HYDROLOGY AND WATER-QUALITY AT THE WELDON SPRING RADIOACTIVE WASTE-DISPOSAL SITES, ST. CHARLES COUNTY, MISSOURI

By Michael J. Kleeschulte and Leo F. Emmett

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DONALD PAUL HODEL, Secretary

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Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
1400 Independence Road
Mail Stop 200
Rolla, Missouri 65401

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CONVERSION FACTORS

For readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply inch-pound unit	By	To obtain SI unit
ton	0.9072	megagram
gallon	3.785	liter
mile	1.609	kilometer
square mile	2.590	square kilometer
acre	0.4047	hectare
foot	0.3048	meter
inch	25.4	millimeter
million gallons per day	3785	cubic meter per day
foot squared per day	0.09290	meter squared per day
gallon per minute	0.06308	liter per second
foot per day	0.3048	meter per day
cubic foot per second	0.02832	cubic meter per second
cubic yard	0.7645	cubic meter

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°F = 1.8\ °C + 32$$

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

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ABSTRACT

During October 1983 a study was begun to determine the extent and magnitude of surface- and ground-water contamination caused by low-level radioactive and associated wastes stored at the Weldon Spring Chemical Plant and nearby quarry site. Water overlying the uranium-processing residues in four raffinate pits had much larger concentrations of calcium, sodium, sulfate, fluoride, nitrate, lithium, molybdenum, strontium, vanadium, radium, and uranium than native surface and ground water. Ground water from five monitoring wells adjacent to the raffinate pits had nitrate concentrations ranging from 53 to 990 milligrams per liter as nitrogen. Most of the water samples from these wells also had increased concentrations of the following inorganic constituents (the maximum concentrations, in milligrams per liter, are shown in parenthesis): calcium (900), magnesium (320), sodium (340), and sulfate (320). Concentrations of several trace elements also were increased (the maximum concentrations, in micrograms per liter, are shown in parenthesis): lithium (1,700), strontium (1,900), and uranium (86). The presence of these constituents in increased concentrations indicates seepage from the raffinate-pits area.

Water-level measurements in wells open to the shallow bedrock aquifer at the chemical plant indicate that the water table is in the Keokuk and Burlington Limestones; however, seismic studies made for the U.S. Department of Energy (Bechtel National, Inc. 1984b) have indicated areas of saturated overburden beneath the center of raffinate pit 3 and possibly adjacent to raffinate pits 1, 2, and 4. A water-balance study made for the U.S. Department of Energy contractor indicated a 0.04 to 0.08 inch per day decrease in the water level of the pits that cannot be explained by calculated evaporation (Bechtel National, Inc. 1986). It was concluded that the loss in water levels in the pits probably results from seepage into the underlying clays.

Uranium concentrations as large as 250 micrograms per liter have been detected in water from Burgermeister spring. The spring is 1.5 miles north of the chemical plant and raffinate pits and is in a different drainage basin. Concentrations of nitrate as nitrogen as large as 54 milligrams per liter and lithium concentrations as large as 77 micrograms per liter also have been detected in the water from Burgermeister spring. Losing streams and springs are typical in karst areas and both are present in the Weldon Spring area. Dye-tracer studies by the Missouri Department of Natural Resources indicate that losing streams north of the chemical plant area are hydrologically connected to Burgermeister spring. One explanation for the increased uranium concentrations in the spring discharge is that the spring receives uranium-contaminated water from losing-stream reaches in the tributary that contains Ash pond. A water sample from Ash pond had a uranium concentration of 1,000 micrograms per liter. The presence of increased concentrations of nitrate and lithium in the spring

water indicates that the spring receives recharge from other sources, possibly seepage from the raffinate pits. Because no contamination plume has been detected between the raffinate pits and Burgermeister spring, it is hypothesized that the contaminants may be migrating through preferred paths in the ground-water system, such as fractures and solution openings.

The Weldon Spring quarry site, 3 miles southwest of the chemical plant, became a low-level radioactive waste-disposal site in 1959. Water sampled from 13 wells near the quarry and north of Femme Osage slough in 1986 had uranium concentrations ranging from 8.9 to 14,000 micrograms per liter (Kleeschulte and others, 1986). Water from six observation wells sampled south of the slough had uranium concentrations of less than 5 micrograms per liter. Water samples collected from the St. Charles County well field, 0.8 miles southeast of the quarry, indicate the water in the well field has background concentrations of uranium (less than 2.1 micrograms per liter).

INTRODUCTION

The Uranium Division of the Mallinckrodt Chemical Works operated a uranium feed materials plant for the U.S. Atomic Energy Commission from 1957 to 1966. The site, now known as the Weldon Spring Chemical Plant, converted uranium-ore concentrates and recycled scrap to pure uranium trioxide, uranium tetrafluoride, and uranium metal. Some thorium also was processed. Waste from the plant operation is referred to as raffinate and includes the waste from the extraction step and the solids that resulted from the neutralization of the waste (Weidner and Boback, 1982). The waste was pumped as a slurry to four large pits (hereafter called raffinate pits) that were constructed near the plant. Lenhard and others (1967) reported the quantity of nuclear material that was considered unrecoverable at the plant and were discharged to the pits from the refinery operations totalled 150 tons of uranium, 76 tons of thorium, and 1.5 tons of slightly enriched uranium. The supernatant liquids from raffinate pits 1, 2, and 3 constantly overflowed to the plant-process sewer. During an average day, the sewer was estimated to discharge about 1 million gallons to the Missouri River; one-half of this was from the raffinate pits (Lenhard and others, 1967). The physical properties of the four raffinate pits are summarized in table 1. An abandoned limestone quarry about 3 miles southwest of the plant also has been used for the disposal of contaminated solids and radioactive residues from various processing sites. Disposal of the radioactive waste in an area underlain by permeable carbonate rocks has created the potential for contamination of the ground water. Contamination of surface water by seepage from the pits to springs and streams and from surface runoff transporting contaminated soil also may occur.

The U.S. Geological Survey began collecting hydrologic information in the Weldon Spring area (fig. 1) in October 1983. The results of the first year of the study are presented in a progress report (Kleeschulte and Emmett, 1986), which also summarizes hydrologic data collected by previous investigators. Water-quality data collected by the U.S. Geological Survey from 1984 through 1986 are presented in a data report by Kleeschulte and others (1986). This report includes seepage-run data for six of the area streams and mean daily discharge data for Burgermeister spring and a nearby wet-weather spring, for the period March 20, 1985, through April 30, 1986.

Table 1.--Physical properties of the four raffinate pits

[Data modified from Lenhard and others, 1967 and Bechtel National, Inc., 1984b]

Pit number	Surface area, in acres	Date used	Altitude of levee top, in feet above sea level	Altitude of pit bottom, in feet above sea level	Design capacity, in million cubic feet	Actual volume, in million cubic feet	Altitude of top of sludge, in feet above sea level	Altitude of spillway, in feet above sea level
1	1.2	1958-60	664	648	0.500	0.470	661	662 to process sewer
2	1.2	1958-60	664	648	.500	.470	661	662 to process sewer
3	8.4	1959-64	663	638-647	4.500	3.500	654-660	656 to process sewer
4	15.0	1964	663	628-650	12.000	1.500	a	[b]656 to pit 3

[a] Sludge unevenly distributed throughout the pit.
[b] Pit 4 was designed to flow into pit 3 but altitude of water has never reached this level in pit 4, however water in pit 3 has flowed into pit 4.

