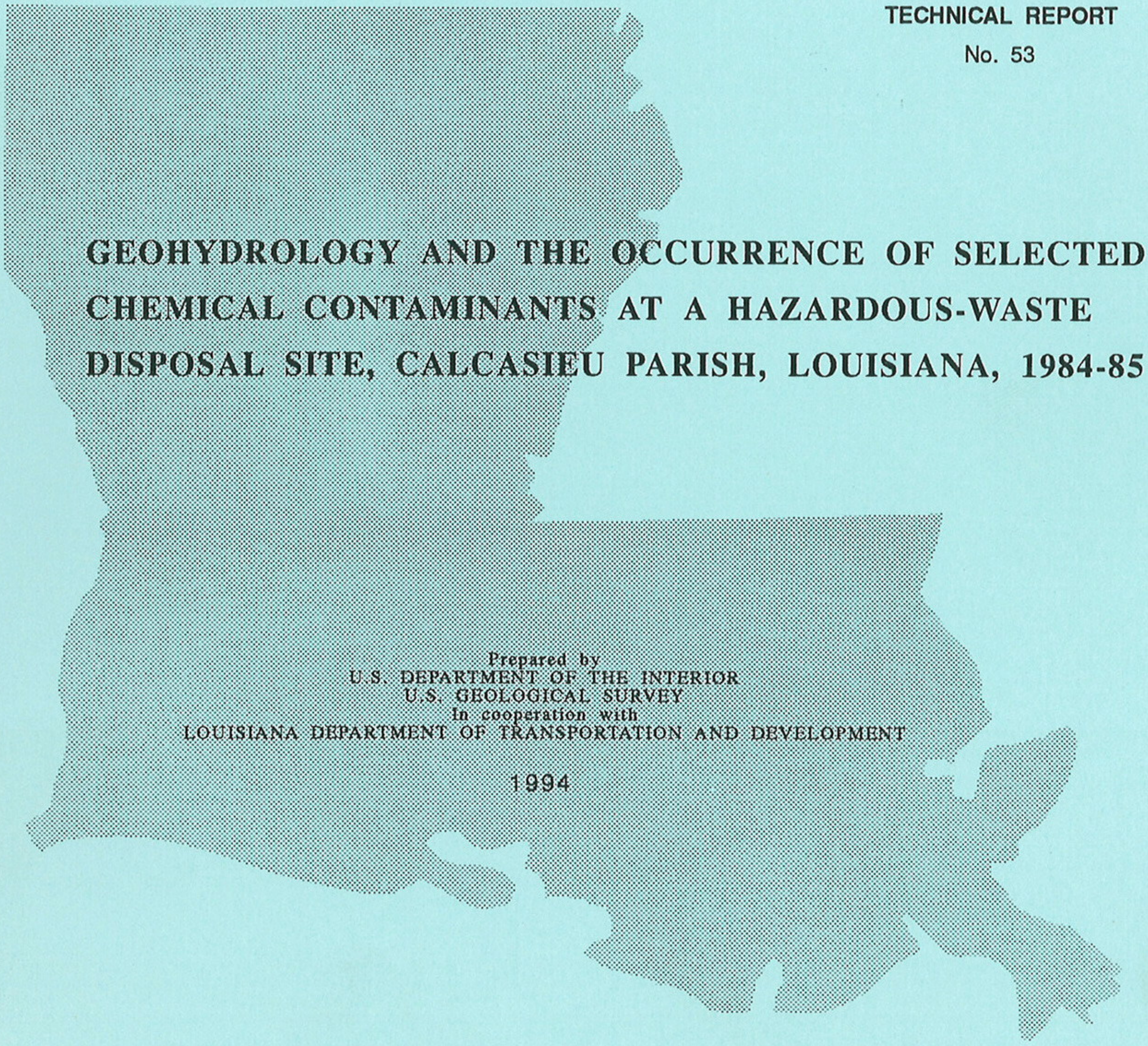
STATE OF LOUISIANA
DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
PUBLIC WORKS AND FLOOD CONTROL DIRECTORATE
WATER RESOURCES SECTION

WATER RESOURCES
TECHNICAL REPORT
No. 53



GEOHYDROLOGY AND THE OCCURRENCE OF SELECTED CHEMICAL CONTAMINANTS AT A HAZARDOUS-WASTE DISPOSAL SITE, CALCASIEU PARISH, LOUISIANA, 1984-85

Prepared by
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY
In cooperation with
LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

1994

STATE OF LOUISIANA
DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
PUBLIC WORKS AND FLOOD CONTROL DIRECTORATE
WATER RESOURCES SECTION
In cooperation with the
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

WATER RESOURCES
TECHNICAL REPORT NO. 53

Geohydrology and the Occurrence of Selected Chemical Contaminants at a Hazardous-Waste Disposal Site, Calcasieu Parish, Louisiana, 1984-85

By
Douglas A. Trudeau
U.S. GEOLOGICAL SURVEY

Published by
LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
Baton Rouge, Louisiana

1994

STATE OF LOUISIANA
EDWIN W. EDWARDS, Governor

DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT
JUDE W.P. PATIN, Secretary
PUBLIC WORKS AND FLOOD CONTROL DIRECTORATE
Curtis G. Patterson, Director
WATER RESOURCES SECTION
Zahir "Bo" Bolourchi, Chief

Cooperative projects with the
U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary
U.S. GEOLOGICAL SURVEY
GORDON P. EATON, Director

For additional information write to:

Edward H. Martin
District Chief
U.S. Geological Survey, WRD
3535 S. Sherwood Forest Blvd.
Suite 120
Baton Rouge, LA 70816
Telephone: (504) 389-0281

Zahir "Bo" Bolourchi, P.E.
Chief, Water Resources Section
Louisiana Department of
Transportation and Development
P.O. Box 94245
Baton Rouge, LA 70804-9245
Telephone: (504) 379-1434

CONTENTS

FIGURES

TABLES

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
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
foot per mile (ft/mi)	0.1894	meter per kilometer
gallon per minute (gal/min)	0.00006309	cubic meter per second
gallon per minute per foot [(gal/min)/ft]	0.000207	cubic meter per second per meter
gallon per day (gal/d)	0.003785	cubic meter per day
million gallons per day (Mgal/d)	3,785,000	liter per day
million gallons per day (Mgal/d)	3,785	cubic meter per day
acre	0.4047	hectare
acre-foot (acre-ft)	0.001233	cubic hectometer
mile (mi)	1.609	kilometer
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 X °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:

micrometer (µm)
millisiemens per meter (mS/m at 25 degrees Celsius)
milligrams per liter (mg/L)
milligrams per kilogram (mg/kg)
micrograms per liter (µg/L)

Geohydrology and the Occurrence of Selected Chemical Contaminants at a Hazardous-Waste Disposal Site, Calcasieu Parish, Louisiana, 1984-85

By Douglas A. Trudeau

Abstract

Oil-field and petrochemical wastes disposed in unlined lagoons at a hazardous-waste disposal site in Calcasieu Parish, Louisiana, have formed plumes of contaminated ground water in low-permeability sediments beneath the unlined lagoons. The low-permeability sediments consist of 70 to 90 feet of clay, silt, and fine sand which overlie the "200-foot" aquifer of the Chicot aquifer system. Stratigraphically included in the low-permeability sediments (in descending order) are: undifferentiated alluvium, surficial sand and clay, clay, the shallow aquifer of the Chicot aquifer system, and clay. Ground water beneath the waste site generally moves downward through the surficial clay. Water then moves toward the northeast and east in the surficial sands and undifferentiated alluvium in the eastern part of the study area and may also move downward to the shallow and "200-foot" aquifers and then generally toward the southeast.

Lateral and vertical variability in mineralogy is great for nonclay and clay minerals, and is most likely depositional in origin. X-ray diffraction analyses indicate that smectite is the most abundant clay mineral, illite is intermediate in abundance, and kaolinite is least abundant. The dominant non-clay minerals are quartz and plagioclase and K-feldspar.

Scanning electron microscope analyses indicate small-scale compositional and textural differences between uncontaminated and contaminated sediment samples. Uncontaminated sediments are composed predominantly of clay-coated detrital grains showing little or no evidence of dissolution. Contaminated sediments are characterized by the dissolution of detrital grains and precipitation of gypsum, aragonite, barite, and quartz.

Sediment contaminated by a nonaqueous phase liquid (NAPL), described as oil, is present beneath the abandoned unlined lagoons. NAPL denser than water has migrated to a depth of at least 51 feet beneath the unlined lagoons, and on the basis of logs of soil borings, is considered the most common and deepest occurring contaminant. Analyses of the NAPL-contaminated sediments indicate that a suite of organic pollutants are present, including halogenated aliphatic hydrocarbons, monocyclic aromatic hydrocarbons, polychlorinated biphenyls (PCB's) and related compounds, and polycyclic aromatic hydrocarbons.

A study of the areal variation in the chemical composition of ground water at the hazardous-waste disposal site has established the existence of overlapping areas of inorganic and organic contamination. The orientation of the plumes of contaminated ground water is generally consistent with the downward migration through surface clay beneath the abandoned unlined lagoons and lateral movement in underlying permeable beds in the directions of ground-water

flow. The axes of the chloride and 1,2-dichloroethane plumes roughly coincide and extend from the northeastern corner of the waste site southwest to the southern boundary of the waste site. Elevated concentrations of chloride have been detected 300 feet northeast and 1,000 feet south of the waste site, but organic contamination has not been detected at these distances. Although much of the contamination is now confined to the low-permeability sediments overlying the "200-foot" aquifer, concentrations of dissolved chloride (greater than 100 milligrams per liter) and some organic pollutants are present within the "200-foot" aquifer.

INTRODUCTION

Petrochemical manufacturing is the primary source of hazardous waste generated in Louisiana; consequently, the potential environmental effect of the disposal of hazardous petrochemical waste is a concern to local, State, and Federal officials. In the past, hazardous petrochemical wastes were commonly stored in unlined lagoons at landfill sites. Potential landfill sites for disposal of such wastes generally are those characterized by thick surficial clays overlying alternating beds of sand, gravel, and clay; the surficial clays were thought to function as barriers preventing contamination of the underlying sand and gravel aquifers. However, of the 60 hazardous-waste disposal sites monitored by the State in 1985, at least half have ground-water contamination problems. Most of the contamination problems are a result of waste disposal in unlined lagoons (George Cramer, Louisiana Department of Environmental Quality, oral commun., 1986).

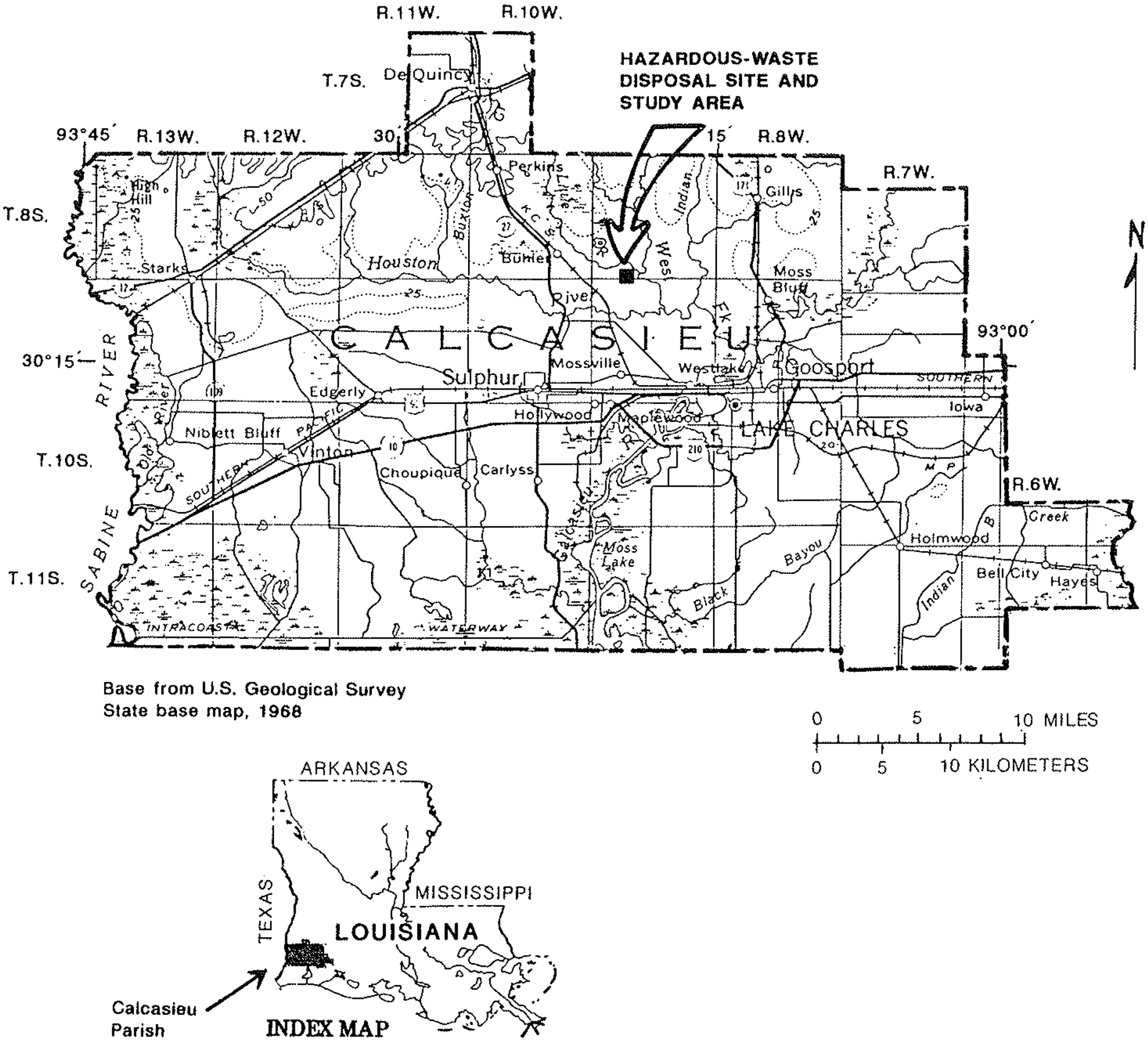
An understanding of the process by which organic contaminants move through surficial clays is needed to assess the potential environmental effects of the disposal of hazardous petrochemical waste. Accordingly, a study was undertaken by the U.S. Geological Survey, in cooperation with the Louisiana Department of Transportation and Development, to gain more knowledge of the occurrence and movement of organic contaminants through surficial clays. A hazardous-waste disposal site in Calcasieu Parish in southwestern Louisiana (fig. 1) was selected for study because the waste has migrated through clays into an underlying aquifer (unpublished data on file, Louisiana Department of Environmental Quality, Baton Rouge, La., 1983).

Purpose and Scope

This report describes the geohydrology and mineralogy of a hazardous-waste disposal site in Calcasieu Parish, Louisiana, and the occurrence of selected inorganic and organic contaminants. Geologic, hydrologic, and water-quality data were obtained from the waste-site owners and from the files of the Louisiana Department of Environmental Quality and the U.S. Geological Survey. The site owners did not permit the drilling of additional onsite test holes or monitor wells, but allowed the collection of additional water-level measurements and water-quality samples from their monitor wells and supplied sediment samples from cores of their wells for mineralogical and geochemical analysis and testing. Additional test holes and monitor wells were installed offsite as part of this study to gather geologic, water-level, and water-quality data. The study was limited to an investigation of shallow contamination and does not address possible effects of onsite deep-well injection.

General Methods of Investigation

Geohydrologic data for 1984-86 and other historical data were used to describe the aquifers and confining units, lithology, hydraulic characteristics, and ground-water flow at the waste site. Twenty test holes were drilled offsite. Cores and cuttings were collected and examined and monitoring wells were



Base from U.S. Geological Survey
State base map, 1968

Figure 1. Location of the hazardous-waste disposal site in Calcasieu Parish.

installed at each site. The offsite subsurface geology was correlated with onsite geology to determine the extent of aquifers and confining units. Existing wells at and surrounding the site were inventoried, and water levels were measured in all inventoried wells to determine the directions and rates of ground-water movement.

Uncontaminated sediment cores from offsite wells and contaminated cores from onsite wells were analyzed to determine their mineralogy and to investigate the nature and extent of possible sediment-contaminant interaction. Mineralogical analyses included X-ray diffractometry, use of scanning electron microscope, energy dispersive spectrometry, and the measurement of cation exchange capacity.

Water-quality samples collected as part of this study and existing water-quality data from the files of the Louisiana Department of Environmental Quality were used to determine the composition and spatial distribution of contaminants in the subsurface.

Definition of Terms

In this report, any substance introduced to the subsurface by waste disposal at the hazardous-waste disposal site is referred to as a contaminant. Ground water that contains dissolved substances introduced into the aquifer by waste disposal is referred to as contaminated ground water. Sediment that contains substances introduced by waste disposal is referred to as contaminated sediment. Sediment contaminated by a nonaqueous phase liquid (NAPL) is described as oil. Bodies of contaminated water are referred to as plumes. Chemical substances that have been classified by the U.S. Environmental Protection Agency (USEPA) as priority pollutants (Keith and Telliard, 1979) and other organic compounds that do not occur naturally were used as indicators of organic contamination. These organic contaminants are grouped into the following classes: monocyclic aromatic hydrocarbons; halogenated aliphatic hydrocarbons; pesticides, polychlorinated biphenyls (PCB's) and related compounds; polycyclic aromatic hydrocarbons; phthalate esters; nitrosamines and miscellaneous compounds; and halogenated ethers (Callahan and others, 1979).

Location and Setting

The hazardous-waste disposal site consists of about 80 acres located 8 mi northwest of Lake Charles in a rural part of Calcasieu Parish (fig. 1). The study area includes the waste site and the area adjacent to the site (fig. 2). The waste site is situated on a flat-lying terrace, the Prairie Terrace, near the confluence of the West Fork Calcasieu River and the Little River. Most of the study area lies at an altitude slightly more than 20 ft above sea level and was originally covered with pine trees. The study area south of the waste site consists of partly to wholly cleared rural homesteads. The swampy low-lying areas near the two rivers are only slightly above sea level and contain many vacation homes and camps.

The study area is characterized by a humid-subtropical climate. The Gulf of Mexico moderates extremes in temperature. Data from the climate station at Lake Charles Airport, approximately 12 mi southeast of the study area, indicate that the average monthly temperature ranges from 11 °C in January to 28 °C in July and that the yearly average is about 20 °C. Monthly average rainfall ranges from a low of 3.0 in. in March to 5.6 in. in July. The yearly average rainfall is 53.0 in.

The principal drainageways in Calcasieu Parish are the Calcasieu River and its main tributaries, the Houston River and the West Fork Calcasieu River. The stream near the north side of the waste site, the Little River, is only a minor tributary. The West Fork Calcasieu River, east of the waste site, is a sluggish stream with a deep channel and flat gradient. At low flows, stages in the Little River and the West Fork Calcasieu River are controlled by the saltwater barrier at Lake Charles and backwater conditions may occur.

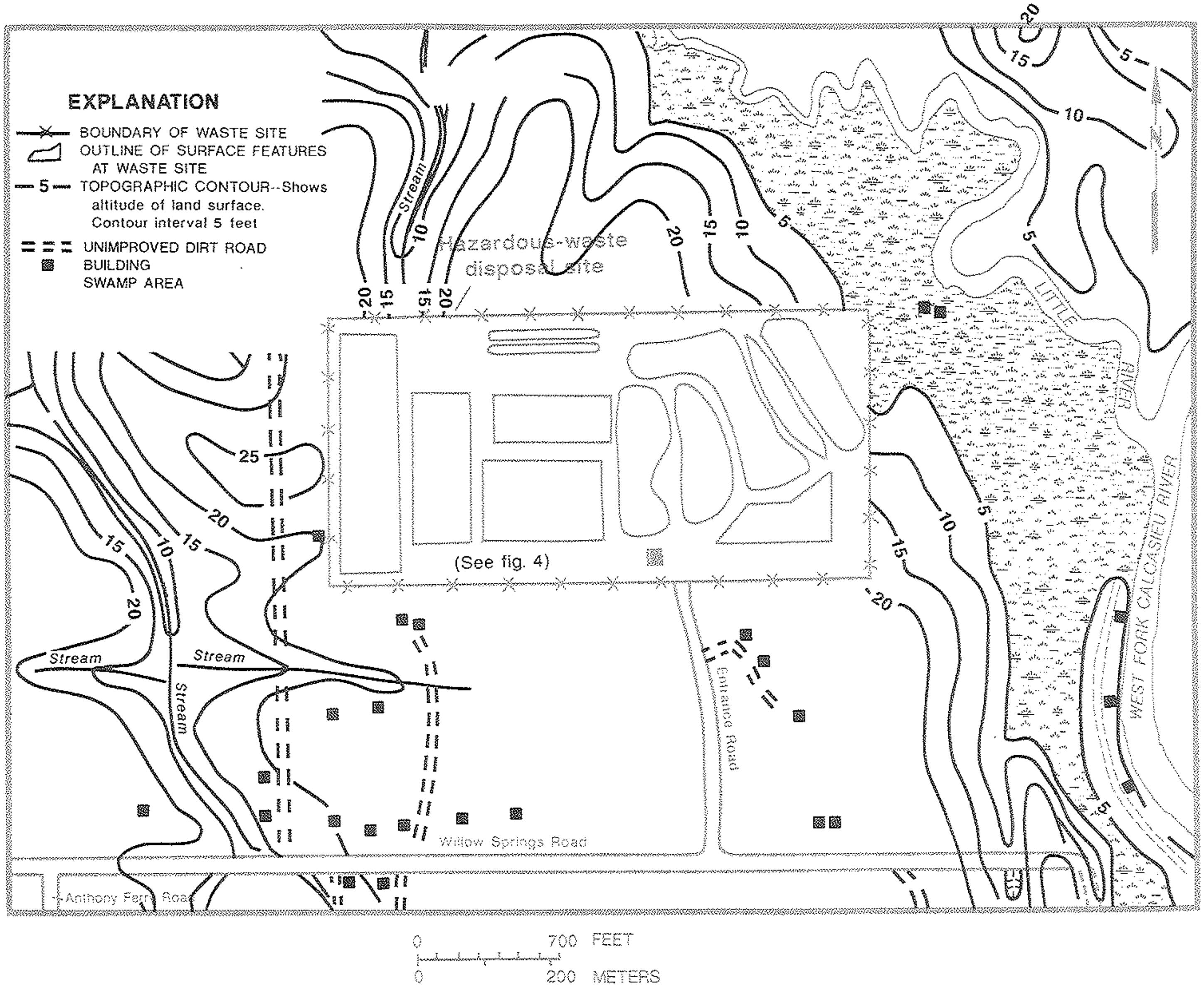


Figure 2. Culture, drainage, and topography of the study area.

Well-Numbering System

In Louisiana, the U.S. Geological Survey assigns wells a number in approximate order of inventory; a letter prefix represents the parish in which the well is located. For example, Cu-1 is the first well inventoried in Calcasieu Parish. More than 200 holes have been drilled on and near the waste site; about 75 of these holes have been completed as monitoring-observation wells and were inventoried for this study. Figure 3 shows the location of inventoried wells within the study area. Note that the prefix (Cu-) has been eliminated from the well numbers shown in figure 3.

Table 1 lists the wells used in this study and the following construction details of the wells; the interval that is open or screened in the well, the well depth, and the aquifer to which the well is open. Two sets of local well numbers in use at the waste site also are given: a monitor-observation well number and a master-boring number. Most offsite water-supply wells in the study area were not inventoried or used in the study because the construction details of these wells could not be determined.