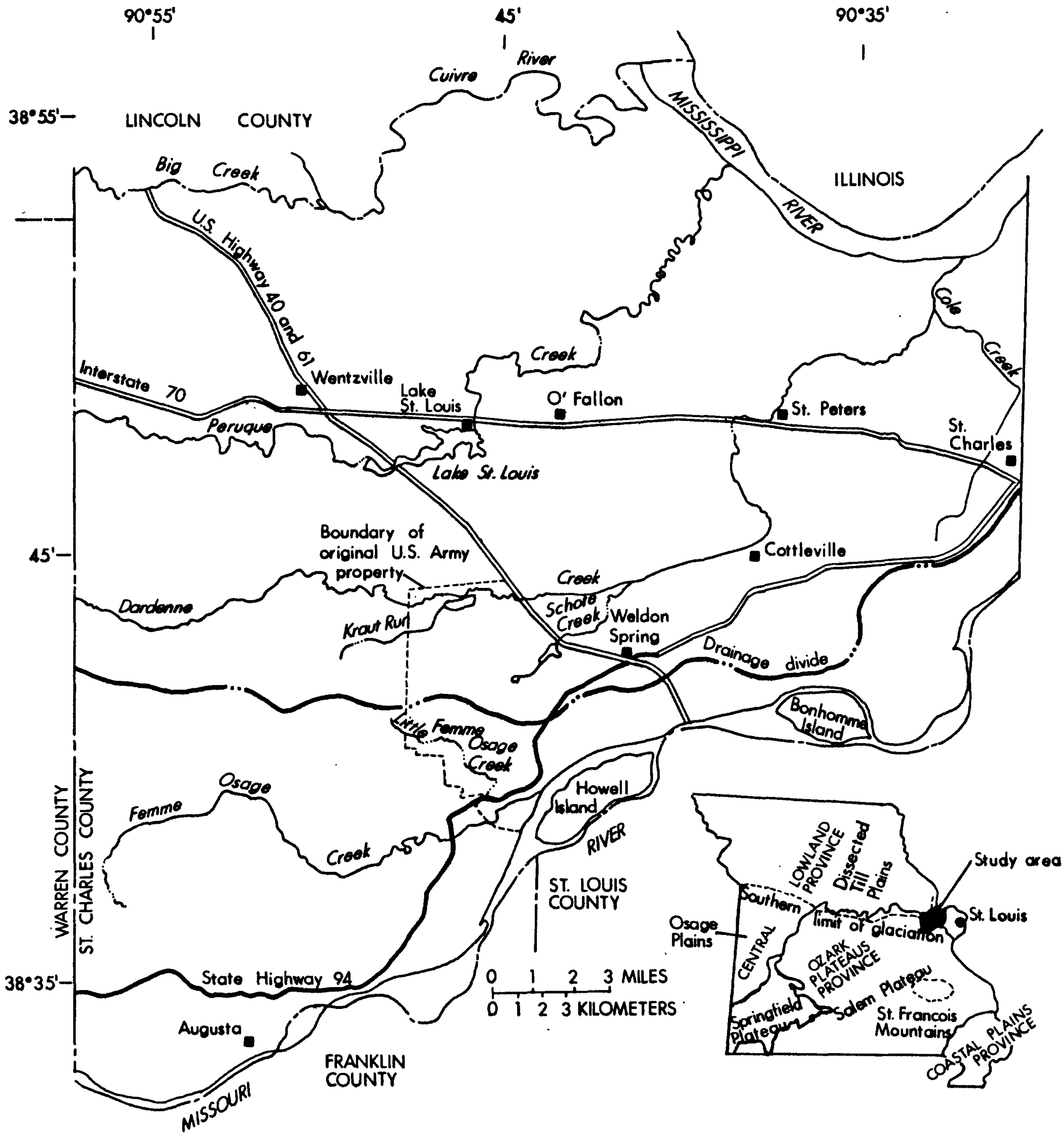


Figure 1.--Study area and drainage network (physiography from Fenneman, 1938).

Purpose and Scope

The purpose of this report is to describe the hydrology and water quality in the Weldon Spring area. The project was funded by the U.S. Geological Survey's Branch of Nuclear Waste Hydrology to help evaluate the extent and magnitude of surface- and ground-water contamination in the vicinity of the Weldon Spring Chemical Plant and the quarry. This report contains an interpretive analysis of the data that were collected from 1984 to 1986 and describes the general ground-water flow system of western St. Charles County and the geohydrology of the Weldon Spring area. Parts of the 1986 progress and data reports are included to provide continuity. Surface- and ground-water relations in the vicinity of the chemical plant and the water-quality characteristics of the aquifers and selected tributaries in the area are described.

Description of Study Area

The study area consists of about 280 square miles in St. Charles County in eastern Missouri (fig. 1), but the data collection and analyses were most intense in a 17,232 acre area (fig. 2) that the Department of the Army acquired in April 1941. Two distinct radioactive waste-disposal sites are on this property. One site consists of about 200 acres at the Weldon Spring Chemical Plant and raffinate-pits area. The other site is a 9-acre abandoned rock quarry (referred to as the Weldon Spring quarry) in a bluff adjacent to the Missouri River flood plain and about 3 miles southwest of the chemical plant.

The study area is in two physiographic provinces (fig. 1). The northern two-thirds of the study area is in the Dissected Till Plains section of the Central Lowland province, which includes the chemical plant property. This area is characterized by moderately to slightly undulating topography and thin, dissected glacial deposits, predominantly clay, overlying limestone bedrock. The southern one-third of the area lies on the northeastern flank of the Salem Plateau section of the Ozark Plateaus province, which includes the Weldon Spring quarry site. This area is characterized by rugged topography, narrow, irregular drainage divides and is drained by many short streams with steep gradients. The transition area between the two provinces is just south of the chemical plant and corresponds to a primary drainage basin divide.

The surface water north of the divide flows north to the Mississippi River in Dardenne Creek, the primary tributary and drain for the area immediately north of the chemical plant and raffinate-pits area (fig. 2). Surface drainage at the chemical plant and raffinate-pits area flows into the August A. Busch Memorial Wildlife Area lakes 35 and 36 by intermittent tributaries and then into Schote Creek before reaching Dardenne Creek. The surface water south of the divide flows southward to the Missouri River. Femme Osage Creek is the largest tributary south of the divide.

Because of its midcontinent location, the study area is exposed to cold air from the north, dry air from the west, and warm, moist air from the Gulf of Mexico. Consequently, frequent changes in the weather occur both daily and seasonally. The average annual precipitation is 37 inches. In 1985, temperatures ranged from an average daily minimum of 10 °F in January to an average daily maximum of 88 °F in July (National Oceanic and Atmospheric Administration, 1985).

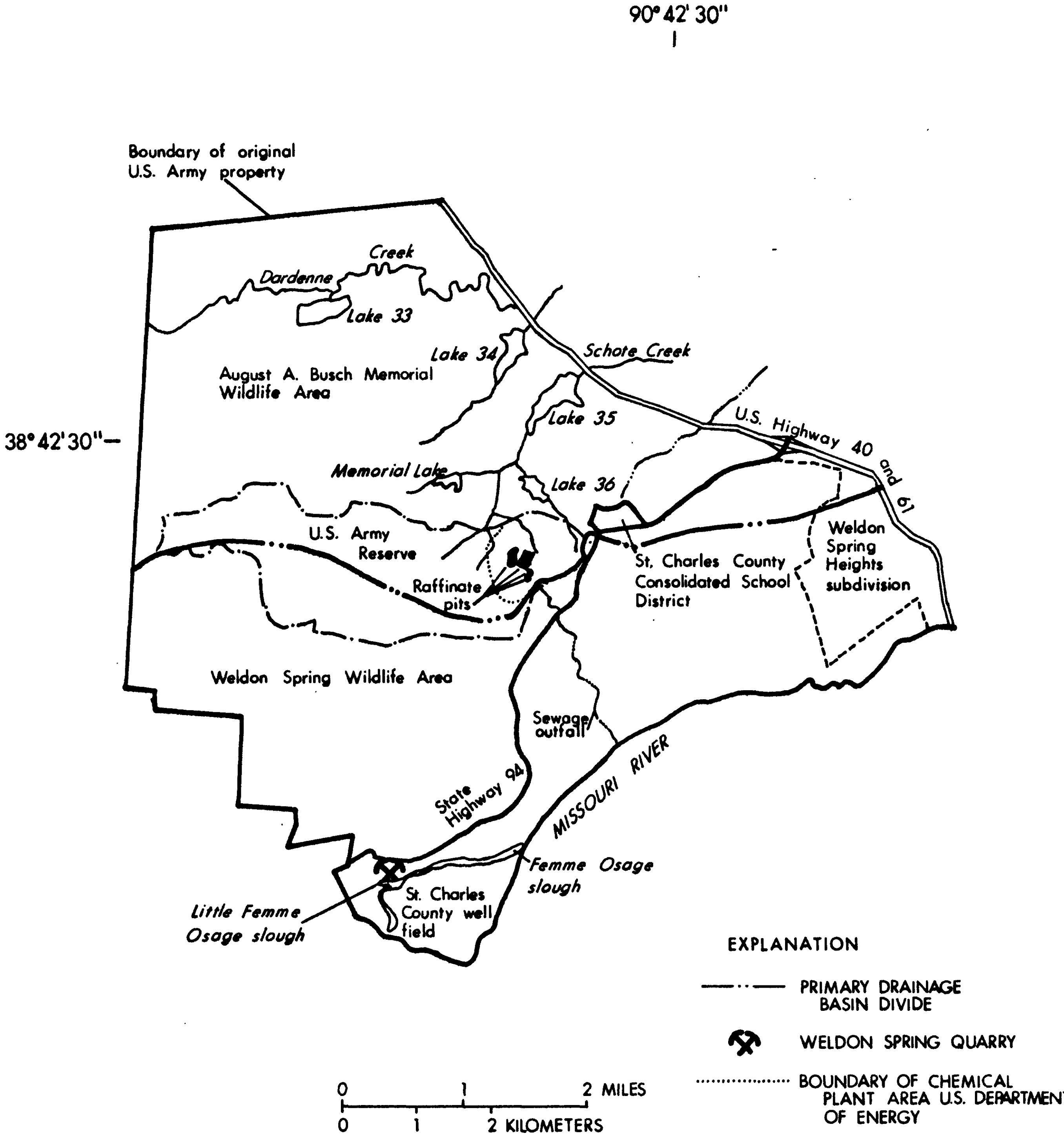


Figure 2.--Original U.S. Army property where data collection and analyses were concentrated.

Population in the study area is increasing because of its proximity to St. Louis. The largest towns (and their 1980 populations) within the study area (fig. 1) are St. Charles (43,551), a part of which lies just inside the eastern boundary, St. Peters (15,700), O'Fallon (8,677), Lake St. Louis (3,843), and Wentzville (3,193; Johnson, 1984).

The Weldon Spring quarry site is near a well field under the jurisdiction of St. Charles County. Between the quarry and the well field is an isolated body of water that consists of two components that locally are known as Femme Osage and Little Femme Osage sloughs (fig. 2). These sloughs were created between 1959 and 1960 when a levee system was constructed diverting the downstream reaches of Femme Osage and Little Femme Osage Creeks from their natural channels. The levee was built to prevent annual flooding of farmland and the well field that are within the levee system.

History of the Radioactive Waste-Disposal Sites

"In April 1941, the Department of the Army acquired 17,232 acres surrounding what is now the WSCP [Weldon Spring Chemical Plant] as the site for an explosives production facility known as the Weldon Spring Ordnance Works" (Ryckman, Edgerley, Tomlinson, and Assoc., 1978, p. 5). Because of the threat of World War II, the plant began manufacturing trinitrotoluene (TNT) and dinitrotoluene (DNT) before adequate arrangements could be made for the disposal of waste liquids from the manufacturing processes. As a result, frequent spillovers of red-sulfonate derivatives from wooden production-line disposal pipes and overflows of the catchment tanks occurred from November 1941 through January 1944. These spills contaminated both the surface- and ground-water resources of the area and were large enough to cause several springs near the Ordnance Works, Dardenne Creek, Schote Creek, and several of their tributaries to visibly flow red at times (V.C. Fischel and C.C. Williams, U.S. Geological Survey, written commun., 1944). These spills not only contaminated the area with sulfate and nitrate, but were the first dye traces (although unintentional and uncontrolled) to indicate subsurface hydraulic connections in the area.

The U.S. Army declared the Ordnance Works surplus property in April 1946. The Army abandoned the processing buildings and transferred ownership of 15,169 acres by the end of 1949. Currently (1987) the U.S. Army has jurisdiction of about 1,655 acres. The rest is owned by the Missouri Department of Conservation, a St. Charles County Consolidated-School District, a local subdivision, and the U.S. Department of Energy.

During 1955, the U.S. Atomic Energy Commission (now known as the U.S. Department of Energy) authorized construction of the Weldon Spring Feed Materials Plant at the site of the old Ordnance Works. The Uranium Division of Mallinckrodt Chemical Works began operating the plant for the Atomic Energy Commission during 1957. The plant converted previously extracted impure uranium concentrates to pure uranium salt and metal. From 1958 to 1964 the plant received ore in excess of plant capacity; however, not all of this material was processed. The ore received was to be sampled, then temporarily stored. Some of the material was shipped to other U.S. Atomic Energy Commission facilities for further processing (L.F. Campbell, U.S. Department of Energy, written commun., 1986). The result was radiological contamination of five primary process buildings, most of the support structures, and land west of the plant with uranium and its decay products (Ryckman, Edgerley, Tomlinson, and Assoc., 1978). Raffinate pits were excavated for disposal of waste from processing uranium and thorium concentrates. Pits 1 and 2 (each 1.2 acres in area) were constructed during 1958, pit 3 (8.4 acres) was constructed during 1959, and pit 4 (15.0 acres) was constructed during 1964 (National Lead Company of Ohio, Inc., 1977).