Acknowledgments

The authors appreciate the assistance provided by Zahir "Bo" Bolourchi and Richard Edwards, Water Resources Section, Louisiana Department of Transportation and Development; Narenda Dave, George Cramer, and Victor Montelaro, Louisiana Department of Environmental Quality; and Austin Arabie and Dan Heintz, Browning-Ferris Industries - Chemical Services Incorporated (BFI-CSI). The Louisiana Department of Environmental Quality provided geologic and water-quality data and permitted access to their files and to their offsite wells to measure water levels and to collect water samples.

BFI-CSI provided geologic, water-level, and hydraulic conductivity data and core samples from wells; and permitted access to measure water levels and to collect water samples from their onsite wells at the hazardous-waste disposal site.

The information and data in the "Mineralogy" section and selected information on geochemistry (pages 35-48) in the section "Occurrence of Selected Chemical Contaminants" were summarized from a written communication in 1986 by Jeffrey S. Hanor, Vishnu Ranganathan, and Kathleen M. McManus of Louisiana State University.

DESCRIPTION OF THE HAZARDOUS-WASTE DISPOSAL SITE

Prior to commercial waste-disposal operations, gas was produced between 1958 and 1960 from a 9,501-foot deep well, now used for injection, located near the center of the site. Brine pumped during gas production may have been disposed of near the injection well in the area shown in figure 4.

Commercial waste-disposal operations began at the hazardous-waste disposal site in 1968 with the disposal in unlined lagoons of oil, sludge, brine, and other wastes from oil and gas drilling. Later, additional petrochemical wastes, some of which were classified hazardous, were disposed in the unlined lagoons; these wastes included coke fines, storage tank bottoms (settled sludge), American Petroleum Institute (API) separator wastes, and waste plastics. Petrochemical wastes disposed onsite were generated by refineries and chemical plants at Lake Charles, La., as well as in other areas of the country. The unlined lagoons, covering a surface area of approximately 45 acres, were located in the eastern two-thirds of the waste site (fig. 4).

The lagoons were constructed by excavating trenches to a depth of about 8 ft and using the excavated materials to build ring levees to form the lagoons. Liquid wastes were stored in these lagoons to a depth of about 6 ft above the natural land surface. From 1976 to 1981 the lagoons were closed using a three-step process: (1) floating oils were recovered, (2) aqueous liquid wastes and contaminated water derived from dewatering of sludge in the bottom of the lagoons were disposed in the onsite injection well, and (3) the oily sludge remaining in the lagoons was solidified by mixing with fly ash or kiln dust. The solidified

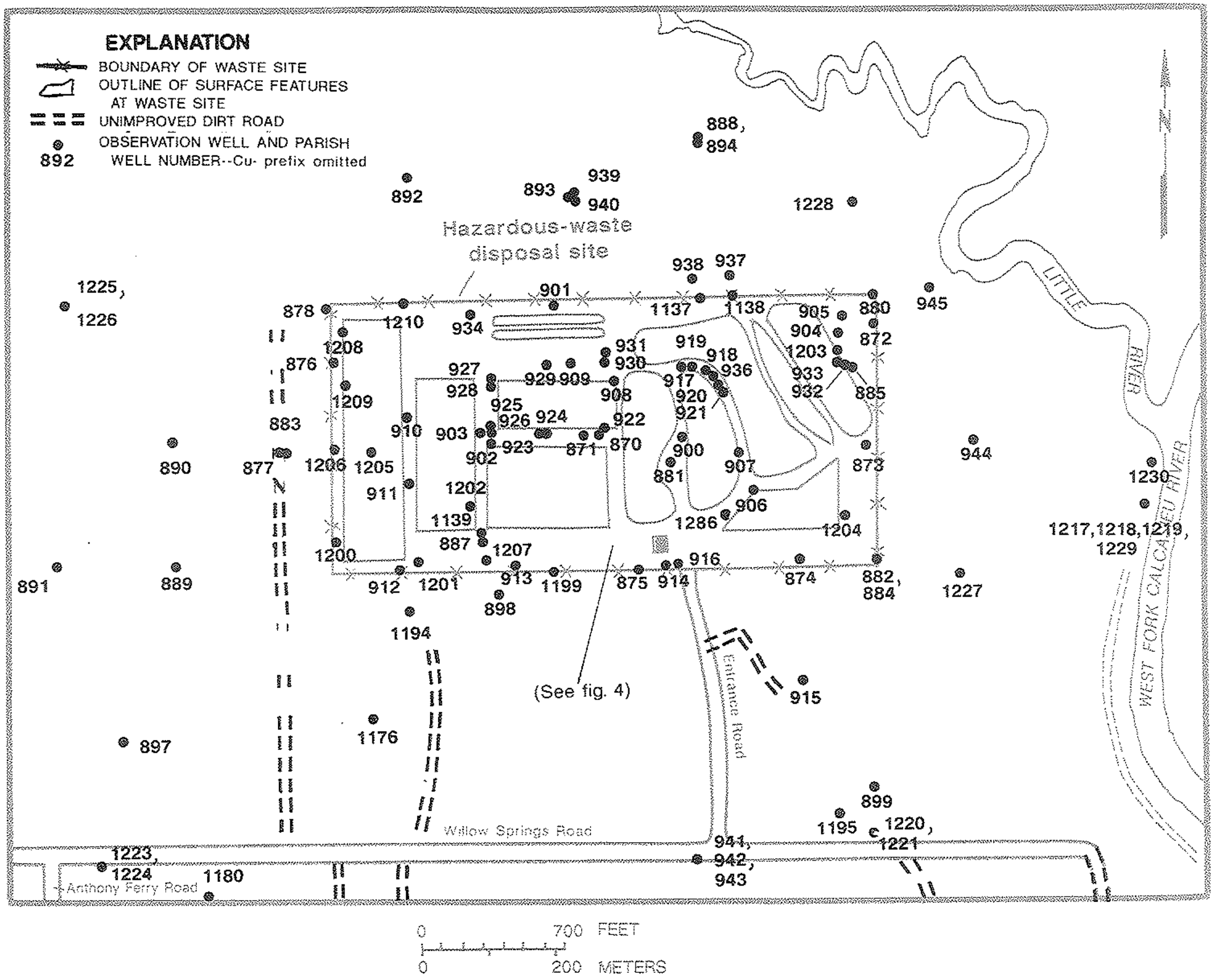


Figure 3. Location of wells in the study area.

Table 1. Well numbers and well-construction details in the study area

[Aquifer codes: 11202LC, "200-foot" aquifer of the Chicot aquifer system; 112CHCTS, shallow aquifer of the Chicot aquifer system; 112SS, surficial sand; 112ALVL, undifferentiated alluvium; 11205LC, "500-foot" aquifer of the Chicot aquifer system; --, no data]

Local well number	Monitor observation well number	Master boring number	Top of screened or open interval	Bottom of screened or open interval	Depth of well	Aquifer code
			in feet below land surface			
Cu-870	MW-17	L-82	145.5	154.25	154.25	11202LC
Cu-871	MW-18	L-83	105.5	114.25	114.25	11202LC
Cu-872	MW-19	L-87	42.75	47.25	47.25	112CHCTS
Cu-873	MW-20	L-88	45.0	49.0	49.0	112CHCTS
Cu-874	MW-21	L-89	46.3	50.6	50.6	112CHCTS
Cu-875	MW-22	L-90	39.75	44.0	44.0	112CHCTS
Cu-876	MW-23	L-91	33.8	38.1	38.1	112CHCTS
Cu-877	MW-24	L-29	40.0	45.0	45.0	112CHCTS
Cu-878	MW-25	L-28	40.0	45.0	45.0	112CHCTS
Cu-880	MW-2R	L-85	7.75	11.33	11.33	112ALVL
Cu-881	MW-27	L-168	50.62	59.37	59.37	112CHCTS
Cu-882	MW-28	L-169	100.92	110.25	110.25	11202LC
Cu-883	MW-24R	L-170	41.67	53.33	53.33	112CHCTS
Cu-884	MW-29	L-171	35.0	43.92	43.92	112CHCTS
Cu-885	MW-30	L-172	14.58	22.92	22.92	112SS
Cu-887	MW-32	L-174	46.0	50.42	50.42	112CHCTS
Cu-888	MW-33	L-175	80.67	88.92	88.92	11202LC
Cu-889	L-24	B-3	40.0	45.0	45.0	112CHCTS
Cu-890	L-26	B-5	40.0	45.0	45.0	112CHCTS
Cu-891	L-27	B-6	40.0	45.0	45.0	112CHCTS
Cu-892	L-34	B-13	40.0	45.0	45.0	112CHCTS
Cu-893	L-37	B-16	40.0	45.0	45.0	112CHCTS
Cu-894	L-40	B-19	40.0	45.0	45.0	112CHCTS
Cu-897	BFI-3	--	145.0	155.0	155.0	11202LC
Cu-898	BFI-4	--	55.0	65.0	65.0	112CHCTS
Cu-899	BFI-5	--	145.0	155.0	155.0	11202LC
Cu-900	P-9	L-193	47.79	57.29	57.29	112CHCTS
Cu-901	P-10	L-194	40.17	49.67	49.67	112CHCTS
Cu-902	P-11	L-195	38.33	47.83	47.83	112CHCTS
Cu-903	P-12	L-196	41.29	50.79	50.79	112CHCTS
Cu-904	MW-35	L-220	10.75	24.75	24.75	112ALVL
Cu-905	MW-36	L-221	7.58	16.75	16.75	112SS
Cu-906	MW-38	L-222	45.5	54.75	54.75	112CHCTS
Cu-907	MW-39	L-223	94.67	103.75	103.75	11202LC
Cu-908	MW-41	L-224	90.5	99.67	99.67	11202LC
Cu-909	MW-42	L-225	50.58	59.75	59.75	112CHCTS
Cu-910	MW-43	L-226	42.08	51.17	51.17	112CHCTS
Cu-911	MW-44	L-227	42.58	51.66	51.66	112CHCTS
Cu-912	MW-45	L-228	42.66	51.66	51.66	112CHCTS

Table 1. Well numbers and well-construction details in the study area–Continued

Local well number	Monitor observation well number	Master boring number	Top of screened or open interval	Bottom of screened or open interval	Depth of well	Aquifer code
			in feet below land surface			
Cu-913	MW-46	L-229	40.50	49.66	49.66	112CHCTS
Cu-914	MW-47	L-230	45.83	59.66	59.66	112CHCTS
Cu-915	--	--	--	--	37.0	112CHCTS
Cu-916	MW-16	--	--	--	340.0	11205LC
Cu-917	PT-1	L-176	45.3	55.0	55.0	112CHCTS
Cu-918	PT-2	L-177	47.25	57.42	57.0	112CHCTS
Cu-919	PT-3	L-178	51.33	61.0	61.0	112CHCTS
Cu-920	PT-4	L-179	44.1	53.6	53.6	112CHCTS
Cu-921	PT-5	L-180	44.5	53.83	53.83	112CHCTS
Cu-922	P-1	L-181	53.2	58.7	58.7	112CHCTS
Cu-923	P-2	L-182	48.0	53.7	53.7	112CHCTS
Cu-924	P-2A	L-183	52.0	58.0	58.0	112CHCTS
Cu-925	P-3	L-184	45.2	52.8	52.8	112CHCTS
Cu-926	P-3A	L-185	55.0	60.0	60.0	112CHCTS
Cu-927	P-4	L-186	43.33	54.75	54.75	112CHCTS
Cu-928	P-4A	L-187	50.0	54.0	54.0	112CHCTS
Cu-929	P-5	L-188	49.3	58.8	58.8	112CHCTS
Cu-930	P-6	L-189	47.5	56.8	56.8	112CHCTS
Cu-931	P-6A	L-190	44.0	50.0	50.0	112CHCTS
Cu-932	P-7	L-191	17.0	23.3	23.0	112SS
Cu-933	P-8	L-192	17.0	24.0	24.0	112SS
Cu-934	WWNORTH	--	--	--	400.0	11205LC
Cu-936	RW-1	--	53.8	63.8	63.8	112CHCTS
Cu-937	MW-48	L-238	55.83	60.28	60.28	112CHCTS
Cu-938	MW-49	L-239	14.7	24.0	24.0	112SS
Cu-939	--	--	92.15	94.15	95.15	11202LC
Cu-940	--	--	15.8	17.8	17.8	112SS
Cu-941	--	--	69.15	71.15	71.15	11202LC
Cu-942	--	--	35.85	37.85	37.85	112CHCTS
Cu-943	--	--	21.15	23.15	23.15	112SS
Cu-944	--	--	17.95	19.95	19.95	112SS
Cu-945	--	--	22.7	24.7	24.7	112ALVL
Cu-1137	MW-7	L-13	--	--	20.42	112SS
Cu-1138	MW-26	L-41	40.0	45.0	45.0	112CHCTS
Cu-1139	MW-31	L-173	85.40	94.1	94.1	11202LC
Cu-1176	--	--	--	--	37.5	112CHCTS
Cu-1180	--	--	--	--	150.0	11202LC
Cu-1194	--	--	--	--	32.0	112SS
Cu-1195	--	--	--	--	22.0	112SS
Cu-1199	MW-15	L-56	41.0	49.5	49.5	112CHCTS
Cu-1200	MW-14	L-18	38.0	43.0	43.0	112CHCTS
Cu-1201	MW-13	L-20	77.0	80.0	80.0	11202LC

Table 1. Well numbers and well-construction details in the study area--Continued

Local well number	Monitor observation well number	Master boring number	Top of screened or open interval	Bottom of screened or open interval	Depth of well	Aquifer code
			in feet below land surface			
Cu-1202	MW-12	L-19	40.0	45.0	45.0	112CHCTS
Cu-1203	MW-2	L-2	--	--	20.0	112SS
Cu-1204	MW-4	L-4	--	--	53.0	112CHCTS
Cu-1205	MW-5	L-5	--	--	57.0	112CHCTS
Cu-1206	MW-8	L-12	--	--	25.0	112SS
Cu-1207	MW-1	L-1	--	--	25.0	112SS
Cu-1208	MW-9	L-10	--	--	12.0	112SS
Cu-1209	MW-10	L-11	--	--	25.0	112SS
Cu-1210	MW-11	L-9	--	--	25.0	112SS
Cu-1217	--	--	75.0	85.0	85.0	11202LC
Cu-1218	--	--	60.8	62.8	62.8	112SS
Cu-1219	--	--	21.95	23.95	23.95	112ALVL
Cu-1220	--	--	63.6	65.6	65.6	112CHCTS
Cu-1221	--	--	23.97	25.97	25.97	112SS
Cu-1223	--	--	86.98	88.98	88.98	11202LC
Cu-1224	--	--	29.16	30.16	30.16	112CHCTS
Cu-1225	--	--	94.8	96.8	96.8	11202LC
Cu-1226	--	--	29.3	31.3	--	112CHCTS
Cu-1227	--	--	20.0	22.0	22.0	112ALVL
Cu-1228	--	--	17.9	19.9	19.9	112SS
Cu-1229	--	--	12.5	15.0	15.0	112ALVL
Cu-1230	--	--	9.7	11.7	11.7	112ALVL
Cu-1286	L-217	--	--	--	80	11202LC

sludge in some of the lagoons was left in place and capped with clay; sludge from other lagoons was excavated and placed in secure landfill cells elsewhere onsite.

Current waste-disposal operations at the site include the disposal of liquid wastes in an injection well, and disposal of solidified industrial waste in secure landfill cells (fig. 4). The old gas well onsite was converted to an injection well with an injection interval of 4,490 to 4,610 ft below land surface. Recompacted clay-lined basins, less than 15 ft deep, are used in conjunction with the injection well for pH adjustment and equalization of the liquid wastes (fig. 4).

Secure landfill cells at the hazardous-waste disposal site are excavations about 35 ft deep that are lined with 5 ft of compacted clay. A leachate collection system is installed in each cell. Eight secure landfill cells were constructed but only seven had been filled and capped with clay at the time of this study (fig. 4). Unlined pits in the mixing area are used to solidify liquid and semisolid waste prior to disposal in the secure landfill cells (fig. 4)

Chemical analyses of wastes stored in the unlined lagoons are not available. Waste oils disposed of in the unlined lagoons were presumably generated from crude oil, which contains monocyclic aromatic hydrocarbons such as benzene and polycyclic aromatic hydrocarbons such as naphthalene (Murray and others, 1984). The API separator sludge is heavier than water and contains monocyclic aromatic hydrocarbons such as phenol and benzene, and polycyclic aromatic hydrocarbons such as naphthalene (Brown

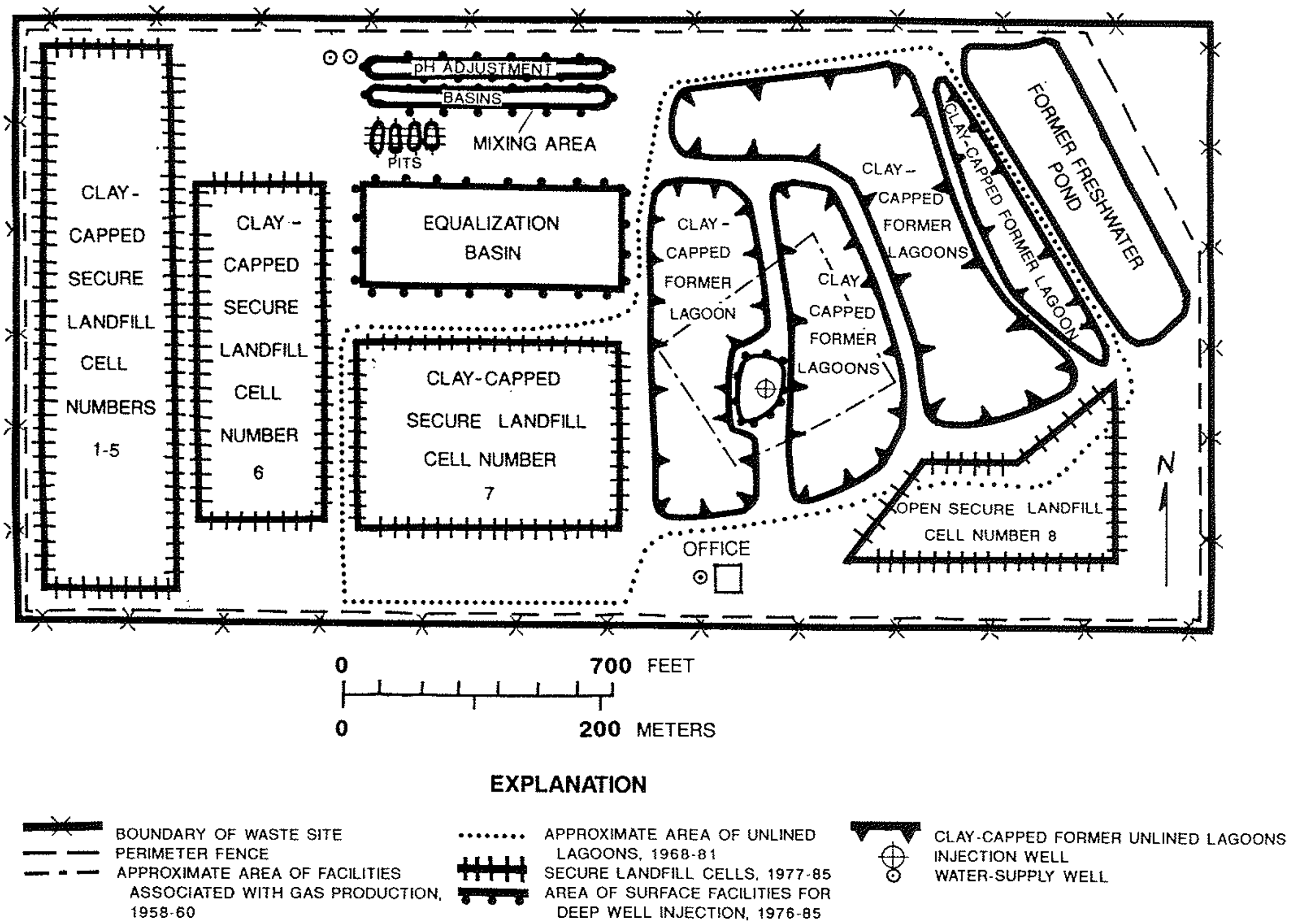


Figure 4. Status of facilities at the hazardous-waste disposal site.

and others, 1983). Petroleum refinery wastewater contains a broad range of priority and nonpriority pollutants including monocyclic aromatic hydrocarbons, halogenated aliphatic hydrocarbons, polycyclic aromatic hydrocarbons, phthalate esters, and miscellaneous compounds (table 2). Chemical analyses indicate the solidified sludge from the bottom of the now-closed unlined lagoons contains a variety of organic pollutants from the following classes: monocyclic aromatic hydrocarbons, halogenated aliphatic hydrocarbons, polycyclic aromatic hydrocarbons, and phthalate esters (table 3). Organic pollutants were detected in monitoring wells at the site beginning with the advent of intensive sampling for organic compounds in late 1982.

GEOHYDROLOGY

The study area is underlain by sediments containing freshwater to a depth of about 900 ft (fig. 5). The sediments consist of southward dipping beds of clay, silt, sand, and gravel and range in age from Pliocene to Holocene. Aquifers underlying Calcasieu Parish include undifferentiated alluvium, the Chicot aquifer system, and the Evangeline aquifer. Surficial clay covers most of the parish and forms an upper confining unit for the aquifers in most areas. Intervening confining clays generally separate the aquifers. The Chicot aquifer system in the Lake Charles area has been divided into four aquifers named for their depth of occurrence at Lake Charles (Harder, 1960): the shallow, the "200-foot," the "500-foot," and the "700-foot" aquifers. These aquifers occur at shallower depths in the study area than indicated by their names because the units dip southward and the study area is north of Lake Charles.

Aquifers and Confining Units

The aquifers (sand and gravel) and confining units (clays) above the base of the "200-foot" aquifer are the units of interest in this report, and include (in descending order) surficial sand and clay and undifferentiated alluvium, the shallow aquifer of the Chicot aquifer system, clay, and the "200-foot" aquifer of the Chicot aquifer system. In Calcasieu Parish, the "200-foot" aquifer is the shallowest of the principal freshwater-bearing sands that underlie the parish (Harder, 1960, p. 10).

In the study area, the interval between land surface and the top of the "200-foot" aquifer at a depth of 70 to 90 ft is dominated by low-permeability sediments consisting of clay, silt, and fine sand and includes the surficial sands, undifferentiated alluvium, and the shallow aquifer. An exception occurs near the Little River and the West Fork Calcasieu River where alluvial silt and sand predominate in the interval. Much of the sand and silt in this interval is mixed with clay to form sandy or silty clay or clayey sand or silt; but irregular, discontinuous beds and pockets of sand and silt occur throughout the interval. A relatively continuous zone of sand and silt that occurs beneath much of the study area at a depth of about 50 ft below land surface has been referred to locally as the "50-foot pervious zone." This zone is the main updip equivalent of the shallow aquifer of the Lake Charles area and will be referred to as the shallow aquifer in this report. Irregular, discontinuous beds of sand and silt within the surficial clay above the shallow aquifer will be referred to as surficial sands.

Occurrence

The study area is located in an area of local thickening of silts and sands in the shallow subsurface. Undifferentiated alluvium, essentially insignificant on a regional scale, is present along the northern and eastern sides of the study area. The shallow aquifer is present beneath most of the study area but becomes discontinuous to the south. Regionally, the "200-foot" aquifer is continuous, but the aggregate thickness of sand and silt beds making up the "200-foot" aquifer thins from a maximum of 130 ft beneath the study area to as little as 20 ft to the south (fig. 5).