During 1958, the U.S. Atomic Energy Commission acquired the abandoned Weldon Spring quarry for a low-level radioactive waste-disposal site. Radioactive wastes began arriving at the quarry in 1959. A report by Kleeschulte and Emmett (1986) gives a detailed description of these wastes and a history of the original U.S. Army property.

Previous Investigations

In October 1943, the Chief of Engineers of the War Department requested the U.S. Geological Survey to investigate the extent of contamination caused by the sulfonate-derivative spills during TNT production. Contamination that originated on the Weldon Spring Ordnance Works property north of the drainage divide was limited to springs, streams, and wells south of Dardenne Creek and northwest of Schote Creek (V.C. Fishel and C.C. Williams, written commun., 1944). Dardenne Creek contained contaminated water about 2,000 feet downstream from its junction with Kraut Run (the mouth of Kraut Run is now occupied by Lake 33) to its junction with the Mississippi River (fig. 1). The streams that entered Dardenne Creek from the north did not seem to be affected by contaminants. This indicated that Dardenne Creek was a drain for the area and shallow ground water did not move beyond Dardenne Creek. Uncontaminated water entered Dardenne Creek from streams downstream from Schote Creek.

Water-level data were collected from wells and springs in 1943 (Fishel and Williams, written commun., 1944) and in 1951 (Roberts, 1951). Roberts (1951) reported that ground water south of the drainage divide at altitudes of less than 580 feet above sea level moved toward the Missouri River.

In 1960, R.M. Richardson (U.S. Geological Survey, written commun., 1960) evaluated the hydrology of the Weldon Spring quarry site. He concluded that leaving the water level in the quarry sump at equilibrium would cause ground-water flow through the quarry toward the Missouri River alluvium and possibly would contaminate the water being pumped from the St. Charles County well field.

While studying the solids buried at the quarry, Huey (1978, p.2) concluded from the data that "* * * there is no doubt that soluble contaminants have and will continue to escape from the quarry via ground water through fissures, voids, etc * * *." However, semiannual water sampling at that time indicated the concentration of contaminants to be less than the standard of the U.S. Department of Energy for controlled and uncontrolled areas.

From 1979 to 1981, Berkeley Geosciences Assoc. (1984) investigated contamination associated with the quarry site. They suggested the bulk of radionuclides migrating from the quarry would move into the alluvium because of fractures in the limestone and the substantial permeability of the alluvium. Uranium contents larger than background were detected in soil from the area between the quarry and Femme Osage slough and in water and soil samples from the quarry and the slough. Ground-water samples collected from the area between the slough system and the Missouri River had approximately background concentrations of uranium.

Bechtel National, Inc. began environmental monitoring at the Weldon Spring sites in October 1981 and continued until October 1986. They drilled numerous observation wells at the chemical plant and in the vicinity of the quarry. During 1982, uranium concentrations migrating from the quarry area to observation wells north of Femme Osage slough in the Missouri River alluvium and nitrate migrating from the seepage of the raffinate-pits transfer line into the sewer system outfall exceeded the standard of the U.S. Department of Energy (Bechtel National, Inc., 1983b).

Oak Ridge National Laboratory collected five soil samples from various locations near raffinate pit 4. Illite was the primary clay constituent. Soil composition of the samples was clayey sand or sandy, silty clay. Particle-size distributions of the five soil samples were variable, with the 50 percent distribution point ranging from 12 to 81 micrometers and the surface areas ranging from 13 to 62 meters squared per gram. Uranium sorption ratios, the concentration of uranium in the soil after the soil is put in a test solution divided by the uranium concentration of the test solution after contact, for four of the soil samples were moderate to large (about 300 to 1,000 milliliters per gram). The fifth sample had a ratio of 12 milliliters per gram. Radium sorption ratios for the 5 samples were moderate to large (about 600 to 1,000 milliliters per gram). Seeley and Kelmers (1985, p. 13 and 15) concluded that "At least four of the five soil samples could probably be characterized as having sufficient sorption capacity to significantly retard the migration of uranium. * * * the sorption ratio for each of the five soil samples indicates favorable retardation of radium; that is, it may be high enough to retard this radionuclide from migrating into the environment to any significant degree."

Shell Engineering and Associates, Inc. (Bechtel National, Inc., 1986) made a water-balance study of the raffinate pits for the U.S. Department of Energy. The report concludes the raffinate pits have a 0.04 to 0.08 inch per day decrease in water levels that could not be attributed to calculated evaporation (the decrease in water levels and total water loss were converted from values given in Bechtel National, Inc., 1986). This implies a soil permeability rate of 10^{-7} centimeter per second, which is in the range of expected permeability values for the overburden in the area. This 0.04 to 0.08 inch per day loss in water levels translates to a total water loss of about 216 to 324 cubic feet per day for pits 1 and 2, and about 3,240 cubic feet per day for combined pits 3 and 4. This indicates a probable seepage of water from the raffinate pits into the underlying clays (Bechtel National, Inc. 1986).

In 1986, Layne-Western Company, Inc. published the results of their ground-water model of the St. Charles County well field. They concluded that, during normal operation of the well field (pumpage of 10.39 million gallons per day), two-thirds of the water pumped comes directly from infiltration from the Missouri River. When pumpage from test well 8 was added to the model, nearly 100 percent of the increased pumpage was infiltration from the river. They also reported the limestone bedrock was not contributing significant water inflow to the alluvial aquifer flow system (Layne-Western Company, Inc., 1986).

A more detailed account of previous investigations at the Weldon Spring sites can be found in Kleeschulte and Emmett (1986). Many of the earlier studies are summarized in that report.

Acknowledgments

The authors are grateful to the residents of St. Charles County, public water-supply operators, and superintendents who allowed us access to their wells and files. We thank the U.S. Department of Energy, and especially John Henry, the former Weldon Spring site manager, for allowing us frequent access to the raffinate-pits and quarry area; Perley Cassady and the other conservation agents of the Missouri Department of Conservation for allowing us to construct observation wells, make dye-tracer studies, and perform water-sampling studies on the August A. Busch Memorial Wildlife area; and the Missouri Department of Natural Resources, Division of Geology and Land Survey, for assisting the authors and analyzing the charcoal packets from our dye trace on their spectrofluorometer. We also give a special acknowledgment to the late T.J. Dean of the Missouri Department of Natural Resources, Division of Geology and Land Survey, for the previous work he performed at the Weldon Spring sites. His dye-tracer studies on the losing-stream reaches in the vicinity of the raffinate pits greatly helped in defining the relation between surface water onsite and the shallow ground-water system.

GEOLOGIC BACKGROUND

Stratigraphy

Geologic formations ranging in age from Holocene (alluvium) to Early Ordovician (Cotter Dolomite) are exposed in the area. The unconsolidated formations are alluvial deposits, loess, glacial deposits, and residuum, which are composed of varying particle sizes ranging from clay to boulder. Consolidated formations primarily are dolomite and limestone with small quantities of shale and sandstone. A generalized description of geologic formations that are in the area is listed in table 2. A geologic section across the southern part of the study area (fig. 3) illustrates the structural relation of formations from the surface to the top of the St. Peter Sandstone.