Table 2. Organic pollutants in petroleum refinery wastewater discharge
[From Brown and Associates, 1980, p. 329]

Monocyclic Aromatic Hydrocarbons
Benzene
Chlorobenzene
Ethylbenzene
Pentachlorophenol
Phenol
Toluene
2,4-Dimethylphenol
2,4-Dinitrotoluene
Halogenated Aliphatic Hydrocarbons
Methylene chloride
Tetrachloroethane
1,2-Dichloroethane
1,1,1-Trichloroethane
Chloroform
Polycyclic Aromatic Hydrocarbons
Benzo(a)anthracene
Anthracene
Fluorene
Phenanthrene
Pyrene
Naphthalene
Phthalate Esters
Butylbenzyl phthalate
Di-n-butyl phthalate
Di-n-octyl phthalate
Diethyl phthalate
Miscellaneous Compounds
1,2-Diphenylhydrazine
Isophorone

Descriptions of the occurrence of each of the aquifers and confining units in the study area are based on geohydrologic sections through the area (figs. 6 and 7) and on structure contour and thickness maps (not shown). Surficial clay occurs over most of the study area, but is absent in places within the valleys of the Little River and the West Fork Calcasieu River. The surficial clay generally ranges from 20 to 60 ft in thickness with a maximum observed thickness from soil boring logs of 90 ft in the northwestern part of the waste site where the shallow aquifer is absent. Clay overlying the undifferentiated alluvium in the flood plains of the Little River and the West Fork Calcasieu River resembles, but is younger than, the surficial clay overlying the shallow aquifer in the rest of the study area. Black, organic clay occurs near the contact between the surficial clay and the shallow aquifer in the central and eastern parts of the waste site.

Table 3. Analyses of organic pollutants in solidified sludge from unlined lagoons at the hazardous-waste disposal site in Calcasieu Parish

[Unpublished data are on file at the Louisiana Department of Environmental Quality, Baton Rouge, La., 1985. See figure 4 for location of unlined lagoons. Concentrations in milligrams per kilogram; --, not detected]

Organic pollutant	Unlined lagoon no. 4[a] Sampled 04-10-84 Depth 0-6 feet	Unlined lagoon no. 5[b] Sampled 01-30-84 Depth 7-9 feet
Monocyclic Aromatics		
Benzene	12	--
Chlorobenzene	31	--
Dichlorobenzene	1.5	--
Ethylbenzene	28	--
Toluene	4.2	--
1,2,4-Trichlorobenzene	--	124
Halogenated Aliphatic Hydrocarbons		
Chloroform	0.1	0.1
1,1-Dichloroethane	.2	--
1,2-Dichloroethane	9.8	--
1,1-Dichloroethene	.4	--
Trans-1,2-dichloroethene	.2	--
Methylene chloride	.4	--
1,1,2,2-Tetrachloroethane	1.3	--
Tetrachloroethene	1.6	--
1,1,1-Trichloroethane	.0	--
1,1,2-Trichloroethane	.0	--
Trichloroethene	.5	--
Polycyclic Aromatic Hydrocarbons		
Anthracene	--	1,125
Benzo(a)pyrene	--	436
Benzo(ghi)perylene	--	100
Chrysene	--	306
Fluorene	--	199
Naphthalene	--	380
Pyrene	--	488
Phthalate Esters		
Diethyl phthalate	--	100

[a] Soil sample from boring L-208, 300 feet northeast of well Cu-931 (fig. 3).
[b] Soil sample from boring L-202, 150 feet southwest of well Cu-936 (fig. 3).

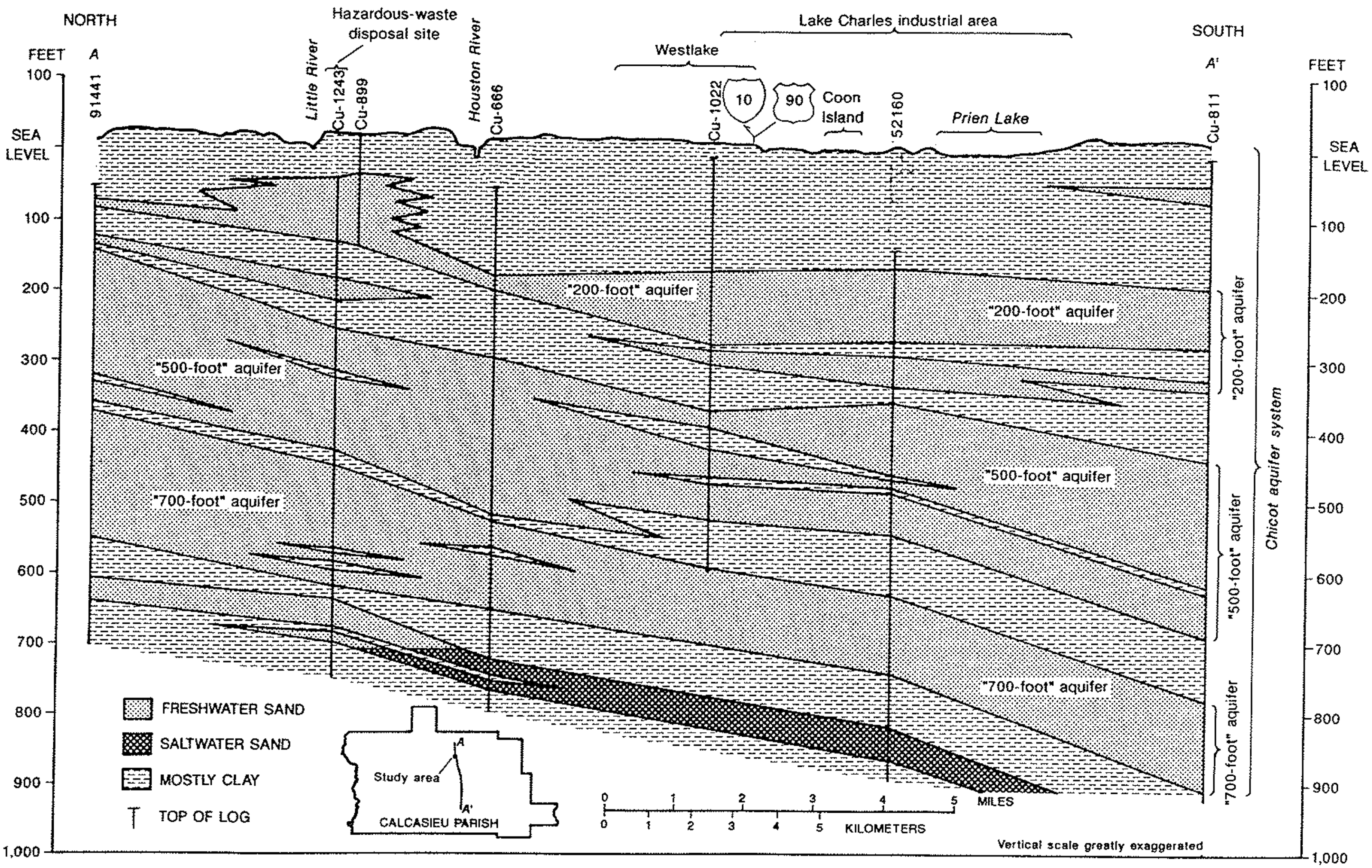


Figure 5. Geohydrologic section A-A' across the study area and the Lake Charles industrial area.

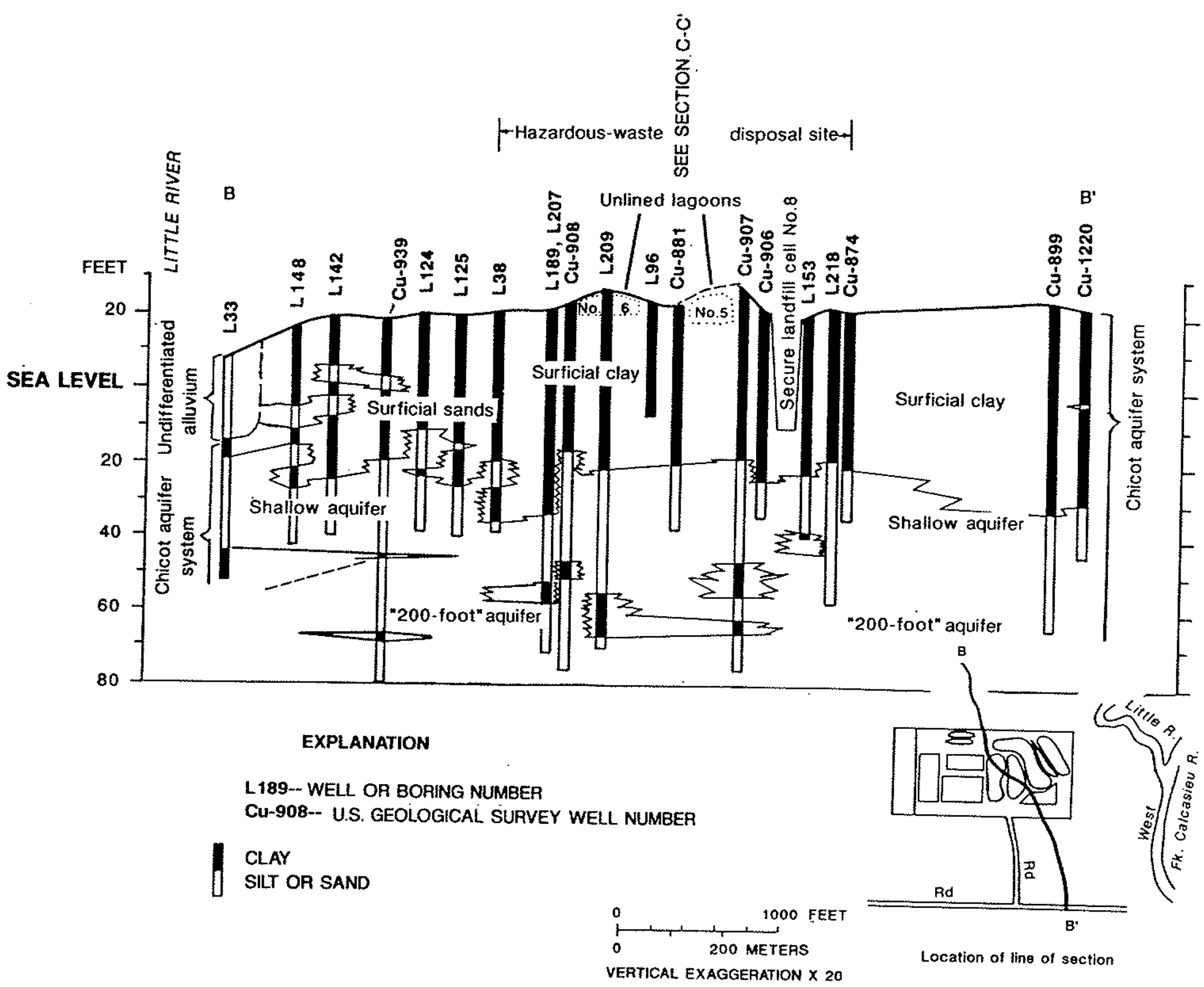


Figure 6. Geohydrologic section B-B' through the hazardous-waste disposal site.

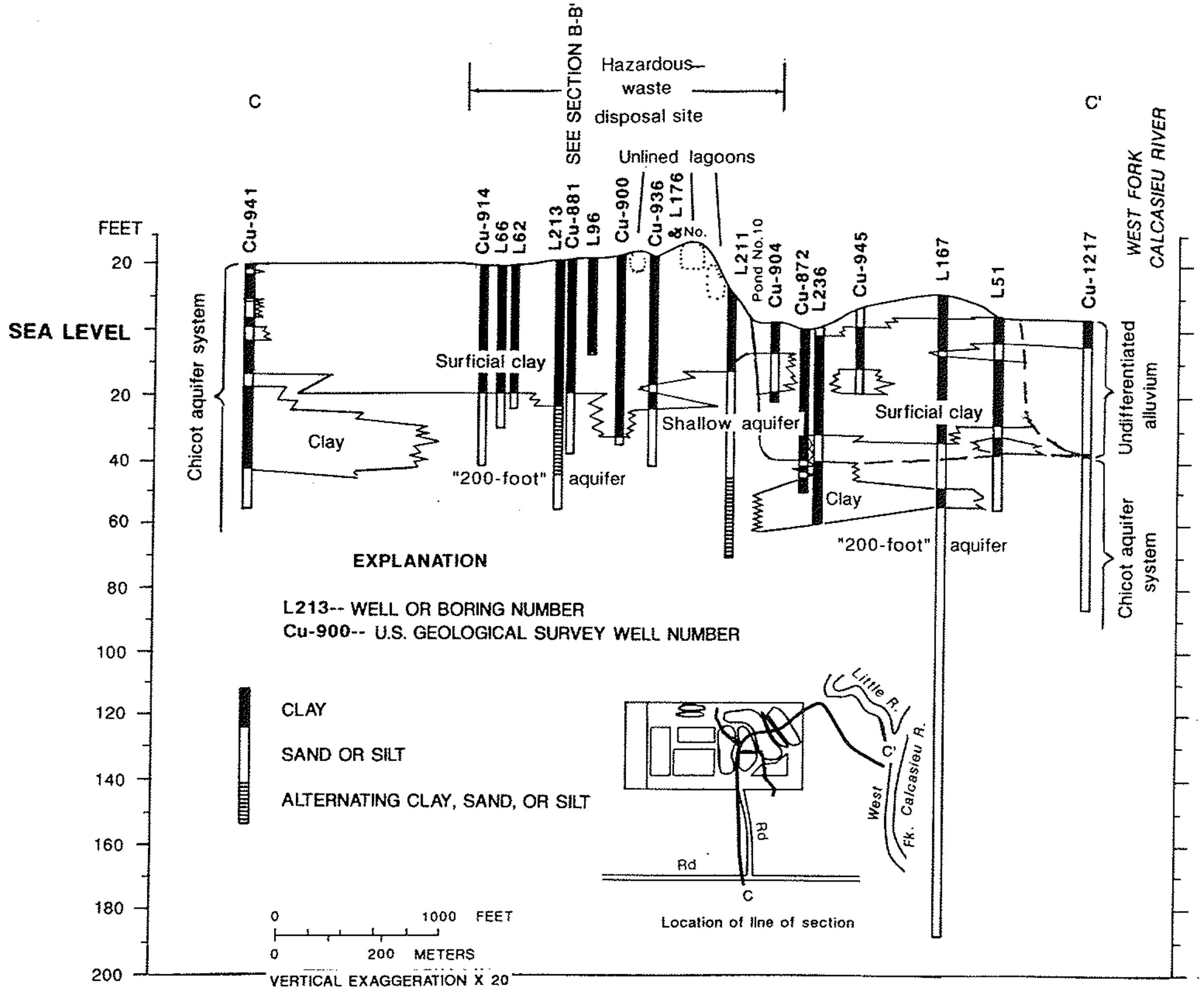


Figure 7. Geohydrologic section C-C' through the hazardous-waste disposal site.

The undifferentiated alluvium occurs only beneath the flood plain of the Little River and the West Fork Calcasieu River (figs. 6 and 7). The undifferentiated alluvium was deposited in valleys entrenched into or through the surficial clay and the shallow aquifer and possibly into the top of the "200-foot" aquifer by the Little River and the West Fork Calcasieu River. The maximum thickness of the alluvium is undetermined because of the difficulty of distinguishing the alluvium from the shallow and "200-foot" aquifers.

An intervening clay separates the undifferentiated alluvium and the shallow aquifer in some areas near the two rivers (fig. 6). The clay is thin or missing in other areas beneath the Little River and the West Fork Calcasieu River where thick sands are present (fig. 7). The clay is generally less than 20 ft thick. The maximum observed thickness is 40 ft.

The shallow aquifer is nearly continuous across the study area. The shallow aquifer generally is less than 10 ft thick across the western part of the waste site, and it is generally 10 to 20 ft thick across the eastern part. The shallow aquifer thickens toward the West Fork Calcasieu River. The shallow aquifer is missing in several relatively small areas within the study area, the largest of which is in the northwestern part of the waste site. (See figure 10.)

The clay separating the shallow aquifer and the "200-foot" aquifer is discontinuous (figs. 6 and 7). The clay is missing in the eastern third of the waste site and is generally less than 20 ft thick over the rest of the study area. The maximum thickness is 30 ft. The "200-foot" aquifer is continuous across the study area. The maximum thickness of sand and silt beds within the "200-foot" aquifer is 130 ft.

Lithology

The descriptions of the lithology of the units that occur beneath the study area are based on soil-boring logs and grain-size analyses obtained from BFI-CSI and from data collected during this study. The surficial clay is heterogeneous as it characteristically contains the silt and sand stringers, lenses, pockets, and layers that form the surficial sands. Calcareous and ferrous nodules and organic matter also are prevalent. An iron sulfide mineral was found when drilling well Cu-1220 (fig. 3). Locally, naturally-occurring organic matter within the clay is so abundant that the clay is classified as organic clay. Less widespread than the surficial sands but perhaps more significant in terms of vertical movement of fluids are joints, silt and sand filled joints, and slickensided joints within the clay. Root networks and crawfish holes are other secondary permeability features present in the surficial clay that could have the effect of greatly increasing the vertical permeability.

The undifferentiated alluvium is composed of interfingering, discontinuous, lenticular bodies of fine sand or silt, or more commonly, mixtures of both. Clay beds commonly separate individual sand or silt beds but clay is less abundant in this unit than in the adjoining surficial clay. Inclusions of organic matter are also common. The undifferentiated alluvium contains enough naturally-occurring organic matter in places to be classified as organic silt.

The shallow aquifer is lithologically similar to the undifferentiated alluvium except that clay is more common within and between the sand beds. Layers and pockets of organic matter, disseminated organic matter, organic silt and clay, wood, and roots are reported in numerous boreholes penetrating this unit.

The upper part of the "200-foot" aquifer is lithologically similar to the shallow aquifer. In places where intervening clays are absent, contacts between alluvial sands, the shallow aquifer, and the top of the "200-foot" aquifer are not readily distinguishable from cores or boring logs. In general, the "200-foot" aquifer contains less organic matter than occurs in the overlying units. The "200-foot" aquifer coarsens downward from fine sand and silt mixtures near the top of the unit to gravelly sand below 150 ft. Individual sand beds within the "200-foot" aquifer are discontinuous and are often separated by clays.

Hydraulic Characteristics

Data on the horizontal and vertical hydraulic conductivity of sediments underlying the waste site were obtained from BFI-CSI and are summarized in table 4. In general, the data presented in table 4 represent field determinations of the horizontal hydraulic conductivity from aquifer tests in wells and laboratory determinations of the vertical hydraulic conductivity of cores. The average vertical hydraulic conductivity of the surficial clay is 2.4×10^{-4} ft/d. This value is for uniform samples from cores and does not reflect the effects of joints or other secondary permeability features. The average horizontal hydraulic conductivities of the undifferentiated alluvium and shallow aquifer are relatively low (2.6 and 2.8 ft/d). The reported average horizontal hydraulic conductivity of the "200-foot" aquifer at Lake Charles is 107 ft/d (Harder, 1960, p. 28). The ranges in hydraulic conductivity given in table 4 indicate the high degree of heterogeneity and anisotropy that occur in the hydraulic characteristics of the sediments in the study area.

Table 4. Summary of field and laboratory measurements of hydraulic conductivity of sediment at the hazardous-waste disposal site in Calcasieu Parish

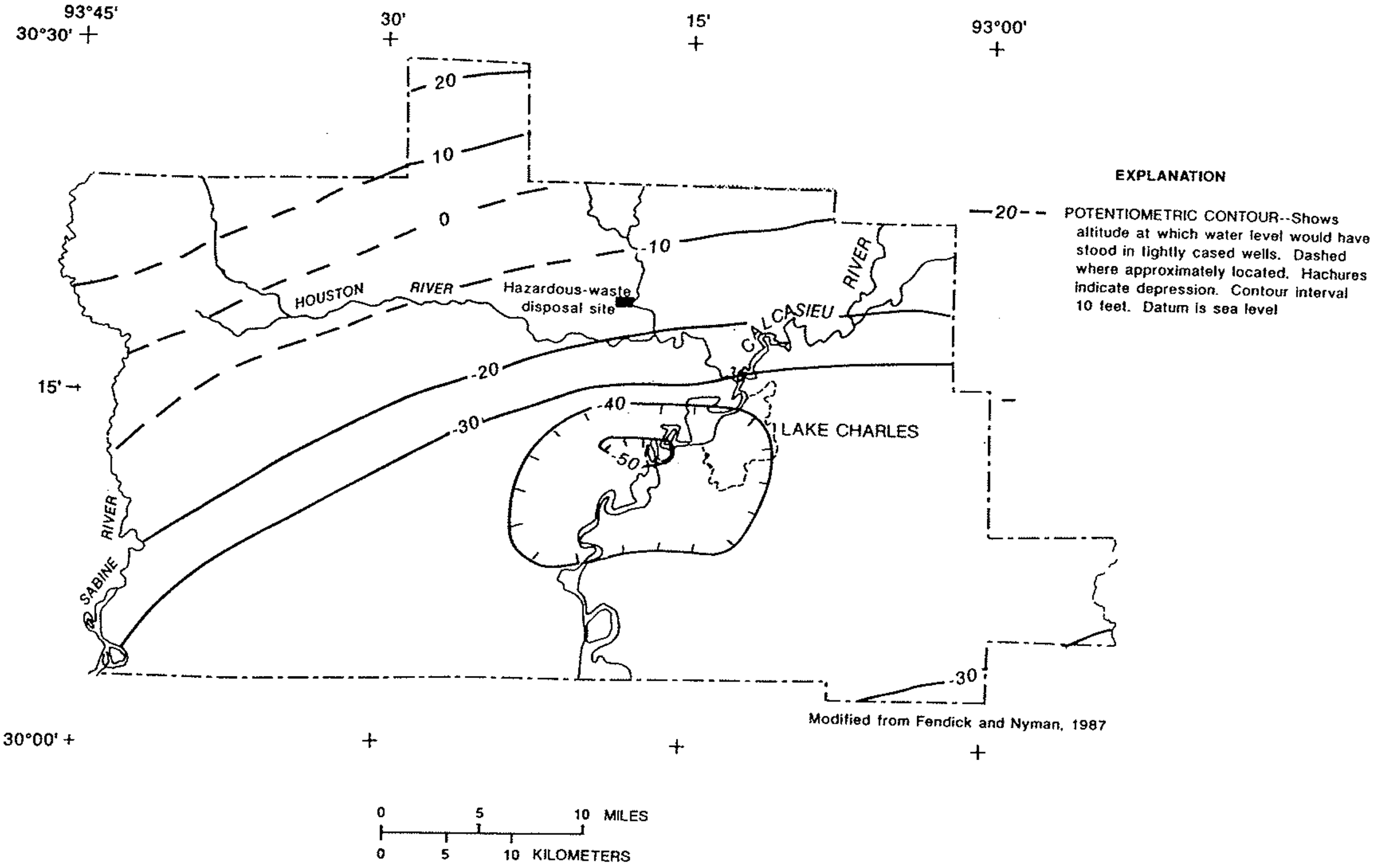
[Unpublished data obtained from Browning-Ferris Industries - Chemical Services Incorporated, Houston, Texas; units are in feet per day; -- no data]

Geohydrologic unit	Horizontal hydraulic conductivity			Vertical hydraulic conductivity		
	Number of tests	Range	Average	Number of tests	Range	Average
Surficial clay	2	5.7×10^{-5} to 2.8×10^{-4}	1.7×10^{-4}	25	1.3×10^{-6} to 2.8×10^{-3}	2.4×10^{-4}
Undifferentiated alluvium	1	--	2.6	8	8.5×10^{-5} to 1.3×10^{-2}	2.4×10^{-3}
Shallow aquifer, Chicot aquifer system	7	5.7×10^{-2} to 11.0	2.8	15	1.1×10^{-4} to 1.2×10^{-1}	2.3×10^{-2}
Intervening clay	--	--	--	8	1.7×10^{-5} to 1.7×10^{-4}	1.1×10^{-4}
"200-foot" aquifer, Chicot aquifer system	--	--	--	3	6.8×10^{-4} to 6.8×10^{-3}	4.8×10^{-3}

Ground-Water Flow System

Ground water moves from areas of recharge to areas of discharge in an aquifer system. The principal recharge area for the Chicot aquifer system in Calcasieu Parish is the outcrop area, which is north of Calcasieu Parish in Beauregard and Allen Parishes (Nyman, 1984, p. 9). The discharge area in Calcasieu Parish coincides with pumping centers, of which Lake Charles and the industrial area west of Lake Charles are the most important to this investigation. Water enters the aquifers in the outcrop area, moves downdip in a general south to southeasterly direction, and is eventually discharged from the aquifer system through ground-water pumping. Downdip of the outcrop area, ground water generally is confined by overlying clays.

The patterns of ground-water flow are reflected in maps of the potentiometric surfaces of the aquifers. Water-level contours of the "200-foot" aquifer (fig. 8) are highest in the northern part of the parish and lowest west of Lake Charles. In the "200-foot" aquifer, water moves from the north to the south-southeast where it is intercepted by pumping near Lake Charles. Water levels in the "200-foot" aquifer at Lake Charles are largely controlled by pumping from the "500-foot" aquifer which induces downward leakage of water from the "200-foot" aquifer (Nyman, 1984, p. 8). The flow of ground water in aquifers above the "200-foot" aquifer is controlled by the interaction of topography, configuration and interconnection of individual sand beds, and local pumping. Flow in these aquifers will be described in the section "Water Levels and Ground-Water Movement in the Study Area."



Modified from Fendick and Nyman, 1987

Figure 8. Potentiometric surface of the "200-foot" aquifer, Calcasieu Parish, spring 1985.

Recharge

The amount and location of ground-water recharge will affect water levels in an aquifer and the corresponding directions of ground-water flow. Estimates of the rate of ground-water recharge to the outcrop area of the Chicot aquifer system vary from 0.8 in/yr (Jones and others, 1956, p. 228) to more than 4 in/yr (D.J. Nyman, U.S. Geological Survey, oral commun., 1986). The outcrop of the Chicot aquifer system is characterized by sands and gravels overlain by a thin veneer of clay, whereas the waste site is characterized by silts and sands overlain by up to 90 ft of clay. Although not determined, the ground-water recharge rate at the waste site is presumably less than that in the outcrop area of the Chicot aquifer system because of lithologic conditions.

Water Levels and Ground-Water Movement in the Study Area

Water-level measurements, made between February 27 and March 1, 1985, were used to prepare the potentiometric surface maps for aquifers within the study area (figs. 8-11). Water levels during the spring generally are at their highest (Harder, 1960, p. 44). The ground-water flow system in the study area is complex because ground water flows in different directions in the different aquifers.

Comparison of figures 9 through 11 shows that water levels generally are highest in the undifferentiated alluvium and the surficial sands, and decrease with depth in the shallow aquifer and into the "200-foot" aquifer. Water-level measurements made in the study area show that the downward gradient continues into the "500-foot" aquifer. The downward gradient exists over the entire study area showing that the Chicot aquifer system has the potential to be recharged in the study area by rainfall and by water infiltrating from the two nearby rivers.

The top of the saturated zone generally occurs within the surficial clay across the study area, so a true water table exists only locally in isolated surficial sand beds or in sandy zones near the top of the undifferentiated alluvium. The top of the saturated zone occurs at depths of a few feet to 10 ft below land surface. The maximum hydraulic gradient occurs between the top of the saturated zone and the top of the shallow aquifer. The gradient in this interval approaches one, 1-foot change in water level per 1-foot change in depth.

The number and distribution of water-level measurements of wells in the undifferentiated alluvium and surficial sands were insufficient for preparing a contour map of water levels for the spring of 1985. Water levels in the northeastern part of the waste site were low because of pumping for contaminant recovery from wells Cu-885 and Cu-904 (figs. 3 and 9). Water-level data collected from wells (Cu-944, Cu-945, Cu-1227, Cu-1228, and Cu-1230) drilled after the spring of 1985 in the eastern part of the study area indicate that water levels in the surficial sands and the undifferentiated alluvium reflect the surface topography. Water movement in the eastern part of the study area is generally northeasterly and easterly toward the two nearby rivers. Additional water-level data are needed to describe the direction of water movement within the surficial sands beneath the rest of the waste site. Because the surficial sands beneath the western part of the waste site are laterally discontinuous, the primary direction of water movement is probably downward.

Ground water moves away from areas of high water levels in the shallow aquifer toward the southeast; the area with the lowest water levels in the study area (fig. 10). Movement is perpendicular to the potentiometric contours. Areas of high water levels include the valleys of the Little River and the West Fork Calcasieu River and an area of hydraulic connection with surficial sands west of the waste site. Water moving from the surficial sands and the undifferentiated alluvium recharges the shallow aquifer in these areas. In the areas of mergence between the shallow and "200-foot" aquifers in the study area, ground water moves from the shallow aquifer into the "200-foot" aquifer. Water levels in the shallow and "200-foot" aquifers in the area of mergence south of the waste site are similar (wells Cu-899 and Cu-1220), indicating good hydraulic connection between the aquifers in this area.

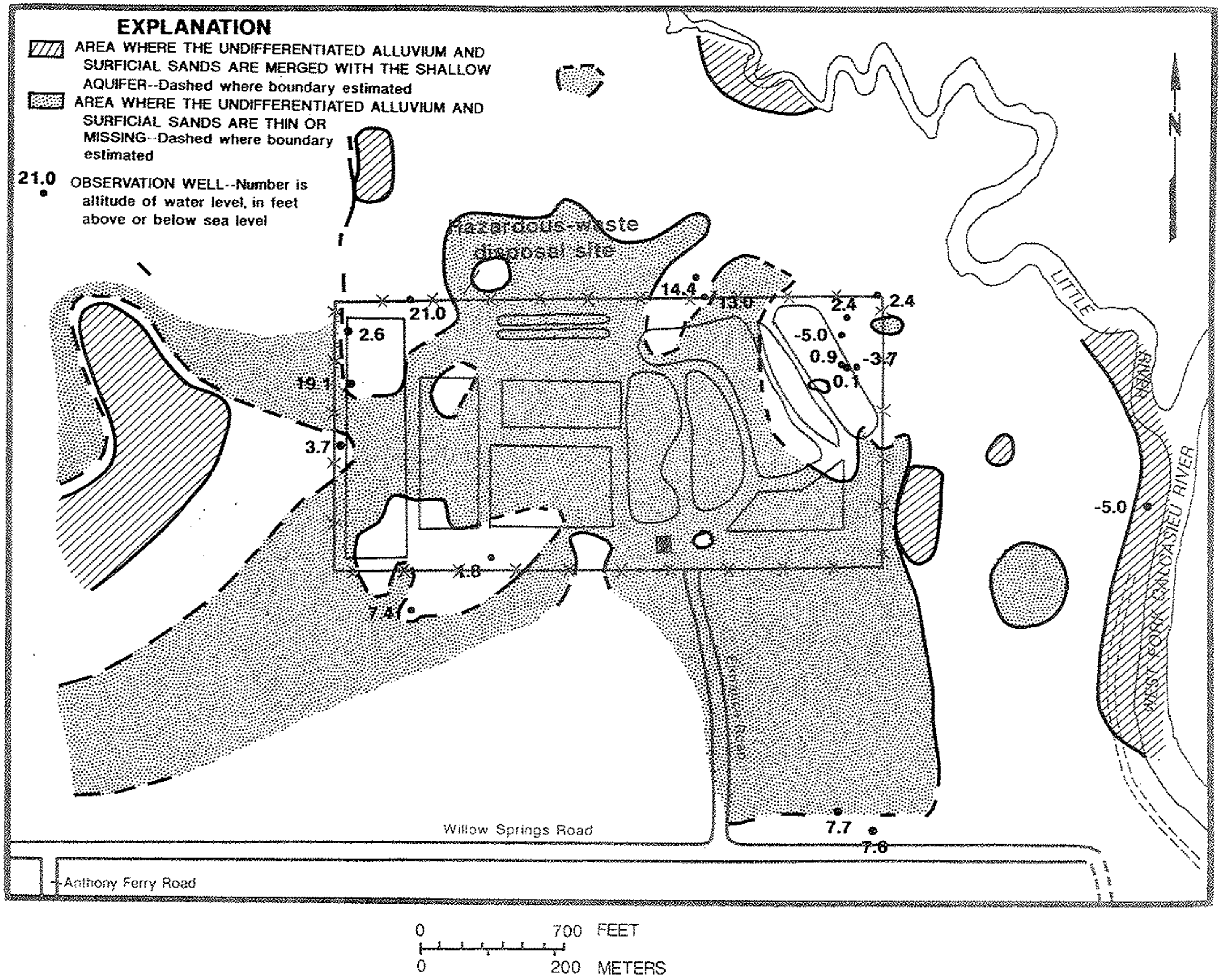


Figure 9. Altitude of water levels in the undifferentiated alluvium and surficial sands, spring 1985.

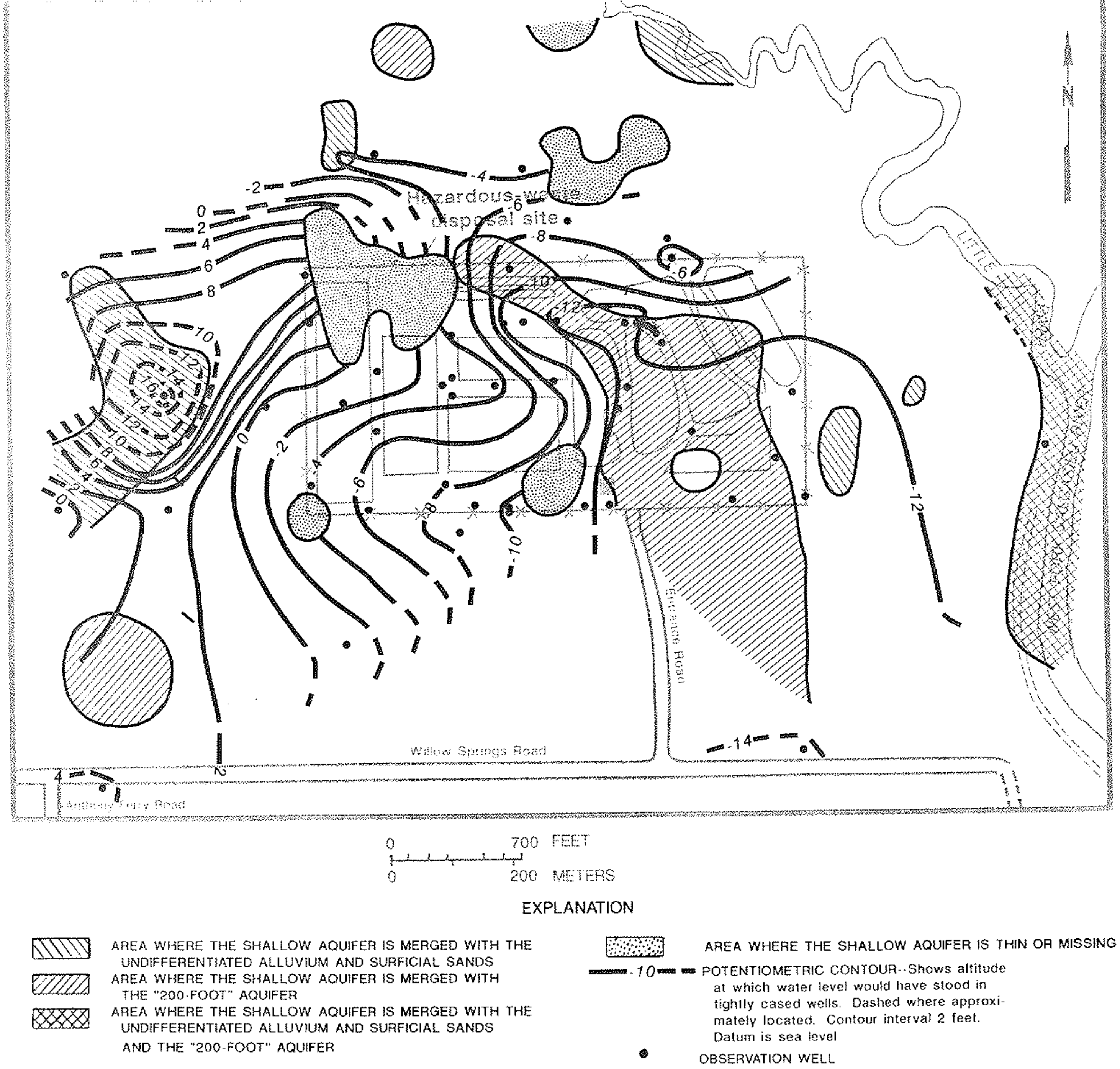


Figure 10. Potentiometric surface of the shallow aquifer of the Chicot aquifer system, spring 1985.

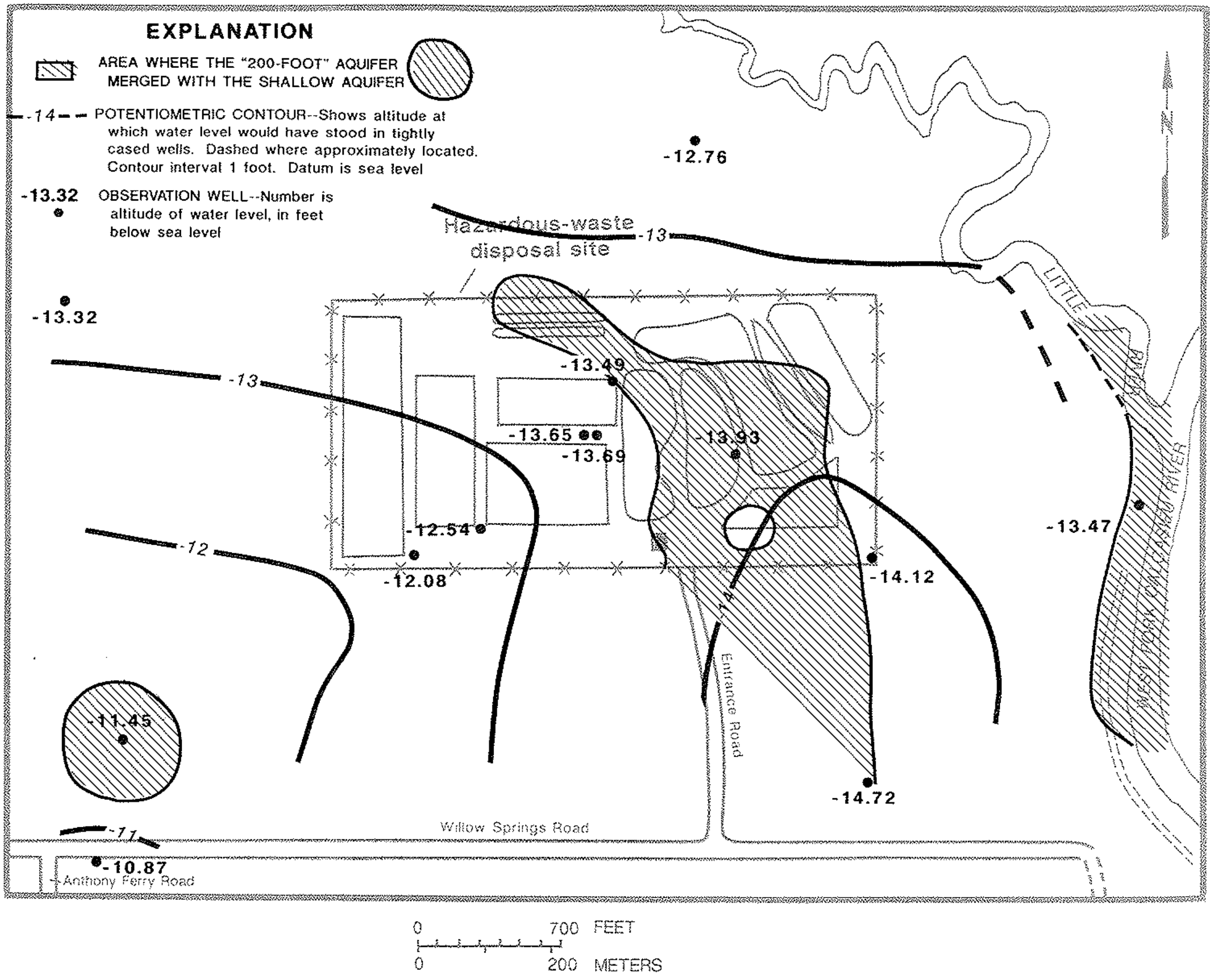


Figure 11. Potentiometric surface of the "200-foot" aquifer of the Chicot aquifer system, spring 1985.

In the "200-foot" aquifer, water moves away from areas of high water levels and eventually toward the southeast (fig. 11). Areas of high water levels in the "200-foot" aquifer are north of the waste site, at the West Fork Calcasieu River, and southwest of the waste site (fig. 11). The high water levels in wells in the "200-foot" aquifer southwest of the site and at the West Fork Calcasieu River are believed to be caused by the movement of water from the shallow aquifer into the "200-foot" aquifer. Water also moves downward from the "200-foot" aquifer to the "500-foot" aquifer.

Water-level fluctuations in wells in the surficial sands, the shallow aquifer, and "200-foot" aquifer at the waste site are shown in figure 12. The most rapid and largest fluctuation in water level occurs in the surficial sands. Rapid changes in water level in the surficial sands reflect the influence of recharge. A general pattern of low water levels in summer and high water levels in spring is observed (fig. 12). Water levels in the shallow and "200-foot" aquifers reflect a similar but subdued pattern. Fluctuations of water levels greater than 10 ft are observed in the surficial sands; fluctuations of 2 to 4 ft are observed in the shallow aquifer; and fluctuations of less than 3 ft are observed in the "200-foot" aquifer.

Pumpage

Pumping of ground water affects water levels and the rate and direction of ground-water flow. Water is pumped in the study area from all the aquifers under consideration, but use is small in comparison to pumpage of 1.89 Mgal/d in 1984 from the "200-foot" aquifer at Lake Charles (unpublished data on file, U.S. Geological Survey, Baton Rouge, La., 1985). Residents in the study area obtain water for domestic purposes primarily from wells completed in the "200-foot" and "500-foot" aquifers. Use of water from wells completed in aquifers above the "200-foot" aquifer for domestic purposes generally ceased with the discovery of ground-water contamination at the waste site. Ground water is pumped at the waste site from the "200-foot" aquifer for domestic use (an office well, located 150 ft west of well Cu-914) and from surficial sands and the shallow aquifer for contaminant recovery (wells Cu-885, Cu-904, and Cu-936). Also, water is pumped from the "500-foot" aquifer (well Cu-934) for industrial purposes. Pumping from the office well is at a low enough rate to have little effect on water levels in the "200-foot" aquifer (fig. 11). Contaminant-recovery pumping affects water levels somewhat in the northeastern part of the waste site (figs. 9 and 10) even though pumpage rates average less than 1 gal/min per well (unpublished data on file, Louisiana Department of Environmental Quality, Baton Rouge, La., 1985).

Rates of Movement

The rate of flow of water in the saturated zone at the waste site can be estimated using Darcy's Law:

$$\bar{v} = \frac{K(dh/dl)}{n},$$

where $\bar{v}$ = average ground-water velocity, in foot per day;
K = hydraulic conductivity, in foot per day;
dh/dl = hydraulic gradient, dimensionless; and
n = effective porosity, dimensionless.

Using an average vertical hydraulic conductivity of 2.4×10^{-4} ft/d, an assumed hydraulic gradient of 1 ft/ft, and assumed effective porosities of 0.2 and 0.5 for a clay, the estimated rate of movement ranges from 4.8×10^{-4} to 1.2×10^{-3} ft/d. The time required for ground water to move through saturated surficial clay using the estimated velocity ranges from 91 to 228 years assuming an average saturated clay thickness of 40 ft.

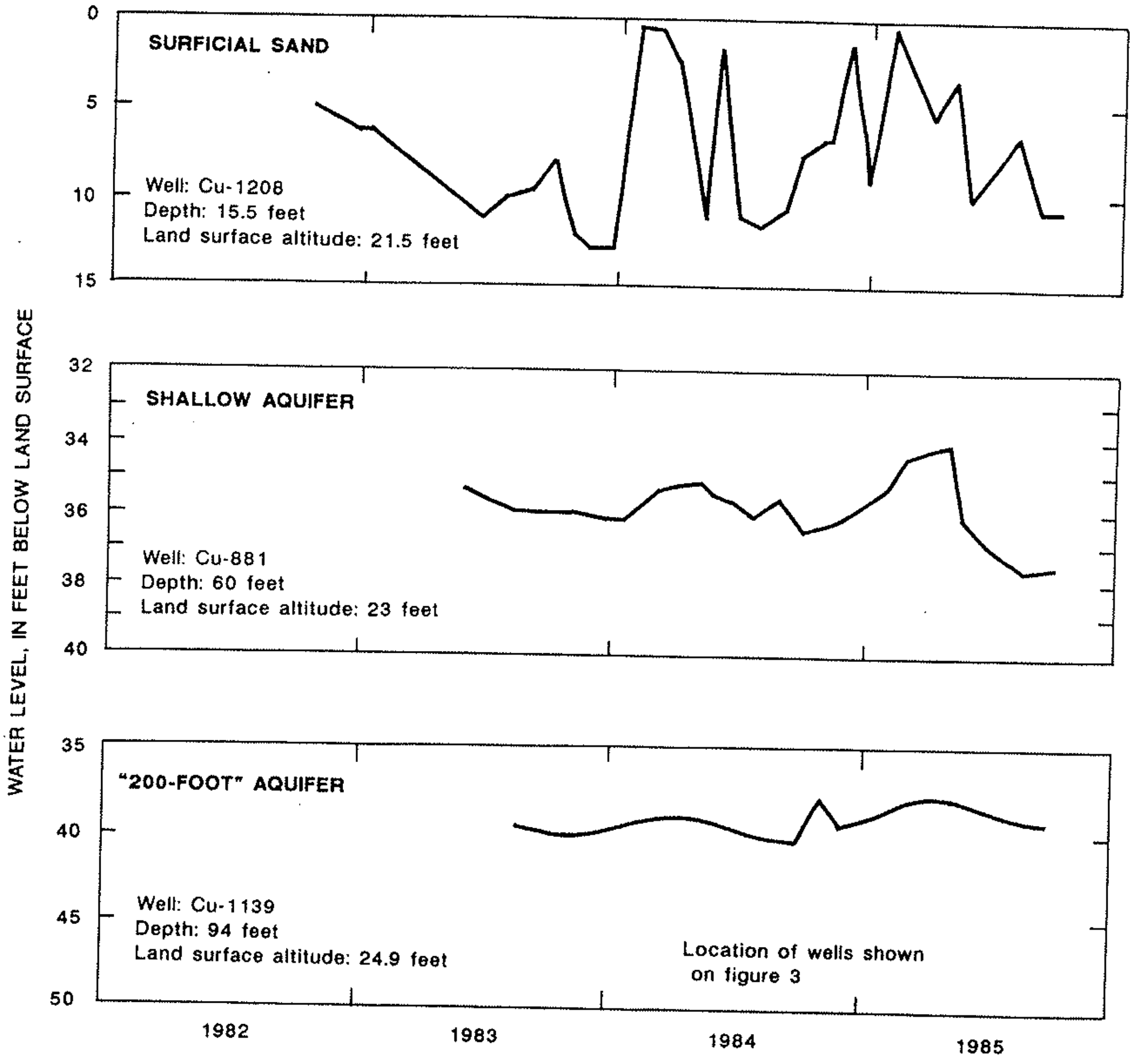


Figure 12. Fluctuation of water levels in wells, 1982-85.