Chemical-plant and raffinate-pits area

The chemical-plant area is characterized by slightly to moderately undulating topography, dissected till deposits ranging from 0 to 50 feet thick, and the underlying Keokuk and Burlington Limestones. The overburden on the chemical-plant property primarily consists of clay, silty clay, and clayey silt with varying quantities of chert. These deposits are thickest on the ridge tops. A residuum layer ranging from 0 to 22 feet thick also is directly above the bedrock on the chemical-plant site (Bechtel National Inc., 1987). This layer consists of cobbles and boulders of limestone and chert in a silty, sandy, clay matrix. The permeability of the residuum is not known. Bechtel National, Inc. (1984b) reported variable drilling water losses (0 to 100 percent) while drilling wells in this zone at the chemical-plant area. This same residuum layer offsite is characterized by relict chert beds at or near the surface. This type of material has been determined to be permeable elsewhere in the State by the Missouri Department of Natural Resources, Division of Geology and Land Survey (Bechtel National, Inc., 1984b). Because the residuum onsite is at greater depths, the matrix is believed to be more consolidated than the layer offsite and the beds are only partially disintegrated. This indicates that the average permeability of the residuum onsite is less than offsite, but it has a larger permeability than the overlying glacial till (Bechtel National, Inc., 1984b).

The underlying Keokuk and Burlington Limestones are cherty limestones that locally are fractured and have solution channels. While doing geophysical work at the site, Bechtel National, Inc. (1984b) observed the upper 40 feet of the limestone to be gradationally weathered and to have a surface of irregular pinnacles. One pinnacle has a possible relief of 8 feet. When considering the pinnacles and depressions, the top of the bedrock may have 40 feet of relief. The bedrock depressions typically are filled with clay. The upper 35 feet of competent limestone generally is fractured and has iron-oxide stains because of weathering. The formation also has numerous clay-filled and open spaces (Bechtel National, Inc., 1984b).

Altitude of the top of the bedrock and thickness of overburden near the chemical plant are shown in figures 4 and 5. More detail can be shown in figure 5 around the raffinate pits because of the extensive work done by Bechtel National, Inc. The bedrock beneath the site and in the vicinity of the chemical plant generally dips to the north. A depression is in the bedrock southwest of Burgermeister spring. Also, the top of bedrock within the losing-stream reaches near the chemical plant appears to be irregular and may have been eroded or modified by dissolution.

Table 2.--Generalized description of the lithologic and hydrologic properties of the aquifers

[Modified from Koenig (1961); Miller and others (1974); gal/min, gallons per minute; --, insufficent data to make estimate; <, less than; Typical thickness refers to thickness of formation normally encountered while drilling and does not include extremes]

System	Series	Stratigraphic unit	Depth from ground level to top of formation, in feet	Thickness, in feet	Typical thickness, in feet	Physical characteristics		Remarks
QUATERNARY	HOLOCENE	Alluvium	0	0-65	10-30	Gravelly, silty loam over occasionally gravelly, silty clay loam.	Alluvial aquifers	Deposits underlie tributaries to Missouri and Mississippi rivers.
			0	65-120	100-110	Silty loam, clay, and sand over sand and gravelly sand.		Deposits underlying Missouri and Mississippi River flood plains generally yield large quantities of water to wells. (600-2,600 gal/min).
	PLEISTOCENE	Loess and glacial drift	0	0-150	5-30 30-60	Silty clay, silty loam, clay, or loam over residuum and bedrock, or both		Yields little water to wells (<5 gal/min).
PENNSYLVANIAN		Undifferentiated	0-120	0-75	--	Partly silty red shale with purplish-red to light gray clay.		Limited occurence. Yields small quantities of water to wells (<1-10 gal/min).
MISSISSIPPIAN	MERAMECIAN	St. Louis Limestone	0-120	0-105	70-75	Limestone; white to light gray, lithographic to finely crystalline, medium- to thickly bedded. Contains some shale.	Shallow bedrock aquifer	
		Salem Limestone	0-225	0-140	90-130	Limestone; light gray white, fine to coarsely crystalline, cross-bedded. Some siltstone and shale lower part.		Individually, the rock units yield small to moderate quantities of water to wells (5-50 gal/min). Collectively, these units yield sufficient water to supply most domestic and stock needs.
		Warsaw Formation	0-345	0-95	70-90	Calcareous shale and interbedded shaly limestone, grades downward to shaly dolomitic limestone.		
	OSAGEAN	Keokuk and Burlington Limestones	0-405	0-220	160-200	Limestone; white to bluish-gray, medium to coarsely crystalline, thickly bedded. Cherty.		
		Fern Glen Limestone	0-500	0-85	50-70	Limestone; yellowish-brown, fine-grained, medium- to thickly bedded. Contains appreciable chert.		
	KINDERHOOKIAN	Chouteau Limestone	0-580	0-105	50-70	Dolomitic limestone; gray to yellowish-brown, fine-grained, thinly to medium-bedded.		
DEVONIAN	UPPER	Bushberg Sandstone	0-625	0-20	5-15	Quartz sandstone; reddish-brown, fine- to medium-grained, friable.		Yields small to moderate quantities of water to wells. (5-50 gal/min).
		Lower part of Sulphur Spring Group undifferentiated	0-625	0-60	35-40	Calcareous siltstone and sand-stone with oolitic limestone with some dark, hard, carbonaceous shale.		Sulphur Spring Group also includes Glen Park and Grassy Creek Formations. Units in the Sulphur Spring Group are the usage of the Missouri Division of Geology and Land Survey.