Organic waste stored in unlined lagoons in 1968 or later, migrated through the surficial clay and contaminated the shallow aquifer by 1982, indicating that the waste took less than 15 years to reach the shallow aquifer. Thus, the observed rate of contaminant movement is much higher than the estimated rates of ground-water movement. This discrepancy is best explained by assuming that the effective vertical hydraulic conductivity of the surficial clay is higher than the average value of 2.4×10^{-4} ft/d and that the effective thickness is less than the 40 ft used in estimating the rate of ground-water movement.

The presence of joints, root networks, and other features of secondary permeability in the surficial clay provides strong evidence that locally the vertical hydraulic conductivity may be much higher, possibly by an order of magnitude or more, than the values measured on relatively uniform, unfractured samples selected from cores. Preferential movement of waste along the joints is shown by notations in the core descriptions such as "sand-filled joints with black oily substance" and "slickensided joints with oily sheen." In addition, there are places within the waste site where less than 10 ft of surficial clay overlies surficial sands or alluvial sands that are in contact with the shallow aquifer. It is possible that a relatively small volume of waste percolating downward through joints or other secondary permeability features at spots where the surficial clay is thin can contaminate a large volume of the shallow aquifer within a relatively short time. Thus, the average rate of movement of water and contaminants through the surficial clay is less important than the maximum rate of movement of contaminants through the thinnest sections of the clay in determining the potential for ground-water contamination.

The rate that ground water moves laterally from the waste site towards Lake Charles in the "200-foot" aquifer can also be estimated using Darcy's Law. Using a horizontal hydraulic conductivity of 107-ft/d, a regional horizontal gradient of 4.0 ft/mi near the hazardous-waste disposal site (fig. 8), and an effective porosity of 0.2, the estimated rate of movement is about 4.1×10^{-1} ft/d. The rate of movement would increase as the gradient increases closer to Lake Charles. Using the average gradient over the entire distance of about 5. 2 ft/mi, the average rate of ground-water movement would be about 5.3×10^{-1} ft/d, indicating that it would take about 210 years for water to move from the waste site to Lake Charles in the "200-foot" aquifer. Although subject to some error resulting from heterogeneity of the aquifer and from uncertainty as to the true value of lateral hydraulic conductivity of the aquifer, the estimate of the rate of lateral movement of water through the "200-foot" aquifer should be better than the estimate of the rate of vertical movement through the surficial clay.

MINERALOGY

To determine the nature and extent of possible interactions between sediment and contaminants, mineral compositions of 68 sediment samples taken from cores of eight drill holes were examined. Six holes were drilled onsite in the contaminated area and two holes offsite in an uncontaminated area. The eight drill holes are located along or near north-south section B-B' (fig. 6).

The mineralogy of the less than 2 μm clay-size fraction was determined by X-ray diffraction for 63 of the 68 samples. Bulk mineralogy was determined for 35 samples, and measurements of bulk cation exchange capacity were made for 32 samples. Nine samples were studied using a scanning electron microscope and energy dispersive spectrometer.

One bulk powder mount was prepared for each sample after oven drying at 110 °C for 24 hours for X-ray diffraction analysis. Semi-quantitative estimates of clay mineral abundance were calculated from diffractograms using a method described by Griffin (1971), with a minor modification. In this study, the mounts were heated at 300 °C for 1 hour rather than being heated at 180 °C for 1 hour. Relative proportions of illite, smectite, and kaolinite were determined. The use of the total clay peak follows procedures described by Schultz (1964). Ratios of peak intensities were calculated for (1) quartz/(quartz + plagioclase), (2) total clay/(quartz + plagioclase), and (3) plagioclase/(plagioclase + K-feldspar).

The procedure followed for preparing samples for the measurements of cation exchange capacity is that of Busenburg and Clemency (1973). An ammonia electrode was used to measure the cation exchange capacity.

The samples examined by scanning electron microscope were mounted in aluminum stubs, dried at room temperature overnight in a vacuum oven, and carbon coated. An energy dispersive spectrometer was used in conjunction with a scanning electron microscope for the analysis.

The results of the solid-phase analyses are presented in table 5. Analyses indicate quartz, plagioclase feldspar, and K-feldspar are the most abundant non-clay minerals in the bulk sediment. Calcite and dolomite occur only rarely and in trace amounts. Quartz is more abundant than the two feldspars. The proportion of clay minerals to quartz and feldspar varies widely, depending on the grain size distribution of the bulk sediment and depositional controls.

Analysis of the less than 2 µm fraction indicates that in most samples smectite is the most abundant clay mineral (averaging 45 percent), illite is intermediate in abundance (averaging 35 percent), and kaolinite is least abundant (averaging 20 percent).

Generally, the samples were from the low-permeability sediments overlying the "200-foot" aquifer, but samples from the "200-foot" aquifer also were included. The variability in the relative abundances of kaolinite, smectite, and illite, of more than 50 percent is most likely depositional in origin. The X-ray diffraction analysis indicates no apparent difference between the bulk clay mineralogy of uncontaminated and contaminated samples.

A preliminary analysis using a scanning electron microscope and an energy dispersive spectrometer indicates that there may be small-scale compositional and textural differences between uncontaminated and contaminated sediment samples. The uncontaminated sediments are predominantly composed of clay-coated detrital grains with variable amounts of authigenic clay and no evidence of dissolution, whereas contaminated sediments are characterized by dissolution of detrital grains and precipitation of diagenetic minerals. Diagenetic minerals (gypsum, aragonite, barite, and quartz) in sediments from the contaminated zone may reflect the influx of high-salinity brines. Preferential dissolution of detrital grains is restricted to sediments within the contaminated zone and is, therefore, thought to be caused by chemical changes resulting from waste disposal. Illite and smectite are the only authigenic minerals observed in uncontaminated samples.

The relative rates and timing of dissolution and precipitation could affect the permeability of the sediment and the rate of contaminant transport through the sediment. Although the permeability of the sediment samples used in the scanning electron microscope study were not determined, changes in permeability as a result of dissolution could explain the apparent speed of contaminant movement through the low permeability sediments at the waste site.

OCCURRENCE OF SELECTED CHEMICAL CONTAMINANTS

Available data showed that contaminants are present beneath the waste site in both the sediment and the ground water, the solid and liquid phases. Water-quality samples were collected and analyzed from onsite and offsite wells for use in conjunction with previously collected data in defining the nature and extent of ground-water contamination. Because of the lack of access to enable onsite drilling for additional sediment samples, only previously collected data were used to describe the extent of onsite contamination in sediment.

Analysis of the Solid-Phase Data

Contaminated sediment is described in the logs of 39 soil borings and in records of excavations onsite (unpublished data on file, Louisiana Department of Environmental Quality, Baton Rouge, La., 1985). Figure 13 shows the location of borings and excavations in which contaminated sediment was encountered. The most common and deepest occurring contaminant is a nonaqueous phase liquid (NAPL) described in the boring logs as oil. Oil is described in the logs as occurring as pockets, streaks, spots, generally dispersed in the interval, or along fractures. Other descriptors used to describe contaminated sediment in the logs include chemical odors and waste. The maximum depth of reported NAPL-contaminated sediment was 51 ft.

Table 5. Results of the solid phase analysis

[QTZ, quartz; FSP, total feldspar; PLAG, plagioclase feldspar; KSP, potassium feldspar. Stratigraphic code: 1 = surficial clay; 2 = surficial sand; 3 = shallow aquifer of the Chicot aquifer system; 4 = clay separating 3 and 5; 5 = "200-foot" aquifer of the Chicot aquifer system]

Local well number	Interval (feet)	Kaolinite	Illite	Smectite	QTZ/ (QTZ+ FSP)	Total clay/ (QTZ+ FSP)	PLAG/ (PLAG+ KSP)	Cation exchange capacity[1]	Strati-graphic code	Scanning electron microscope description
		percent of total clay in less than 2 micron fractions								
Cu-870	2.0 - 4.0	--	--	--	0.86	0.10	0.70	20.0	1	
	10.0 - 12.0	32	36	32	.77	.36	.00	19.2	1	
	20.0 - 22.0	37	34	29	.77	.11	.69	23.3	1	
	30.0 - 32.0	7	13	80	.73	.13	.44	29.3	1	
	34.0 - 36.0	14	32	54	.71	.17	1.00	31.6	1	
	36.0 - 38.0	20	27	53	.71	.38	.60	46.4	1	
	40.0 - 42.0	13	59	28	.83	.08	.60	--	1	
	42.0 - 44.0	14	39	47	.83	.08	.33	38.3	1	
	44.0 - 46.0	25	38	37	--	--	--	--	1	
Cu-874	44.0 - 46.0	26	19	55	--	--	--	--	3	
	50.0 - 52.0	21	15	64	--	--	--	30.4	3	
Cu-875	2.0 - 4.0	46	48	6	1.00	.15	.00	25.9	1	
	10.0 - 12.0	27	53	20	.58	.07	.69	30.4	1	
	20.0 - 22.0	24	47	29	--	--	--	32.9	1	
	28.0 - 30.0	20	44	36	--	--	--	--	1	
	34.0 - 36.0	14	32	54	--	--	--	45.2	1	
	36.0 - 38.0	19	51	30	--	--	--	--	1	
	38.0 - 40.0	39	36	25	--	--	--	--	3	
	40.0 - 42.0	33	26	41	.83	.08	.60	--	4	No authigenic clay, authigenic gypsum.
	50.0 - 52.0	18	37	45	.71	.20	.53	8.5	4	
	58.0 - 60.0	17	40	43	.47	.04	.53	--	4	Minor authigenic illite/smectite, phosphates. Locally extensive dissolution.
Cu-881	8.0 - 10.0	23	41	36	--	--	--	--	1	
	12.0 - 14.0	23	26	51	--	--	--	--	1	
	16.0 - 18.0	25	27	48	--	--	--	--	1	
	38.0 - 40.0	15	46	39	--	--	--	--	1	
	40.0 - 42.0	27	30	43	--	--	--	--	1	No authigenic clay, clay, authigenic barite, gypsum, quartz, aragonite, and silver.
	42.0 - 44.0	22	18	60	--	--	--	--	3	
	58.0 - 60.0	19	16	65	--	--	--	--	3	
Cu-908	2.0 - 4.0	16	27	57	--	--	--	--	1	
	6.0 - 8.0	32	32	36	--	--	--	--	1	Amorphous coating; dissolution of detritals.
	20.0 - 22.0	38	37	25	--	--	--	--	1	Authigenic illite/ smectite, dissolution of detritals.

See footnote at end of table.

Table 5. Results of the solid phase analysis--Continued

Local well number	Interval (feet)	Kaolinite	Illite	Smectite	QTZ/ (QTZ+ FSP)	Total clay/ (QTZ+ FSP)	PLAG/ (PLAG+ KSP)	Cation exchange capacity[1]	Strati-graphic code	Scanning electron microscope description
		percent of total clay in less than 2 micron fractions								
Cu-908 - Continued										
	30.0 - 32.0	15	34	51	--	--	--	--	1	
	32.0 - 34.0	8	34	58	--	--	--	--	1	
	34.0 - 36.5	15	37	48	--	--	--	--	1	
	38.0 - 40.0	22	48	30	--	--	--	--	1	
	40.0 - 42.0	44	28	28	--	--	--	--	1	
	46.0 - 48.0	26	37	37	--	--	--	--	3	
	60.0 - 62.0	24	34	42	--	--	--	--	3	No authigenic clay, authigenic quartz and gypsum, dissolution of detritals.
	68.0 - 70.0	17	39	44	--	--	--	--	3	
	86.0 - 88.0	17	40	43	--	--	--	--	5	
	98.0 - 100.0	18	34	48	--	--	--	--	5	
Cu-939	2.5 - 4.0	39	33	28	0.91	0.14	1.00	24.9	1	Clay covered detrital grains.
	5.0 - 6.5	27	32	41	.43	.04	.76	--	1	Authigenic illite/smectite.
	12.5 - 14.0	21	37	42	.68	.10	.45	24.9	1	
	17.5 - 19.0	22	32	46	.76	.06	.50	--	2	
	22.5 - 24.0	17	28	55	.57	.11	.45	23.0	1	Authigenic illite/smectite.
	25.0 - 26.5	14	38	48	.70	.20	.49	--	1	
	27.0 - 29.0	14	34	52	.62	.32	.50	--	1	
	30.0 - 31.5	--	--	--	.67	.29	.55	--	1	
	37.5 - 39.0	23	33	44	.62	.02	.82	4.9	3	
	42.0 - 44.0	31	31	38	.68	.03	.20	5.7	3	
Cu-1220	10.0 - 11.5	17	44	39	--	--	--	29.2	1	
	20.0 - 21.5	30	36	34	--	--	--	--	1	
	30.0 - 31.5	11	32	57	--	--	--	53.0	1	
	32.0 - 33.5	22	50	30	--	--	--	45.2	1	
	35.0 - 36.5	--	--	--	.60	.17	.57	--	1	
	40.0 - 41.5	15	32	53	.52	.51	1.00	43.4	1	
	42.0 - 43.0	--	--	--	.69	.08	.47	--	1	
	45.0 - 46.5	28	25	47	.68	.06	.62	14.9	1	
	55.0 - 56.5	--	--	--	.81	.07	.50	--	3	
Cu-1286	2.0 - 4.0	--	--	--	.63	.10	.37	23.3	1	
	8.0 - 10.0	27	32	41	.60	.08	.68	17.8	1	
	20.0 - 22.0	27	34	39	.68	.07	.56	18.5	1	
	28.0 - 30.0	14	40	46	.62	.24	.73	39.8	1	
	34.0 - 36.0	--	--	--	.63	.26	.60	39.8	1	
	36.0 - 38.0	13	40	47	.65	.47	.50	48.2	1	
	38.0 - 40.0	16	16	68	.77	.39	1.00	43.0	1	
	40.0 - 42.0	38	19	43	--	--	--	20.7	1	
	42.0 - 44.0	24	64	12	--	--	--	17.1	3	

[1] Concentrations in milliequivalents per 100 grams.

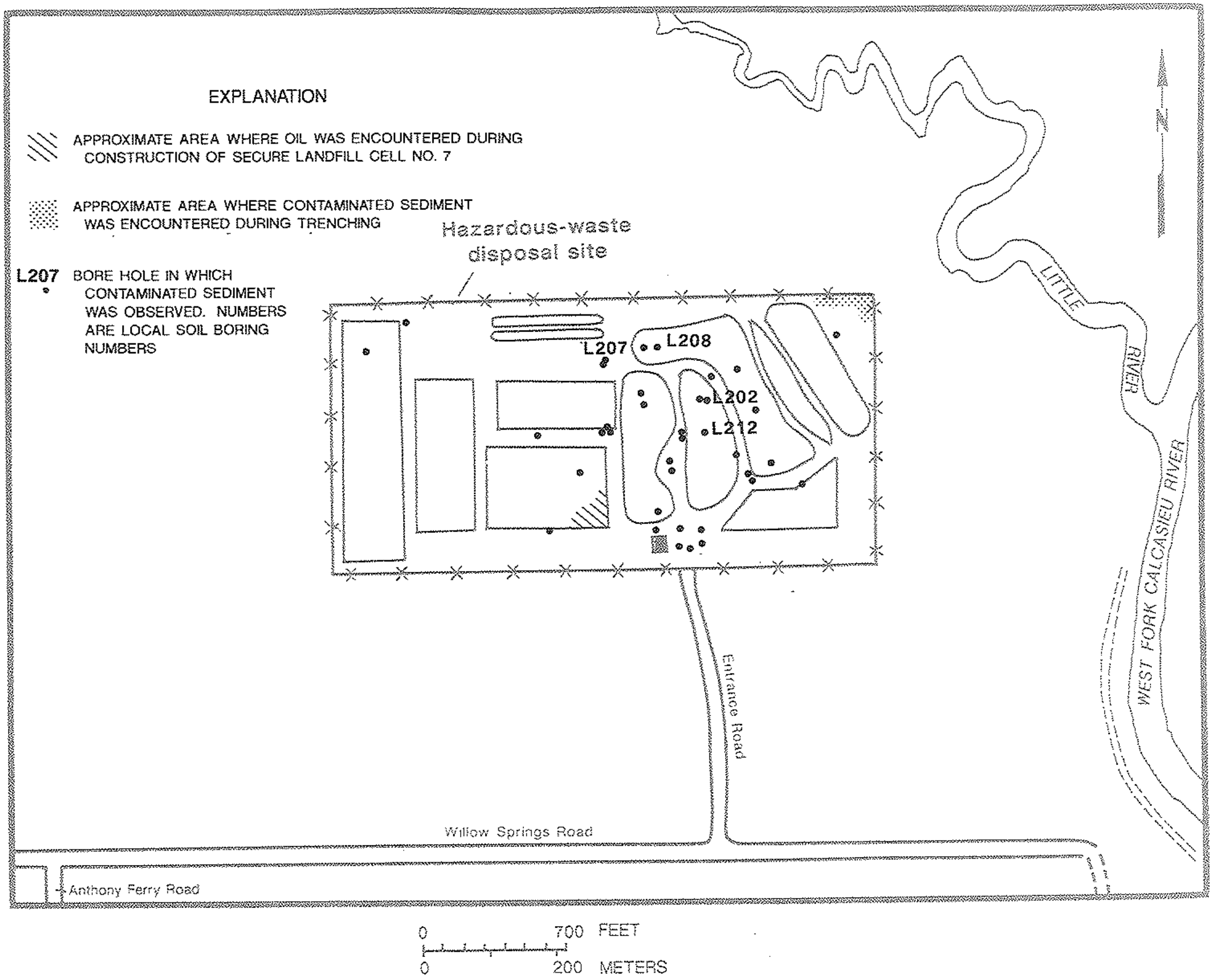


Figure 13. Locations of soil borings and excavations onsite that indicate contaminated sediment.

In 1982, during construction of secure landfill cell no. 7, NAPL was observed on the eastern and southern walls of the excavation (fig. 13). The NAPL occurred as a layer at a depth of about 36 ft below land surface and was moving into the excavation through joints in the clay. NAPL and odor also were observed during trenching to depths of 15 ft in the northeastern corner of the waste site (fig. 13).

The location of contaminated sediment (fig. 13) generally conforms to the location of the abandoned unlined lagoons (fig. 4). The two borings having contaminated sediment in the northwestern corner of the waste site were drilled to determine the thickness of the clay cap overlying the secure landfill cells in that area and penetrated waste in the cells. Contaminated sediment is generally confined to the low-permeability sediments overlying the "200-foot" aquifer.

The suite of organic pollutants present in NAPL-contaminated sediment beneath the unlined lagoons (table 6) indicate the NAPL is probably not a crude oil. Included in the table are organic pollutant analyses of sediment from two soil borings and one sample of the NAPL-contaminated sediment found in the bottom of secure landfill cell no. 7. Organic contaminants found in the sediment include the following classes of pollutants: monocyclic aromatic hydrocarbons, halogenated aliphatic hydrocarbons, and polycyclic aromatic hydrocarbons. The only known measurement of NAPL density is a measurement of NAPL seeping into secure landfill cell no. 7. Austin Arabie (Browning-Ferris Industries - Chemical Services Incorporated, oral commun., 1985) found the NAPL to be denser than water, having a computed specific gravity of 1.09. The presence of NAPL to depths of 51 ft in water-saturated sediments indicates the NAPL found in the subsurface generally is denser than water.

The importance of the occurrence of a NAPL, such as that found at the hazardous-waste disposal site, is that the NAPL may move differently in the subsurface than does ground water. Denser-than-water NAPL will generally move downward under the influence of gravity and will spread under the influence of capillary forces (Schwille, 1967; 1981). Once the NAPL reaches the water table, the movement of denser-than-water NAPL is largely uncoupled from the hydraulic gradient that controls ground-water movement (Schwille, 1981). The NAPL will continue to move downward until a flat-lying, relatively impermeable layer is reached and form an oil core on top of the impermeable layer.

In the subsurface, NAPL will be a continued source of organic contamination of ground water even though, as is the case with the unlined lagoons at the hazardous-waste disposal site, the NAPL source at the land surface has been eliminated. Ground-water flow that comes into contact with the NAPL will become contaminated with water-soluble organic contaminants present in the NAPL (table 6).

The distribution of NAPL in the subsurface, in part, controls the occurrence of ground-water contamination. Schwille (1981) showed the relation between the distribution of a denser-than-water NAPL and the occurrence of ground-water contamination (fig. 14). Many of the features associated with the distribution of NAPL in the subsurface shown in figure 14 are observed at the hazardous-waste disposal site. Oil spots and streaks noted in the logs of soil borings may be indicative of residual oil. The oil layer encountered in secure landfill cell no. 7 may be indicative of an oil core. Odors noted in cuttings and in trenching may be indicative of a gas zone. The plumes associated with the site are discussed later in this report. On the basis of the relation between NAPL occurrence and ground-water contamination, ground-water contamination is expected in the low-permeability deposits overlying the "200-foot" aquifer in the area where NAPL was formerly stored in unlined lagoons.

Other important aspects of NAPL movement that might affect the occurrence of contaminants at the hazardous-waste disposal site are fractionation and clay-organic reactions. Heaver-than-water NAPL has been known to fractionate into lighter (floating) and heavier (sinking) fractions (Brown and others, 1983, p. 64; Plice, 1948, p. 414; Duffy and others, 1977, p. 476) and could account for the occurrence of both fractions in the subsurface. Clay-organic reactions could accelerate the movement of contamination into the subsurface. Green and other (1983), and Brown and Anderson (1983) report on reactions between organic fluids (NAPL's) and clays in which the clays underwent large permeability increases.