ORDOVICIAN	UPPER	Maquoketa Shale	0-650	0-75	30-50	Calcareous or dolomitic shale; typically thinly laminated, silty, with shaly limestone lenses.	Leaky confining layer	Yields small quantities of water to wells.
ORDOVICIAN	MIDDLE	Kimmswick Limestone	0-710	0-140	90-100	Limestone; white to light gray, coarsely crystalline, medium- to thickly bedded. Cherty near base.	Leaky confining layer	Yields small to moderate quantities of water to wells (10-50 gal/min).
ORDOVICIAN	MIDDLE	Decorah Formation	0-810	0-35	30	Interbedded green and yellow shale with thin beds of limestone.	Leaky confining layer	
ORDOVICIAN	MIDDLE	Plattin Limestone	0-840	0-195	100-125	Limestone; light to dark gray, finely crystalline. Thinly bedded; weathers with pitted surface.	Leaky confining layer	
ORDOVICIAN	MIDDLE	Joachim Dolomite	0-950	0-135	90-110	Dolomite; yellowish-brown, silty, thin- to thickly bedded. Grades into siltstone, shales common.	Leaky confining layer	
ORDOVICIAN	MIDDLE	St. Peter Sandstone	0-1,070	0-250	120-150	Quartz sandstone; yellowish-white to white, fine- to medium-grained, massively bedded.	Deep bedrock aquifer	Yields moderate quantities of of water to wells (10-140 gal/min). Everton Formation discontinuous.
ORDOVICIAN	MIDDLE	Everton Formation	0-850	0-65	0	Sandy dolomite.	Deep bedrock aquifer	
ORDOVICIAN	LOWER	Powell Dolomite	0-950	0-65	50-60	Dolomite; medium to finely crystalline, often sandy, occasionally cherty or shaly.	Deep bedrock aquifer	Generally yields small quantities of water to wells (<10 gal/min).
ORDOVICIAN	LOWER	Cotter Dolomite	0-1,250	75-275	200-250	Dolomite; light gray to light brown, medium to finely crystalline, cherty. Argillaceous, interbedded with green shale.	Deep bedrock aquifer	
ORDOVICIAN	LOWER	Jefferson City Dolomite	100-1,500	145-225	160-180	Dolomite; light brown to brown, medium to finely crystalline.	Deep bedrock aquifer	
ORDOVICIAN	LOWER	Roubidoux Formation	350-1,700	150-170	150-170	Dolomitic sandstone.	Deep bedrock aquifer	Yields moderate to large quantities of water to wells (10-300 gal/min).
ORDOVICIAN	LOWER	Gasconade Dolomite	500-1,850	250	--	Cherty dolomite; Gunter Sandstone Member is arenaceous.	Deep bedrock aquifer	Gunter Sandstone Member is about 30 feet thick.
CAMBRIAN	UPPER	Eminence Dolomite	750-2,100	190	--	Dolomite; medium- to massively bedded, light gray, medium- to coarse-grained.	Deep bedrock aquifer	Yields moderate to large quantities of water to wells (10-500 gal/min).
CAMBRIAN	UPPER	Potosi Dolomite	950-2,250	100	--	Dolomite; massive, thickly bedded, medium- to fine-grained. Abundant quartz druse.	Deep bedrock aquifer	Freshwater only in south-west part of St. Charles County and saline water elsewhere in county.
CAMBRIAN	UPPER	Doe Run and Derby Dolomites[1]	1,050-2,350	140	--	Dolomite; thinly- to medium-bedded alternating with thinly bedded silt-stone and shale.		Hydrologic characteristics unknown in St. Charles County. Is a confining bed elsewhere in State.
CAMBRIAN	UPPER	Davis Formation	1,200-2,500	170	--	Shale, siltstone, fine-grained sandstone, dolomite, and lime-stone conglomerate.		
CAMBRIAN	UPPER	Bonneterre Dolomite	1,350-2,650	430	--	Dolomite; typically light gray, medium- to fine-grained, medium-bedded.		Yields unknown in St. Charles County; however, water probably is saline.
CAMBRIAN	UPPER	Lamotte Sandstone	1,800-3,100	460	--	Predominantly quartzose		
PRECAMBRIAN		Igneous rocks undifferen-tiated	2,200-3,500		--	Igneous rocks.		Yields no water.

[1] Designated Derby-Doerun Dolomite by the Missouri Division of Geology and Land Survey.

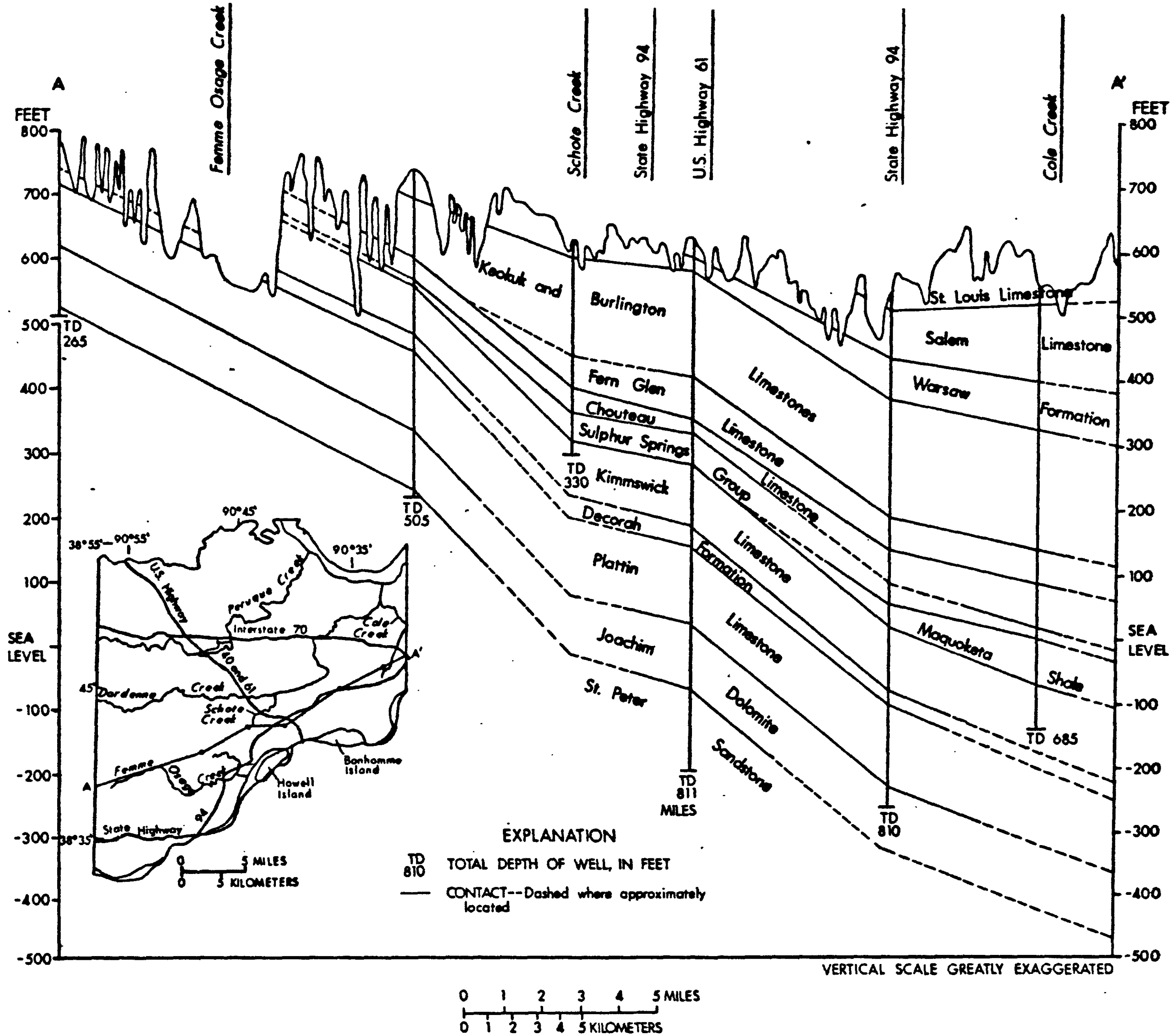


Figure 3.--Geologic section of southern part of study area.