Table 6. Analyses of organic pollutants in oil-contaminated soil samples

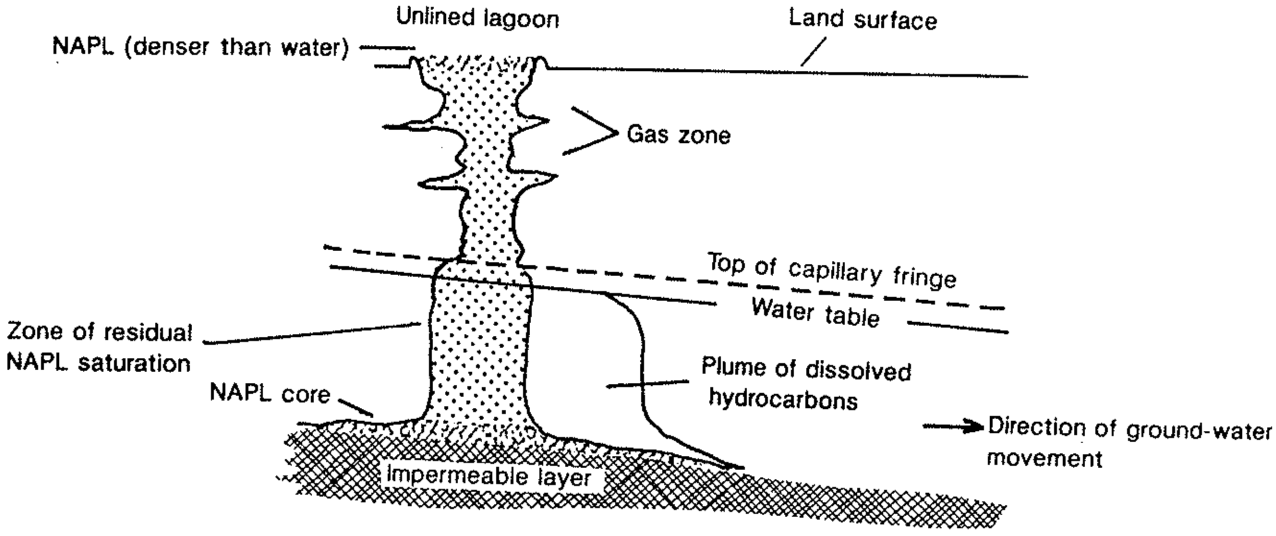
[Unpublished data are on file, Louisiana Department of Environmental Quality, Baton Rouge, La., 1985. Concentrations in milligrams per kilogram; no., number; -- no data]

Organic pollutants	Borehole no. L-212[a] Sampled 04-16-84 Depth 42-48 feet	Borehole no. L-207[b] Sampled 02-03-84 Depth 48-50 feet	Secure landfill cell no. 7[c] Sampled 10-21-82 Depth 36 feet
Monocyclic Aromatic Hydrocarbons			
Benzene	0.03	--	0.38
Chlorobenzene	.04	--	.01
Ethylbenzene	.12	--	--
Toluene	.03	--	.01
Nitrobenzene	--	--	12
Phenol	--	--	2.8
2,4,6-Trichlorophenol	--	--	1.4
Halogenated Aliphatic Hydrocarbons			
Chloroform	2.2	1,025	0.15
1,2-Dichloroethane	--	--	.48
Trans-1,2-dichloroethene	--	--	.04
Methylene chloride	3.1	62	--
1,1,2,2-Tetrachloroethane	--	--	.05
Tetrachloroethene	.05	--	.02
1,1,2-Trichloroethane	--	--	.16
Trichloroethene	.05	--	.02
Polycyclic Aromatic Hydrocarbons			
Anthracene	23	8.8	0.19
Acenaphthylene	--	--	.07
Acenaphthene	--	--	.08
Benzo(a)anthracene	5.0	2.4	.36
Benzo(a)pyrene	--	--	.16
3,4-Benzofluoranthene	--	2.1	.18
Benzo(k)fluoranthene	--	--	.20
2-Chloronaphthalene	--	--	18
Chrysene	10.2	3.8	.37
Fluoranthene	3.1	1.4	.31
Fluorene	--	--	.22
Naphthalene	--	--	.05
Phenanthrene	--	--	1.10
Pyrene	14.6	5.1	.73

[a] Located 150 feet northeast of well Cu-900, see figure 13 for location.

[b] Located next to well Cu-930, see figure 13 for location.

[c] See figure 13 for location where oil was found.



Modified from Schwille(1981)

EXPLANATION

NAPL --- NONAQUEOUS PHASE LIQUID

Figure 14. Diagram of section showing possible distribution of a nonaqueous phase liquid beneath an unlined lagoon at the hazardous-waste disposal site.

Analysis of the Liquid-Phase Data

Two ground-water-quality data bases were used in evaluating the liquid phase. The first consists of analyses of water collected by the site owner to meet the permit requirements of the Louisiana Department of Environmental Quality and its predecessor, the Louisiana Department of Conservation and Natural Resources. The ground-water samples were collected at various times during the period 1978-84 from various onsite wells. The second data base consists of analyses of ground water collected both onsite and offsite during 1985 as part of this study.

Methods

Methods of ground-water sampling and analysis by a site owner have been established by the Louisiana Department of Environmental Quality and are described in a ground-water monitoring plan prepared by the site owner. In accordance with the plan, wells are purged of four well volumes of water prior to sampling. If wells are screened in a low-permeability geohydrologic unit, the well is bailed dry prior to sampling. Samples are collected using polyvinylchloride bailers that are cleaned between samplings and are dedicated to use in a single well. Samples are collected from a spigot from those wells in which submersible pumps are permanently installed. The monitoring plan also establishes sample preservation, shipment, and analytical procedures, which generally follow guidelines of the U.S. Environmental Protection Agency. Field and trip blanks are included and analyzed for quality control. Results of water-quality analyses are reported to the Louisiana Department of Environmental Quality and were obtained for use in this study from that agency (unpublished data on file, Louisiana Department of Environmental Quality, Baton Rouge, La., 1985).

During August and September 1985, 22 wells at and around the waste site were sampled (fig. 3). Two additional wells were sampled in November 1985. Eleven of the wells were located onsite (Cu-872, -874, -875, -881, -904, -906, -907, -908, -909, -914, and -936) and were jointly sampled with the owner by methods described above. Twelve of the wells sampled were located offsite (Cu-899, -939, -940, -941, -942, -943, -945, -1217, -1218, -1219, -1220, and -1221) and were sampled by methods described below. Offsite well Cu-893 was sampled by the U.S. Geological Survey and the owner, using the methods of collection used by the owner.

Offsite wells were sampled after at least two well volumes were purged and the temperature and specific conductance of the water stabilized. Offsite wells were purged by bailing if the well was in a low-permeability geohydrologic unit, or by a submersible pump if the well was screened in a geohydrologic unit having sufficient permeability to yield water. Well Cu-899 was purged by jetting with air because an obstruction in the well would not permit use of a submersible pump. The Teflon bailer used in sampling offsite wells was cleaned between samplings by washing with laboratory-grade methanol followed by rinsing with de-ionized water. Quality-control measures included the analysis of field blanks.

All samples collected during 1985 were analyzed at a U.S. Geological Survey laboratory. Samples collected for analysis of inorganic constituents, including minor elements, were treated and analyzed by methods described by Fishman and Friedman (1985). Samples collected for analysis of purgeable organic compounds, acid-base/neutral extractable compounds, and dissolved organic carbon (DOC) were treated and analyzed by methods described by Wershaw and others (1983). Samples were collected for gas-chromatograph flame-ionization detector (GC-FID) scan from wells not sampled for acid-base/neutral extractable organic analysis. One liter samples of raw water were collected in glass bottles, chilled, and shipped to the laboratory for the GC-FID scan. The method used for the GC-FID scan analysis is that developed by Ralph White (U.S. Geological Survey, written commun., 1985).

Selected Chemical Analyses

Results of selected chemical analyses of samples of uncontaminated and contaminated ground water collected during this study are given in table 7. The chemical analyses of uncontaminated ground water (columns 1, 2, and 3 in table 7) for wells upgradient of the waste site are similar to analyses of uncontaminated ground water elsewhere in the Chicot aquifer system (D.J. Nyman, U.S. Geological Survey, written commun., 1986).

Uncontaminated ground water in the Chicot aquifer system generally has a concentration of dissolved chloride less than 100 mg/L. Areas of higher dissolved-chloride concentrations are present elsewhere in Calcasieu Parish, but these are most commonly associated with upconing of deeper saline or brackish water caused by pumping (Nyman, 1984). High dissolved-chloride concentrations also have been reported by Harder (1960, p. 27) in a shallow aquifer near the Houston River. It is likely that high

Table 7. Chemical analyses of uncontaminated and contaminated ground water at the hazardous-waste disposal site in Calcasieu Parish

[Concentrations in milligrams per liter except as noted]

	Uncontaminated			Contaminated
Well number:	**Cu-940**	**Cu-893**	**Cu-939**	**Cu-904**
Aquifer:	**Surficial sand**	**Shallow aquifer**	**"200-foot" aquifer**	**Surficial sand**
Collection date:	**09-17-85**	**08-28-85**	**08-29-85**	**09-17-85**
Depth, in feet:	**15.8-17.8**	**40-45**	**92.15-94.15**	**10.75-24.75**
Field pH	5.9	7.1	7.0	6.3
Field temperature (°C)	22.5	24	25.5	28
Calcium, dissolved	31	41	59	150
Magnesium, dissolved	11	12	17	46
Potassium, dissolved	1.6	1.4	2.7	1.5
Sodium, dissolved	97	96	61	230
Field alkalinity, total, as $CaCO_3$	216	221	202	117
Sulfate, dissolved	18	13	18	33
Chloride, dissolved	90	78	92	510
Sulfide, total	--	<.5	<.5	.5
Iron, dissolved[1]	17	8	110	50
Barium, dissolved[1]	180	120	370	800
Mercury, dissolved[1]	--	0.1	<0.1	<10
Lead, dissolved[1]	1	2	1	<100
Manganese, dissolved[1]	180	3	630	420
Carbon, organic, dissolved	36	7.7	1.8	76
1,2-Dichloroethane[1]	<3	<3	<3	1,000,000
Chloroform[1]	<3	<3	3	29,000
Benzene, total[1]	<3	<3	<3	<500
Naphthalene, total[1]	--	--	--	450
Phenol[1]	--	--	--	<1,300
Chrysene[1]	--	--	--	1,700
Phenanthrene[1]	--	--	--	2,700
2-Chloroethyl ether[1]	--	--	--	4,700
Oil and grease	--	--	--	45,000

[1] Concentrations in micrograms per liter.

dissolved-chloride concentrations of 370, 440, and 690 mg/L in water from wells Cu-1217, -1218, and -1219, are caused by the natural infiltration of brackish water from the channel of the Houston River.

Uncontaminated ground water in the study area may have high dissolved organic-carbon concentrations, up to 36 mg/L. The high concentrations are not unexpected because of the high organic content of sediment in the subsurface.

The sample of contaminated ground water (table 7, column 4) was collected from well Cu-904 in the plume in the northeastern corner of the waste site. This water contains relatively high concentrations of dissolved chloride and other inorganic constituents; it also contains high concentrations of various organic pollutants and oil.

A NAPL resembling oil was observed in samples from wells Cu-914, -904, and -908 during this investigation. Water samples from wells Cu-914 and Cu-904 had NAPL concentrations respectively of 3,600 and 45,000 mg/L of bulk fluid. The NAPL in these wells is observed to float on the water and is unlike the NAPL in contaminated sediment, which appears to be denser than water. Fractionation of an original NAPL into denser-than-water and lighter-than-water fractions may account for the presence of the two types of NAPL. Alternatively, the two types of NAPL may represent waste from different sources.

Results of the analyses of field and trip blanks during 1984 were not available in the data obtained from the Louisiana Department of Environmental Quality. The extent to which these quality-control measures are used in reporting data to the department was not determined. Field blanks analyzed as part of this study showed the presence of detectable concentrations of chloroform (up to 6.7 μg/L), toluene (4 μg/L), and trichloroethylene (3 μg/L). Results of the analyses of other samples for the above constituents at these concentrations were not deemed indicative of contamination. Results of GC-FID scans of field blanks indicated the presence of one organic compound in each blank, but at a concentration below the detection and identification limit (5 μg/L) for gas-chromatograph mass-spectrometer (GC-MS) analysis.

Spatial Distribution of Selected Chemical Constituents and Physical Properties

Twelve chemical constituents and physical properties have been selected to illustrate the spatial distribution of contamination at the hazardous-waste disposal site. These constituents and properties are dissolved chloride, dissolved barium, benzene, phenol, naphthalene, 1,2-dichloroethane, total organic carbon (TOC), DOC, hydrogen ion activity (pH), field alkalinity, dissolved manganese, and dissolved iron. Because the spatial distribution of sampling points is complex, a variety of maps, sections, and fence diagrams are used to document distributions of the chemical constituents and physical properties in ground water. Four types of plots are used in this report: (1) a series of maps showing areal variations in composition of water collected from wells screened in low-permeability aquifers above the "200-foot" aquifer, most of which are screened in the shallow aquifer; (2) east-west sections across the southern boundary of the waste site, which document the distribution of constituents in water at the site boundary; (3) three-dimensional fence diagrams of the waste site; and (4) a series of longitudinal sections that show distribution of water chemistry along the natural ground-water flow path and that represent composites of the northern half of section B-B' (fig. 6) and the southern half of section C-C' (fig. 7). Data used in plots of types 1, 2, and 3 were obtained from the Louisiana Department of Environmental Quality, and data used in plots of type 4 were obtained from samples collected during 1985 as part of this study. These plots, in addition to showing the spatial distribution, also illustrate some of the natural and anthropogenic processes affecting ground-water composition and contamination in the study area.

Chloride and Barium

The oil-field brines known to have been disposed of at the hazardous-waste disposal site were probably a sodium-chloride type water that is typical of those of the deep subsurface in southwestern Louisiana (Hanor, 1984). The water probably contained high concentrations of many other dissolved inorganic constituents, including dissolved barium. Figure 15 shows the spatial distributions of dissolved chloride and dissolved barium at the site in 1984. The 1984 data define a chloride plume which extends from the northeastern part of the waste site, southwest beneath the abandoned unlined lagoons, to the southern boundary of the waste site. The highest dissolved-chloride concentrations are found in the low-permeability sediments overlying the "200-foot" aquifer, but concentrations in excess of 100 mg/L extend into the "200-foot" aquifer at depths of 100 ft below sea level. Figure 16 shows more details of the vertical distribution of dissolved chloride beneath the waste site. The orientation of the plumes is generally

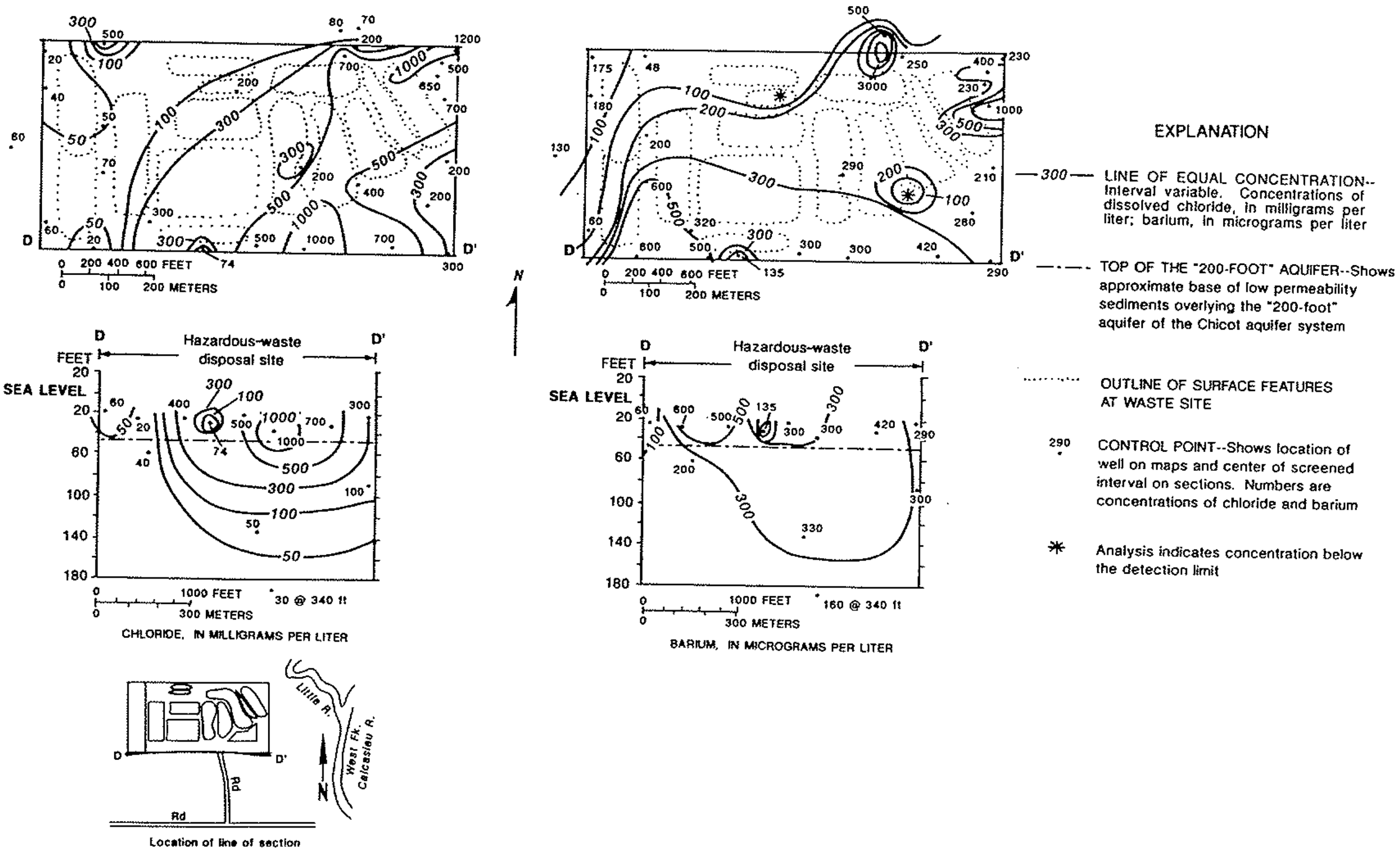
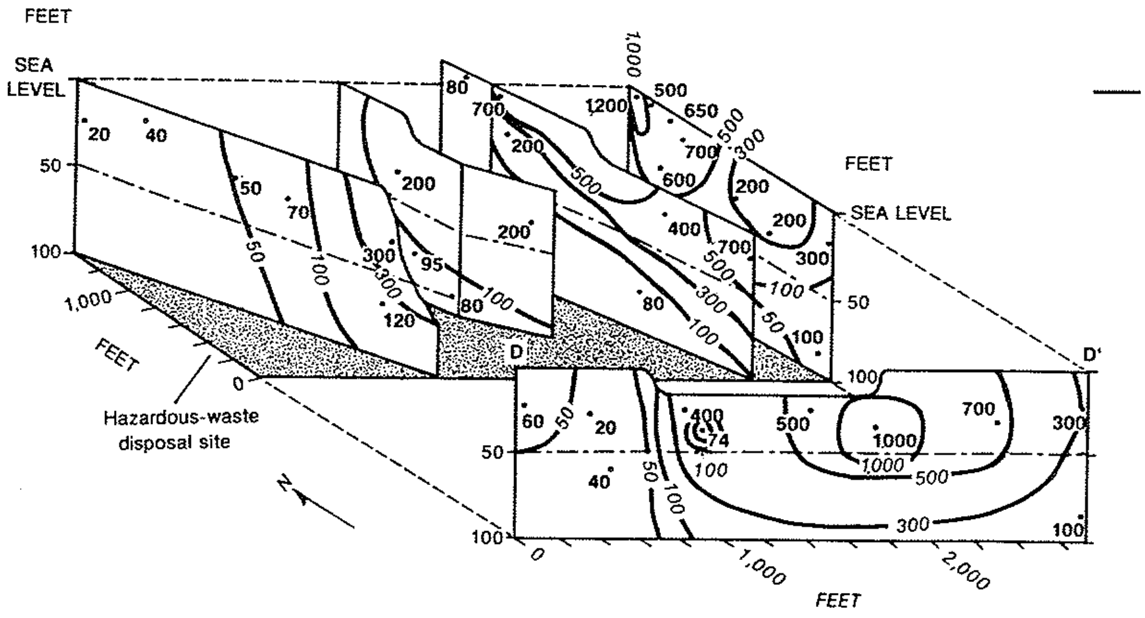


Figure 15. Distribution of dissolved chloride and dissolved barium at the hazardous-waste disposal site, 1984.



EXPLANATION

—— 300 —— LINE OF EQUAL CONCENTRATION--Interval variable. Concentrations of dissolved chloride, in milligrams per liter

—·—·— TOP OF THE "200-FOOT" AQUIFER--Shows approximate base of low permeability sediments overlying the "200-foot" aquifer of the Chicot aquifer system

290 • CONTROL POINT--Shows center of screened interval. Numbers are chloride concentrations, in milligrams per liter

Figure 16. A three-dimensional representation of the chloride within the hazardous-waste disposal site, 1984.

consistent with the directions of ground-water flow beneath the waste site. The origin of the high dissolved-chloride concentrations in the northwestern corner of the waste site, outside of the area of unlined lagoons, is unknown.

The spatial distribution of dissolved barium (fig. 15) is different from that of dissolved chloride. Although the highest observed values are present in the northeastern part of the waste site, there is no well-defined plume extending southward from the area of the abandoned unlined lagoons. If dissolved barium were a significant component of the oil-field brines, as is likely, it has been removed from solution, perhaps by ion-exchange on clays (Hanor and Chan, 1977) or by precipitation as barite. (See results in the section "Mineralogy.") The origin of the high dissolved-barium concentrations in the southwestern corner of the waste site is not known.

Figure 16 shows a three dimensional representation of dissolved chloride concentration within the hazardous-waste disposal site in 1984. This spatial distribution of dissolved chloride generally agrees with that shown for dissolved chloride and dissolved barium in 1985 (fig. 17). A dissolved-chloride concentration above background, 100 mg/L, was found in offsite well Cu-941 (110 mg/L) located downgradient of the waste site in the "200-foot" aquifer. A dissolved-chloride concentration of 480 mg/L was found in well Cu-945 (not shown in figure 17) east of the northeast corner of the waste site in a surficial sand. On the basis of the analyses of samples from wells Cu-941 and Cu-945 in 1985, it is reasonable to assume that the chloride plumes extend at least 1,000 ft south of the waste site in the "200-foot" aquifer and at least 300 ft northeast of the northeast corner of the waste site in surficial sediments. The 1985 analysis of water from well Cu-945 indicates that the high concentrations of dissolved barium shown in figure 15 in the northeastern corner of the waste site extend at least 300 ft offsite to well Cu-945 (530 μg/L).

Selected Organic Constituents

Many of the organic contaminants detected in the solidified waste from the unlined lagoons (table 3) and from the contaminated sediment beneath the lagoons (table 6) as well as other organic contaminants have been detected in ground-water samples at the hazardous-waste disposal site. Four commonly occurring organic pollutants detected in water samples at the waste site have been selected for discussion and illustration: benzene, phenol, naphthalene, and 1,2-dichloroethane. In addition, the distribution of TOC and DOC have been investigated.

Review of the data obtained from the Louisiana Department of Environmental Quality shows intermittent occurrence of organic pollutants in water samples collected, over time, from individual wells. Therefore, the maximum concentrations observed in water from each well in 1984 were used to show the spatial distribution of organic pollutants. Ideally, samples collected for chemical analysis over a much shorter period should be used to show the spatial distribution. Interpretation of the distribution of contaminants in the plume from maximum concentrations observed in analyses of samples collected over a 1-year period may provide a distorted view of the distribution of contaminants. However, the control provided by the 1985 data helps confirm the distribution of contaminants indicated by the data from 1984.

Figures 18 and 19 show the spatial distribution of each of the four pollutants and TOC in 1984. Concentrations for each range over several orders of magnitude. Most striking is a 1,2-dichloroethane, which ranges in concentrations from <1 μg/L (analytical detection limit) to several million micrograms per liter (close to aqueous saturation). The patterns of the distribution of benzene, phenol, naphthalene, and 1,2-dichloroethane are qualitatively similar. These generally coincide with the chloride plume and extend from the northeastern part of the waste site, southwest beneath the abandoned unlined lagoons, to the southern boundary of the waste site. Concentrations of TOC also are high in the northeastern corner of the waste site, but shows much less evidence of a plume along the southern boundary of the waste site.

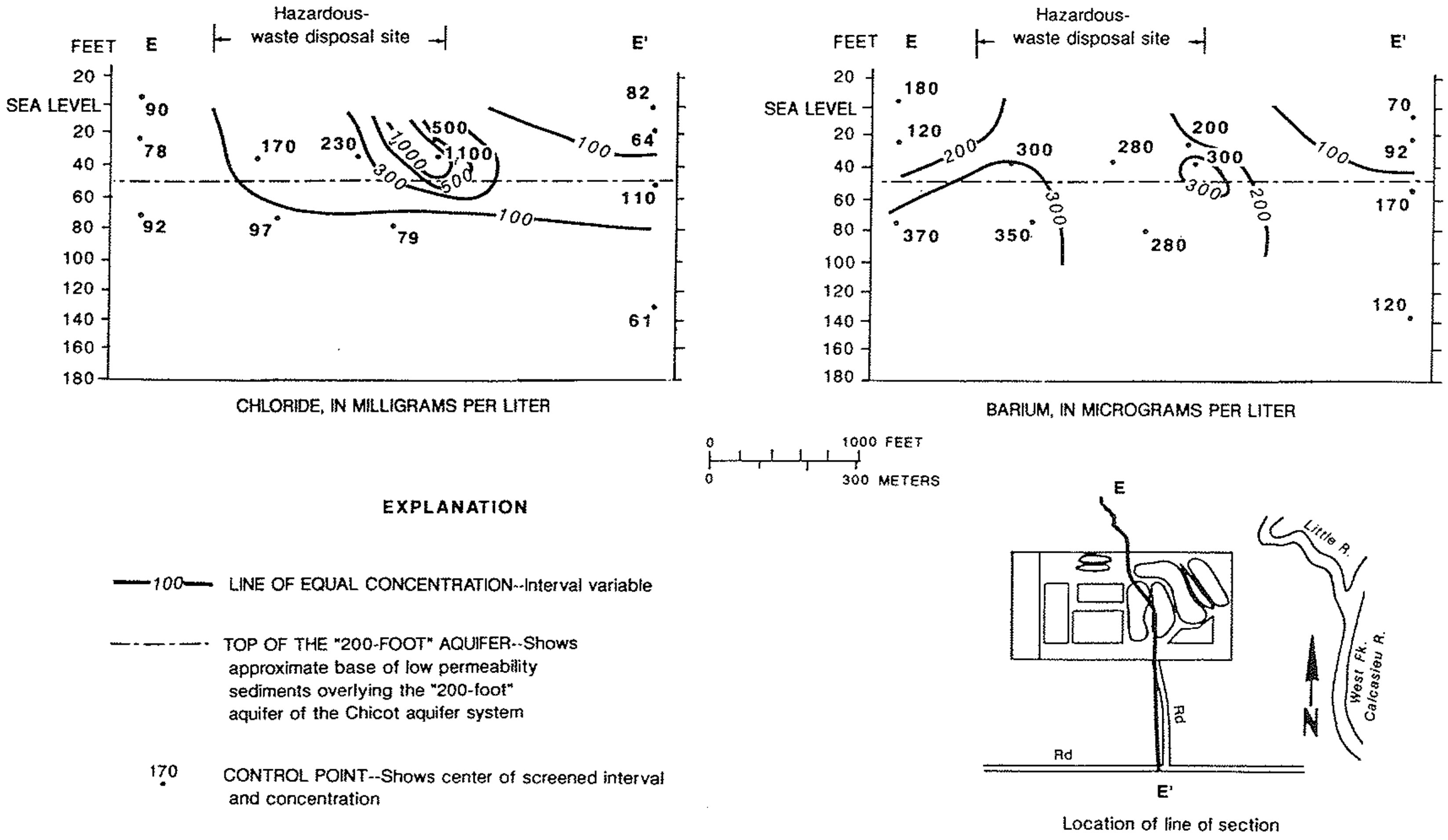


Figure 17. Distribution of dissolved chloride and dissolved barium at the hazardous-waste disposal site, 1985.

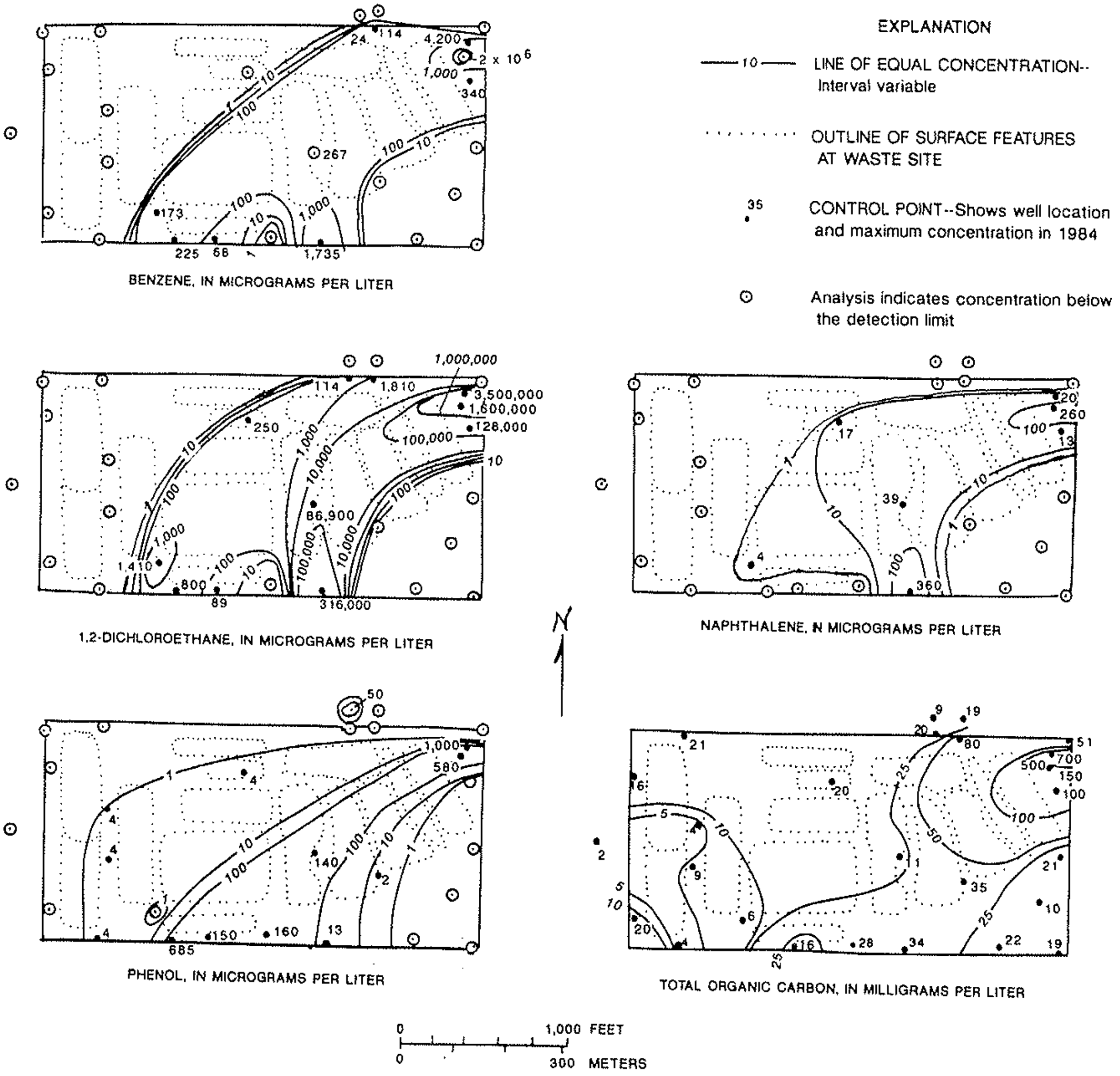


Figure 18. Areal distribution of the aqueous concentration of selected organic pollutants and total organic carbon in the low permeability sediments overlying the "200-foot" aquifer, 1984.

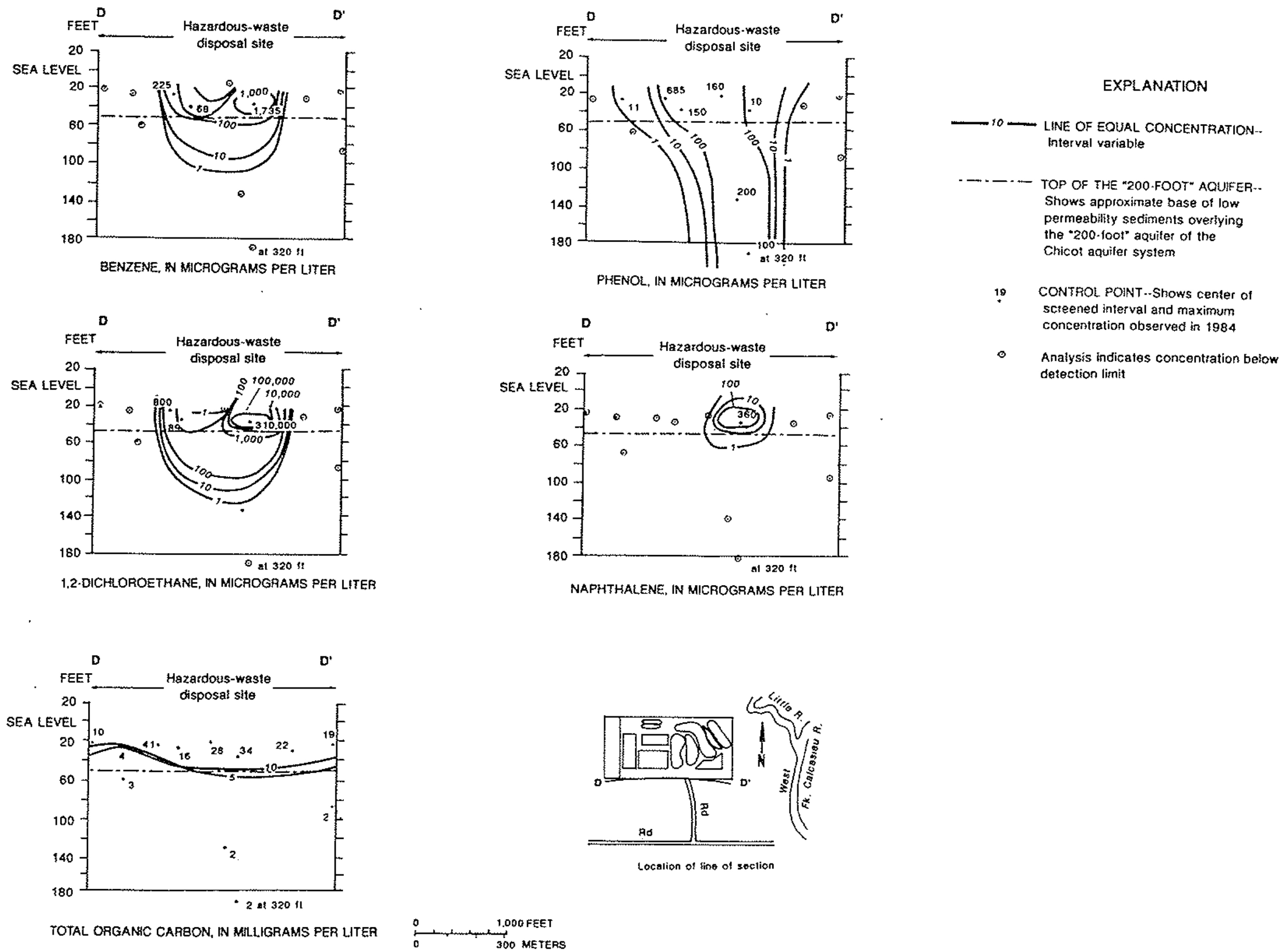


Figure 19. Transverse sections showing lateral and vertical distribution of the concentrations of selected organic pollutants and total organic carbon across the southern boundary of the hazardous-waste disposal site, 1984.

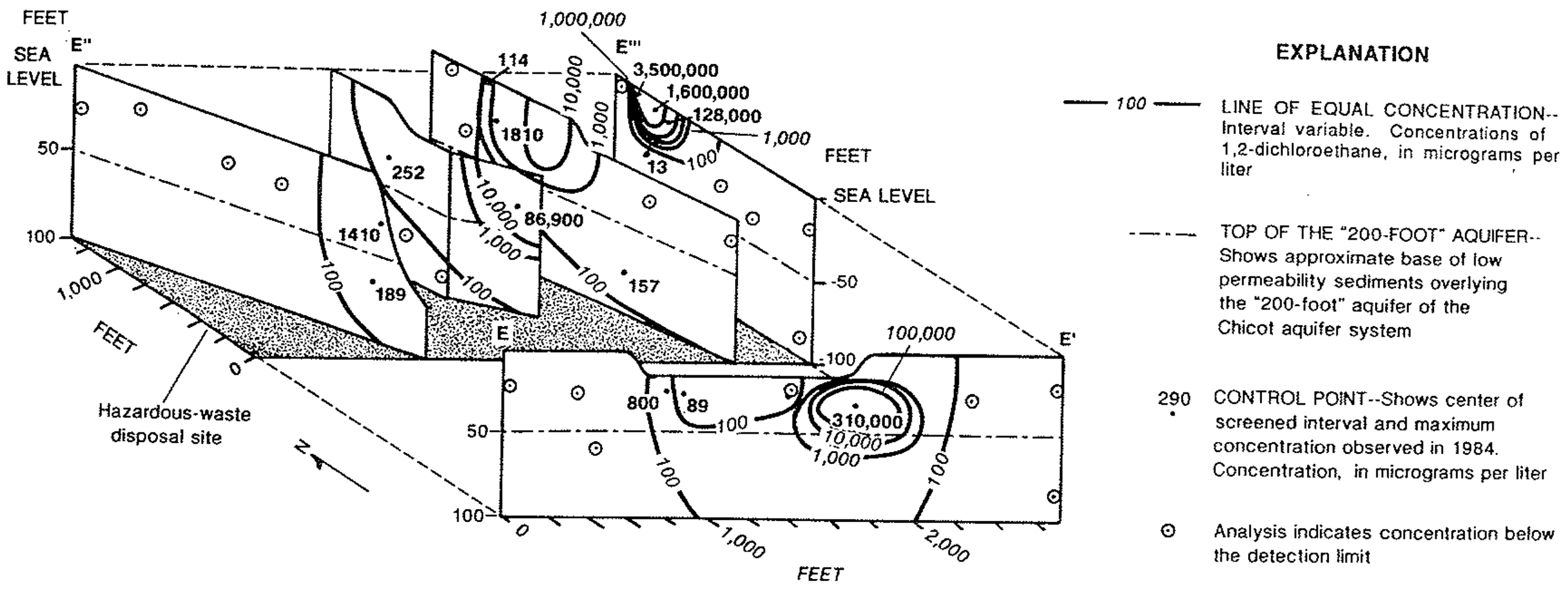
The degree of lateral spreading defines important differences between the benzene, phenol, naphthalene, 1,2-dichloroethane, and TOC plumes (fig. 18). The northeast to southwest axis of highest concentration of each of the four pollutants and TOC is the axis of the plumes and probably corresponds to the locus of points of contaminant introduction. Phenol shows the highest degree of lateral spreading, followed in order by benzene, naphthalene, TOC, and 1,2-dichloroethane. Highest concentrations of these pollutants are found in the low-permeability geohydrologic units above the "200-foot" aquifer, although detectable concentrations have been observed within the "200-foot" aquifer, at altitudes of 80 ft below sea level and lower (fig. 19). Of the four pollutants, phenol also shows the highest degree of vertical spreading; a concentration of 100 μg/L has been detected in water collected at an altitude of 320 ft below sea level. In general, TOC concentrations are observed to decrease with increasing depth (fig. 19). Because TOC concentrations are generally high throughout the study area (fig. 18), TOC alone is not a sensitive indicator of the extent of organic contamination.

Figure 20 shows a three-dimensional representation of the 1,2-dichloroethane plumes as defined by analyses of samples collected in 1984. The 1,2-dichloroethane plumes in figure 20 are similar to the chloride plumes shown in figure 16. The apparent greater downgradient transport of dissolved-chloride contamination than of 1,2-dichloroethane contamination (fig. 17) may reflect the earlier initiation of oil-field brine disposal, or the preferential retardation or removal of 1,2-dichloroethane.

Analyses of water samples collected in 1985 confirm the presence of a 1,2-dichloroethane plume (fig. 21), but do not show benzene, phenol, or naphthalene plumes as extensive as shown by the 1984 data. Benzene was detected in only 2 of the 11 wells sampled onsite in 1985 (Cu-914, 2,000 μg/L; and Cu-936, 65 μg/L). Phenol was not detected (detection limits 5 to 1,300 μg/L) in any of the five wells for which phenol was analyzed (Cu-881, -904, -908, -914, and -936); naphthalene was detected (detection limit 5 μg/L) in three of these same five wells (Cu-881, 25 μg/L; Cu-904, 450 μg/L; and Cu-914, 1,700 μg/L). Many of the wells in which benzene, phenol, and naphthalene were not detected are within the benzene, phenol, and naphthalene plumes depicted in figure 18. The difference between the distribution of contaminants defined by 1984 and 1985 analytical results is unexplained. Contributing factors may be: (1) differences in comparing the maximum concentrations obtained from analyses of samples collected over a 1-year period (1984 data) to concentrations obtained from analyses of samples collected over a short time period (1985 data); (2) differences in analytical results between different laboratories; (3) differences between onsite sample collection methods or equipment between 1984 and 1985; and (4) pollutant movement. Further sampling and analyses are necessary to confirm the presence and extent of the benzene, phenol, and naphthalene plumes.

A GC-FID scan was used to screen samples for the presence or absence of methylene chloride-extractable organic compounds, including phenol and naphthalene. Results of the GC-FID scan of water samples collected in 1985, presented in table 8, indicate that methylene chloride-extractable organic pollutants were absent in two wells (Cu-907 and Cu-909) within the phenol and naphthalene plumes defined by the 1984 data. The GC-FID scan also was used to indicate whether GC-MS analysis might detect and identify organic compounds. The detection limit for methylene chloride-extractable organic pollutants for the GC-FID scan (1 μg/L) is lower than the detection limit for GC-MS (5 μg/L). The GC-FID scan results indicate that if phenol and naphthalene were present in wells Cu-941, -942, -943, and -1221 they were present in concentrations too low to permit positive identification.

Figure 21 also shows the distribution of DOC in 1985. DOC is generally higher in offsite wells than in wells located onsite and, thus, is a poor indicator of the extent of organic contamination. The high DOC concentration in offsite wells is attributed to the high content of organic matter in the sediment. The apparent low DOC concentrations in onsite wells may be due to the abundance of purgeable organic compounds in the water and the probable loss of purgeable organics during field and laboratory treatment of DOC samples (M.P. Schroeder, U.S. Geological Survey, oral commun., 1987). Table 9 lists analyses for constituents detected in water from onsite wells in 1985.



EXPLANATION

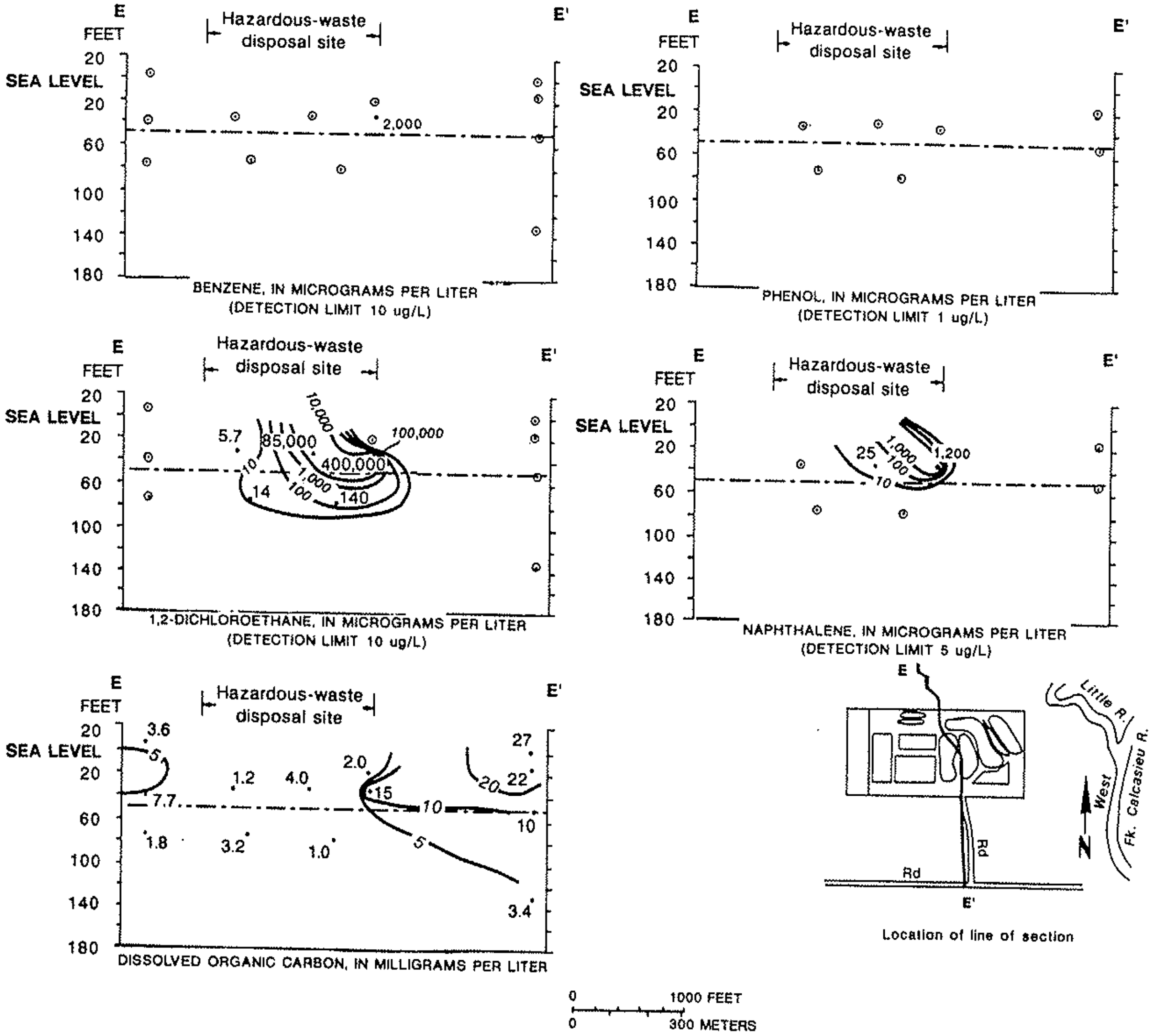
— 100 — LINE OF EQUAL CONCENTRATION--Interval variable. Concentrations of 1,2-dichloroethane, in micrograms per liter

—·— TOP OF THE "200-FOOT" AQUIFER--Shows approximate base of low permeability sediments overlying the "200-foot" aquifer of the Chicot aquifer system

290 ● CONTROL POINT--Shows center of screened interval and maximum concentration observed in 1984. Concentration, in micrograms per liter

⊙ Analysis indicates concentration below the detection limit

Figure 20. A three-dimensional representation of the distribution of 1,2-dichloroethane within the hazardous-waste disposal site, 1984.