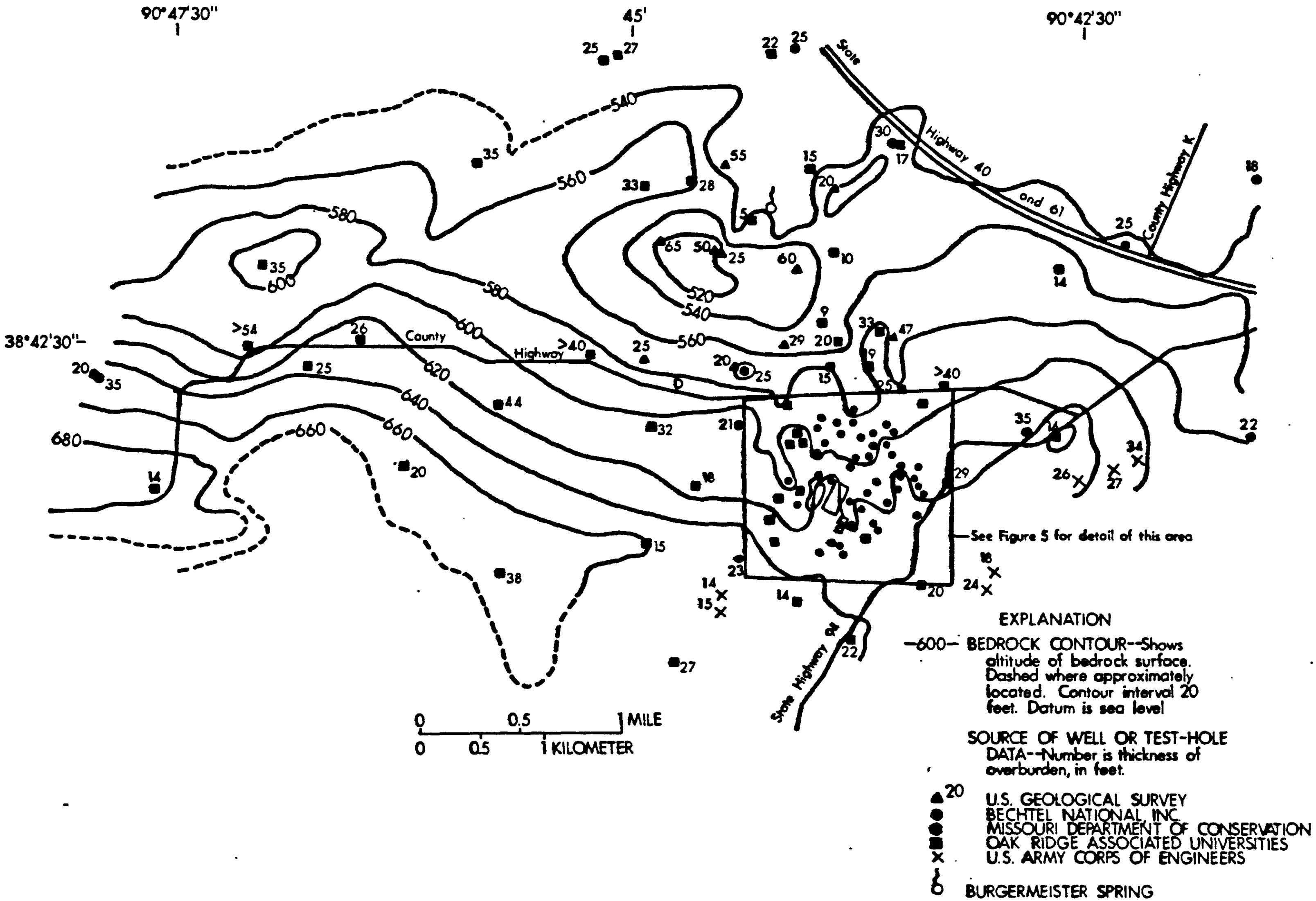
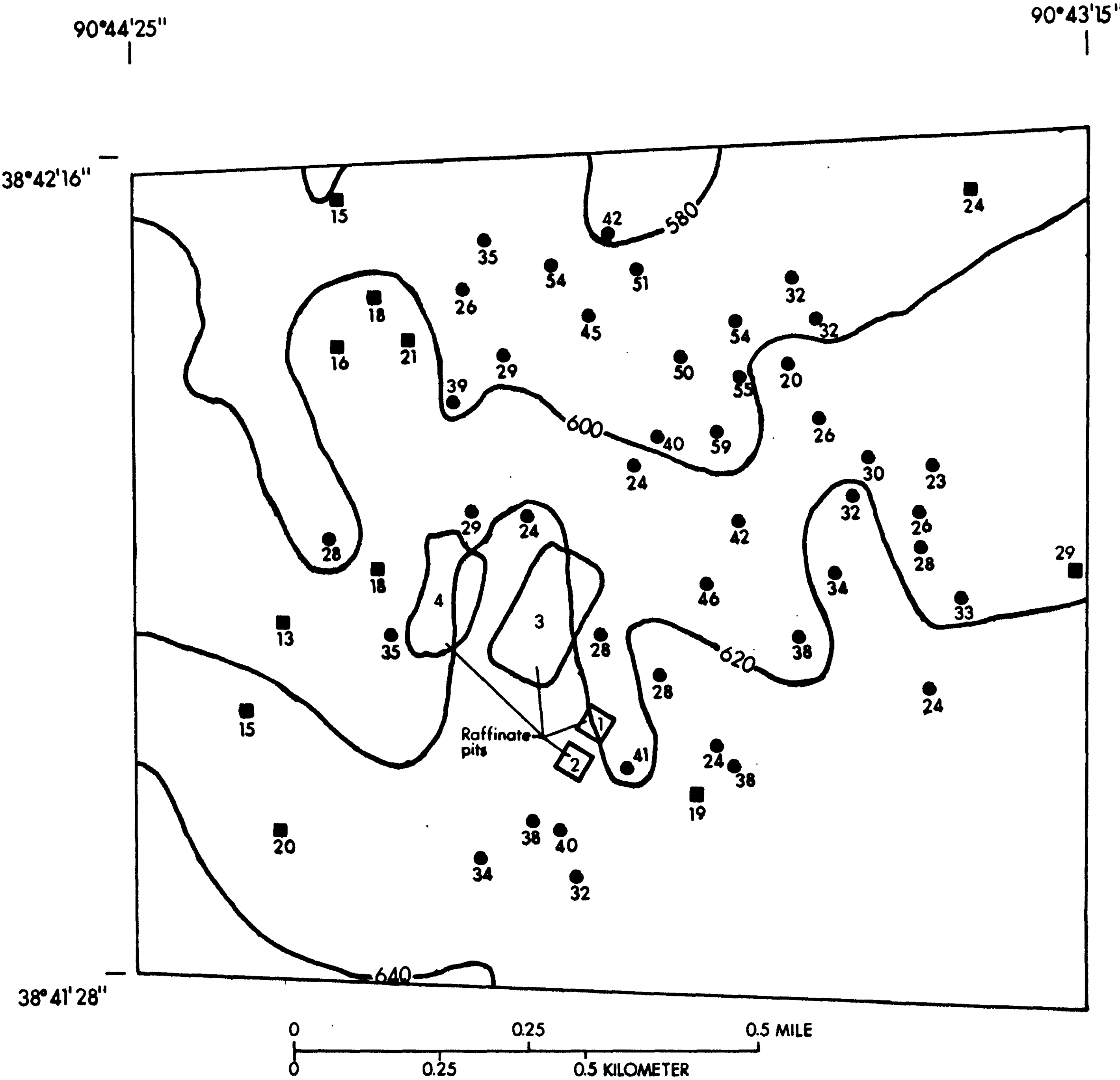


Figure 4.--Altitude of top of bedrock and thickness of overburden at August A. Busch Memorial Wildlife Area.