EXPLANATION

—5— LINE OF EQUAL CONCENTRATION--Interval variable

-·-·- TOP OF THE "200-FOOT" AQUIFER--Shows approximate base of low permeability sediments overlying the "200-foot" aquifer of the Chicot aquifer system

4.0 • CONTROL POINT--Shows center of screened interval. Numbers are concentrations

⊙ Analysis indicates concentration below detection limit

Figure 21. Concentrations of selected organic pollutants and dissolved organic carbon at the hazardous-waste disposal site, 1985.

Table 8. Summary of gas chromatograph-flame ionization detector scan results of 1985 samples

Well number	Number of unidentified organic compounds[1]	Estimated maximum concentration of single unidentified compounds (in micrograms per liter)	Estimated total concentration of all unidentified compounds (in micrograms per liter)
Onsite Wells			
Cu-872	4	17	14
Cu-874	9	26	75
Cu-875	8	7.1	34
Cu-906	5	97	144
Cu-907	0		
Cu-909	0		
Offsite Wells			
Cu-899	5	73	157
Cu-941	2	4.8	9
Cu-942	4	4.3	15
Cu-943	4	5.1	17
Cu-945	12	690	920
Cu-1220	2	20	22
Cu-1221	8	5.1	27
Field blanks	1	1	2.2
Field blanks	1	1	4.1

[1] Unidentified organic compounds with concentrations greater than 2 micrograms per liter (10 percent of internal standard used in the analysis). Unidentified organic compounds that also were found in laboratory blanks were not included.

Additional analysis of the methylene chloride extraction of water from well Cu-904 was undertaken to identify the presence of organic compounds other than the organic pollutants. The method used to analyze the sample is that developed by M.P. Schroeder (U.S. Geological Survey, written commun., 1986). Gas chromatograph peaks were compared by computer library search to the National Bureau of Standards library reference spectra. The best library matches were selected according the reliability factor, which indicates the quality of the match between the sample and the library spectra. The closer the reliability factor to 100, the better the match. Because these identifications have not been verified by comparison with standard compounds, they are tentative. The results of the library matches are given in table 10. Concentrations reported in table 10 do not take into account the difference in chemical compounds relative to the internal standard, perdeuteronaphthalene, and can be interpreted as approximations good to factors of one to five times in most instances. Tentatively identified organic compounds present in the sample included alkanes, naphthalene, phenanthrenes, and pentachloroethane. Purgeable organic compounds such as 1,1,2-trichloroethane and methylated naphthalenes apparently make up the bulk of the organic compounds present in this oil-contaminated sample.

Table 9. Total concentrations of organic pollutants, other organic compounds, and disssolved organic carbon in onsite wells, 1985
[Concentrations in milligrams per liter; --, not detected]

Well number	Organic pollutants		Other organic compounds[1]	Dissolved organic carbon
	Purgeable	Acid-base/neutral extractable		
Cu-872	0	--	0.041	3.6
Cu-874	.005	--	.075	6.4
Cu-875	.015	--	.034	2.0
Cu-881	194	0.037	--	4.0
Cu-904	1,420	13.4	28.5	76
Cu-906	0	--	.144	3.4
Cu-907	.143	--	0	1.0
Cu-908	.0142	0	--	3.2
Cu-909	.006	--	0	1.2
Cu-914	1,550	23.4	--	15
Cu-936	9.58	0	--	1.2

[1] Determined from gas-chromatograph flame ionization detector scan results and non-target compound library search results for well Cu-904.

Hydrogen Ion Activity (pH), Alkalinity, Manganese, and Iron

The distribution of pH, alkalinity, dissolved manganese, and dissolved iron was studied to provide insight into oxidation-reduction potential at the waste site. Field measurements of the pH of ground water in the study area, show increases with depth from less than 6.0 in shallow sediments to more than 7.0 in deeper sediments (fig. 22). This increase in pH along a flow path occurs naturally throughout southwest Louisiana (D.J. Nyman, U.S. Geological Survey, written commun., 1986). No extremely low or high values were measured.

Field measurements of alkalinity are characterized by a zone of maximum concentration approximately 40 ft below sea level in the shallow aquifer beneath the waste site. This observed maximum concentration of alkalinity may be related to waste disposal because alkalinities greater than 300 mg/L were not measured elsewhere in the study area during 1985.

Dissolved iron and dissolved manganese also show maximum concentrations at specific depths (fig. 22). The maximum concentration of dissolved iron occurs at 60 to 80 ft below sea level. The maximum concentration of dissolved manganese occurs concurrent with or just below the depth of maximum concentration of alkalinity at 40 to 60 ft below sea level. This pronounced zonal distribution of dissolved iron and manganese may reflect a progressive increase of reducing conditions with depth. However, additional work is needed to establish the oxidation-reduction potential at the waste site.

Fluctuations in Chloride and 1,2-Dichloroethane Concentrations

The fluctuations in dissolved-chloride and 1,2-dichloroethane concentrations in water from wells at the waste site were studied. These two constituents were chosen because sampling in 1985 confirmed the presence of chloride and 1,2-dichloroethane plumes. A detailed analysis of fluctuations in concentrations of all chemical constituents was not attempted. Although analyses from scattered wells exist from 1978, areally extensive suites of data are available only from 1983 to 1985. Because most of the wells used to define the chloride and organic pollutant plumes were drilled in 1984, temporal trends cannot be established in these wells. Dissolved-chloride and 1,2-dichloroethane concentrations fluctuated sharply but generally increased with time from 1983 to 1985 in well Cu-881 (fig. 23). The trends shown in figure 23 are representative of the trends observed in other wells. When several years of data are available for the wells used to define the plumes, further analysis of fluctuations may help to define contaminant movement at the waste site.

Table 10. Tentative identification of acid-base/neutral extractable organic compounds, well Cu-904

Organic compound	Retention time (in minutes)	Concentration (micrograms per liter)	Reliability factor
Base/Neutral-Extractable Organic Compounds			
1,1,2-Trichloroethane	3.88	100,000	99
Tetrachloroethane	4.83	320	40
1,1,2,2-Tetrachloroethane	8.34	660	86
Alkane[1]	11.19-37.51	12,000	100
1,4-Dichloro 2-butene	12.39	890	41
2-Methyl naphthalene	19.35	3,400	95
1-Methyl naphtahalene	19.77	1,000	86
1-Ethyl naphthalene	21.69	540	95
1,7-Dimethyl naphthalene	21.93	860	96
1,4-Dimethyl naphthalene	22.27	340	89
1,2-Dimethyl naphthalene	22.69	420	73
1,4,6-Trimethyl naphthalene	24.10	440	76
2-Methyl 9H-fluorene	28.00	300	69
9-Methyl 9H-fluorene	28.18	340	79
Dibenzothiophene	29.10	290	79
4-Methyl phenanthrene[2]	31.62-32.16	2,600	76-84
2-Phenyl naphthalene	32.89	360	43
3,6-Dimethyl phenanthrene	33.64	360	81
Acid-Extractable Organic Compounds			
1,1,2-Trichloroethane	3.87	22,000	99
1,1,2,2-Tetrachloroethane	8.44	440,000	97
Pentachloroethane	10.43	2,400	90
3-Chloro 1,2-benzisothiazole	21.33	980	60

[1] Eighteen different peaks identified over retention time ranges shown. Concentration is total of all peaks.

[2] Three different peaks identified over retention time ranges shown. Concentration is total of all peaks. Library search indicates compound could also be 2-methyl anthracene.

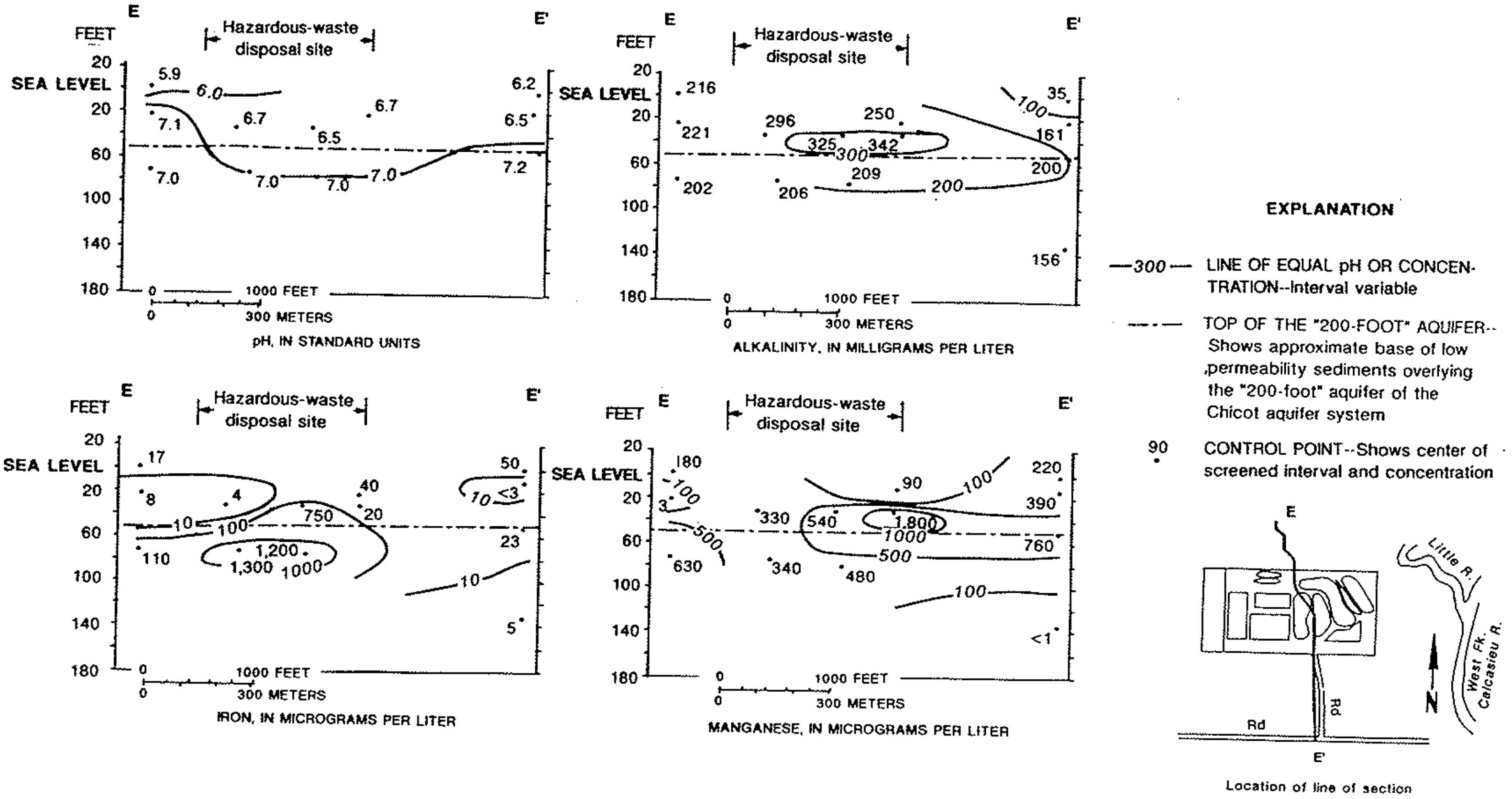


Figure 22. Distribution of pH, alkalinity, dissolved manganese, and dissolved iron at the hazardous-waste disposal site, 1985.

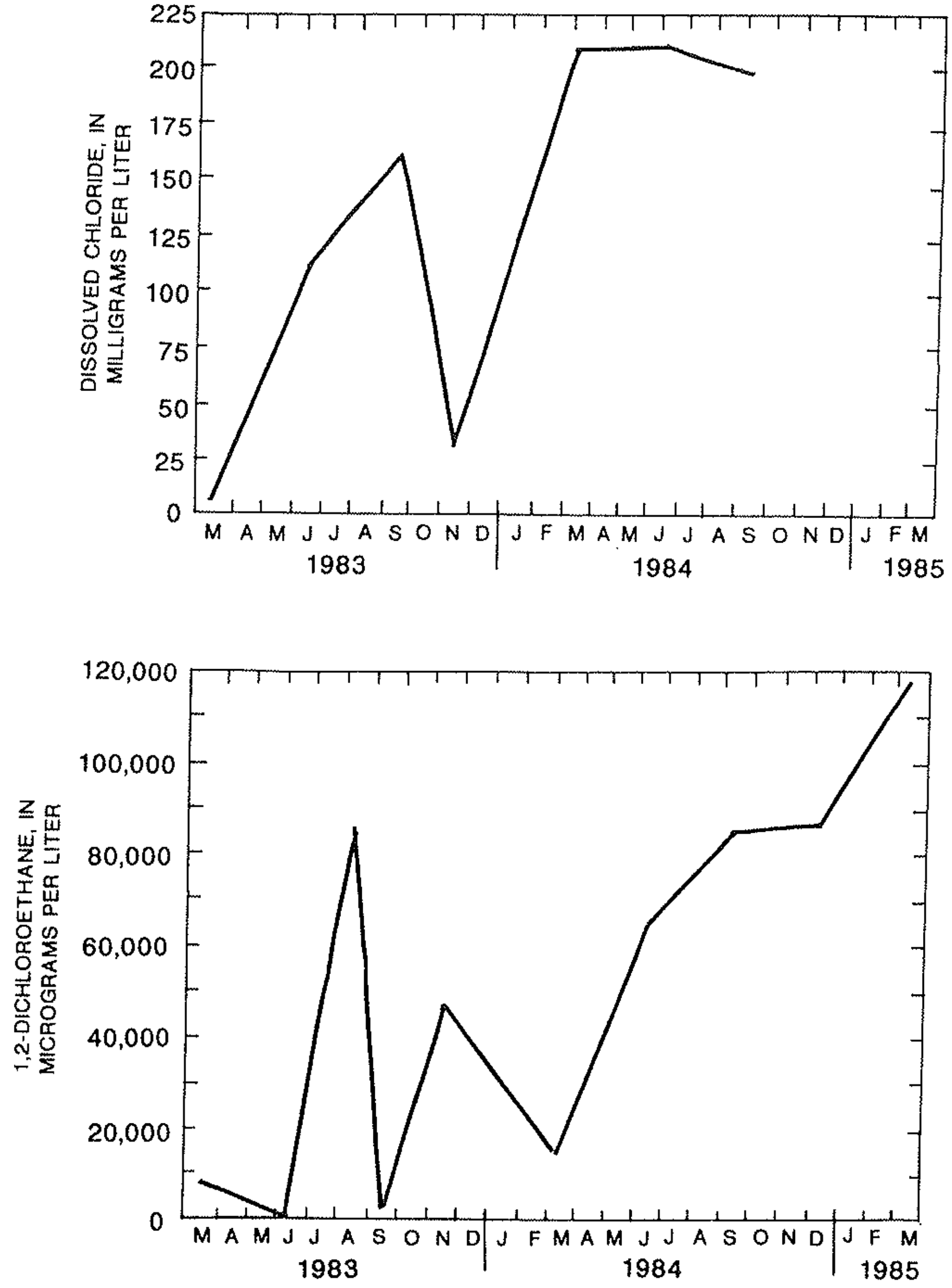


Figure 23. Fluctuation in the concentration of dissolved chloride and 1,2-dichloroethane in water from well Cu-881 in the shallow aquifer of the Chicot aquifer system, 1983-85.

SUMMARY

Oil-field and petrochemical wastes stored in unlined lagoons at a hazardous-waste disposal site in Calcasieu Parish, Louisiana, have formed plumes of contaminated ground water in low-permeability sediments beneath the unlined lagoons. Although the lagoons have been closed, the contaminated water and sediment are still present. The low-permeability sediments include 70 to 90 ft of clay, silt, and fine sand that overlie the "200-foot" aquifer the Chicot aquifer system. Stratigraphically included in the low-permeability sediments (in descending order) are: undifferentiated alluvium, surficial sand and clay, clay, the shallow aquifer of the Chicot aquifer system, and clay. Ground water beneath the waste site generally moves downward through the surficial clay, toward the northeast and east in the surficial sands and undifferentiated alluvium in the eastern part of the study area. Water may also move downward to the shallow and "200-foot" aquifers and then generally toward the southeast.

The mineralogy of the less than 2 µm clay-size fraction was determined by X-ray diffraction for 63 of 68 samples. Bulk mineralogy was determined for 35 samples, and measurements of bulk cation exchange capacity were made for 32 samples. Nine samples were studied using the scanning electron microscope and energy dispersive spectrometer.

Lateral and vertical variability in mineralogy is great for nonclay and clay minerals, and is most likely depositional in origin. Analyses indicate quartz, plagioclase feldspar, and K-feldspar are the most abundant non-clay minerals in the bulk sediment. Calcite and dolomite occur only rarely and in trace amounts. Quartz is more abundant than the two feldspars. The proportion of clay minerals to quartz and feldspar varies widely, depending on the grain-size distribution of the bulk sediment and depositional controls.

Analysis of the less than 2 µm fraction indicates that in most samples smectite is the most abundant clay mineral (averaging 45 percent), illite is intermediate in abundance (averaging 35 percent), and kaolinite is least abundant (averaging 20 percent). Analyses indicate no apparent difference between the bulk clay mineralogy of uncontaminated and contaminated samples.

A preliminary analysis, using a scanning electron microscope, indicates that there may be small-scale compositional and textural differences between uncontaminated and contaminated sediment samples. Uncontaminated sediments are composed predominantly of clay-coated detrital grains showing little or no evidence of dissolution. Contaminated sediments are characterized by the dissolution of detrital grains and precipitation of gypsum, aragonite, barite, and quartz.

Sediment contaminated by a nonaqueous phase liquid (NAPL), described as oil, is present beneath the abandoned unlined lagoons. NAPL denser than water has migrated to a depth of at least 51 ft beneath the unlined lagoons, and on the basis of logs of soil borings, is considered the most common and deepest occurring contaminant. Analyses of the NAPL-contaminated sediments indicate that a suite of organic pollutants are present, including halogenated aliphatic hydrocarbons, monocyclic aromatic hydrocarbons, PCB-related compounds, and polycyclic aromatic hydrocarbons.

Chemical analyses of ground water at the hazardous-waste disposal site have established the existence of overlapping areas of inorganic and organic contamination. The location and extent of the contaminants are generally consistent with downward migration through the surficial clay beneath the abandoned unlined lagoons and lateral movement in underlying permeable beds in the directions of ground-water flow. The axes of the chloride and 1,2-dichloroethane plumes roughly coincide and extend from the northeastern corner of the waste site southwest to the southern boundary. Chloride contamination has been detected 300 ft northeast and 1,000 ft south of the waste site, but organic contamination has not been detected at these distances. Although most of the contamination occurs in the low-permeability sediments overlying the "200-foot" aquifer, concentrations of dissolved chloride above the background level of 100 mg/L and some organic pollutants have been detected in the "200-foot" aquifer.

SELECTED REFERENCES

Brown, K.W., and Anderson, D.C., 1983, Effects of organic solvents on the permeability of clay soils: National Technical Information Service PB83-179978, 153 p.

Brown, K.W., and Associates, 1980, Hazardous waste land treatment: U.S. Environmental Protection Agency SW-874.

Brown, K.W., Deuel, L.E., Jr., and Thomas, J.C., 1983, Land treatability of refinery and petrochemical sludges: National Technical Information Service PB 83-247, 148 p.

Busenburg, E., and Clemency, C.V., 1973, Determination of the cation exchange capacity of clays and soils using an ammonia electrode: Clays and Clay Minerals, v. 21, p. 213-217.

Callahan, M.A., Slimak, M.W., Gabel, N.W., May, I.P., Fowler, C.P., Freed, J.R., Jennings, Patricia, Durfee, R.L., Whitmore, F.C., Maestri, Bruno, Mabey, William, Holt, B.R., and Gould, Constance, 1979, Water related environmental fate of 129 priority pollutants: U.S. Environmental Protection Agency EPA-440/4-79-029b.

Drever, J.I., 1982, The geochemistry of natural waters: New Jersey, Prentice Hall, 388 p.

Duffy, J.J., Mohtadi, M.F., and Peake, E., 1977, Subsurface persistence of crude oil spilled on land and its transport in ground water: Oil Spill Conference, p. 275-478.

Fishman, M.J., and Friedman, L.C., eds., 1985, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 709 p.

Fendick, R.B., Jr., and Nyman, D.J., 1987, Louisiana ground-water map no. 1: Potentiometric surface, 1985, and water-level changes, 1983-85, of the Chicot aquifer in southwestern Louisiana: U.S. Geological Survey Water Resources Investigations Report 86-4348, map, 2 sheets.

Green, W.J., Lee, G.F., Jones, R.A., and Palit, Ted, 1983, Interaction of clay soils with water and organic solvents-implications for the disposal of hazardous wastes: Environmental Science and Technology, v. 17, no. 5, p. 278-282.

Griffin, G., 1971, Interpretation of X-ray data, chapter 24, *in* R. Carver, ed., Procedures in sedimentary petrology: Wiley Interscience, p. 541-569.

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

Hanor, J.S., and Chan, Lui-Heung, 1977, Nonconservative behavior of barium during mixing of Mississippi River and Gulf of Mexico waters: Earth and Planetary Science Letters, v. 37, p. 242-250.

Harder, A.H., 1960, The geology and ground-water resources of Calcasieu Parish, Louisiana: U.S. Geological Survey Water-Supply Paper 1488, 102 p.

Jones, P.H., Hendricks, E.L., Irelan, Burdge, and others, 1956, Water resources of southwestern Louisiana: U.S. Geological Survey Water-Supply Paper 1364, 460 p.

Keith, L.H., and Telliard, W.A., 1979, Priority pollutants I - a perspective view: Environmental Science and Technology, v. 13, no. 4, p. 416-423.

Murray, D.A.J., Lockhart, W.L., and Webster, G.R.B., 1984, Analysis of the water-soluble fraction of crude oils and petroleum products by gas chromatography: Oil and Petroleum Pollution, v. 2, no. 1, p. 39-45.

Nyman, D.J., 1984, The occurrence of high concentrations of chloride in the Chicot aquifer system of southwestern Louisiana: Louisiana Department of Transportation and Development, Office of Public Works Water Resources Technical Report no. 33, 75 p.

Olhoeft, G.R., 1979a, Electrical properties, *in* Hunt, G.R., and others, Initial report of the petrophysics laboratory: U.S. Geological Survey Circular 789, p. 1-25.

-----1979b, Nonlinear electrical properties, *in* Neel, L., ed., Nonlinear behavior of molecules, atoms, and ions in electric, magnetic, or electromagnetic fields: Elsevier Science Publishing Co., p. 395-410.

-----1985, Low-frequency electrical properties: Geophysics, v. 50, p. 2492-2503.

Plice, M.J., 1948, Some effects of crude petroleum on soil fertility: Soil Science Society Proceedings, p. 413-416.

Schultz, L.G., 1964, Quantitative interpretation of mineralogical composition from X-ray and chemical data for the Pierre Shale: U.S. Geological Survey Professional Paper 391-C, p. C1-C31.

Schwille, F., 1967, Petroleum contamination of the subsoil - a hydrological problem, *in* Schwille, F., The joint problems of the oil and water industries: Elsevier Publishing, p. 23-53.

——1981, Groundwater pollution in porous media by fluids immiscible with water, *in* Quality of Groundwater: Studies in Environmental Science 17, Elsevier Publishing, 1,128 p.

Wershaw, R.L., Fishman, M.J., Grabbe, R.R., and Lowe, L.E., eds., 1983, Methods for the determination of organic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, Laboratory analysis, chap. A3, 180 p.