EXPLANATION

-600- BEDROCK CONTOUR--Shows altitude of bedrock surface. Contour interval 20 feet. Datum is sea level

SOURCE OF WELL OR TEST HOLE DATA--Number is thickness of overburden

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Figure 5.--Altitude of top of bedrock and thickness of overburden in the vicinity of the Weldon Spring Chemical Plant.

The four raffinate pits that stored the wastes generated from the chemical plant were constructed by excavating the surface clay and using the removed clay for the construction of the levees around the pits. Using borehole and geophysical data, Bechtel National, Inc. (1984b) constructed thickness maps of the overburden remaining beneath the pits. The data indicate overburden thickness ranges from 10 to 25 feet beneath raffinate pits 3 and 4, with the largest quantity of overburden remaining beneath pit 3, and the least beneath pit 4.

Quarry Site

The abandoned quarry is about 3 miles southwest of the Weldon Spring Chemical Plant between Missouri State Highway 94 and the Missouri-Kansas-Texas Railroad line (fig. 6). The quarry is in the limestone bluff adjacent to the Missouri River flood plain in an outcrop of the Kimmswick Limestone. The quarry sump covers about 0.5 acre and is about 100 to 120 feet below the quarry rim. The main floor is 70 to 90 feet below the rim and covers about 2 acres.

Berkeley Geosciences Assoc. (1984) prepared a generalized cross-section through the quarry (fig. 7). The ridges and bluffs surrounding the quarry are overlain by loess deposits consisting of silty clay. Core samples from the test wells near the quarry indicate the loess has a maximum thickness of 3 feet. The Kimmswick Limestone is the formation that was quarried. The thickness of this formation, measured from the top of the ridges to the top of the underlying Decorah Formation, can be as much as 55 feet. The quarry sump extends into the Decorah Formation. Core samples indicate the Decorah Formation ranges from 14 to 20 feet thick and is limestone that grades downward to shale (Weidner and Boback, 1982). The Plattin Limestone underlies the Decorah Formation, and forms the bedrock surface beneath the Missouri River alluvium. Where the Plattin Limestone is intact in the area, it is about 90 feet thick.

National Lead Company of Ohio, Inc. drilled 12 test holes at the quarry site during 1976. During drilling, numerous cavities were encountered. Fractures and solution-enlarged joints can be seen in the Kimmswick Limestone in the quarry face and along the bluffs facing the Missouri River. These joints extend into the subsurface, as evidenced during drilling of a slant test hole under the quarry sump. During use of an air drilling rig, air bubbled through fractures to the surface of the water in the sump. Air bubbles followed a jagged line extending into the sump about 10 feet from the shore (Huey, 1978, Exhibit C).

Berkeley Geosciences Assoc. (1984) drilled several series of observation wells (fig. 8) principally in the Missouri River flood plain between the slough system and the Missouri-Kansas-Texas Railroad line. Borings from wells OB-3 through OB-17 indicate the alluvium north of the slough system consists of fine-grained clay and silt that extends to bedrock. Bedrock was encountered at depths from 10 to 26 feet, and the alluvium thickens toward the slough system.

The alluvium south of the slough system, in the St. Charles County well field, is about 110 feet thick. In this area the Plattin Limestone has been eroded and is about 40 feet thick. The alluvium in the well field generally consists of clay, silt, and sand at the surface, with sand and gravel at depth.

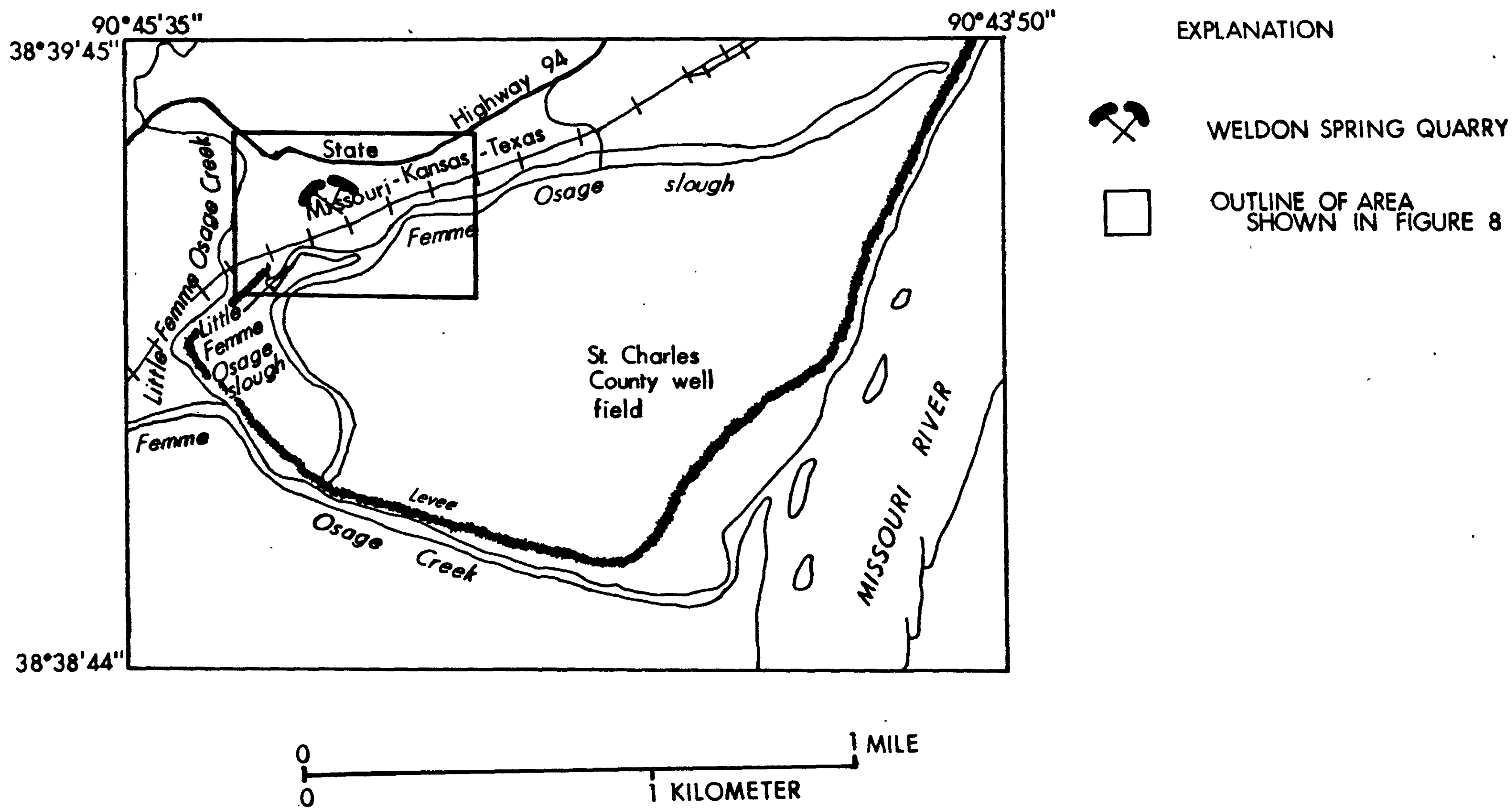

Figure 6.--Location of the Weldon Spring quarry and St. Charles County well field.

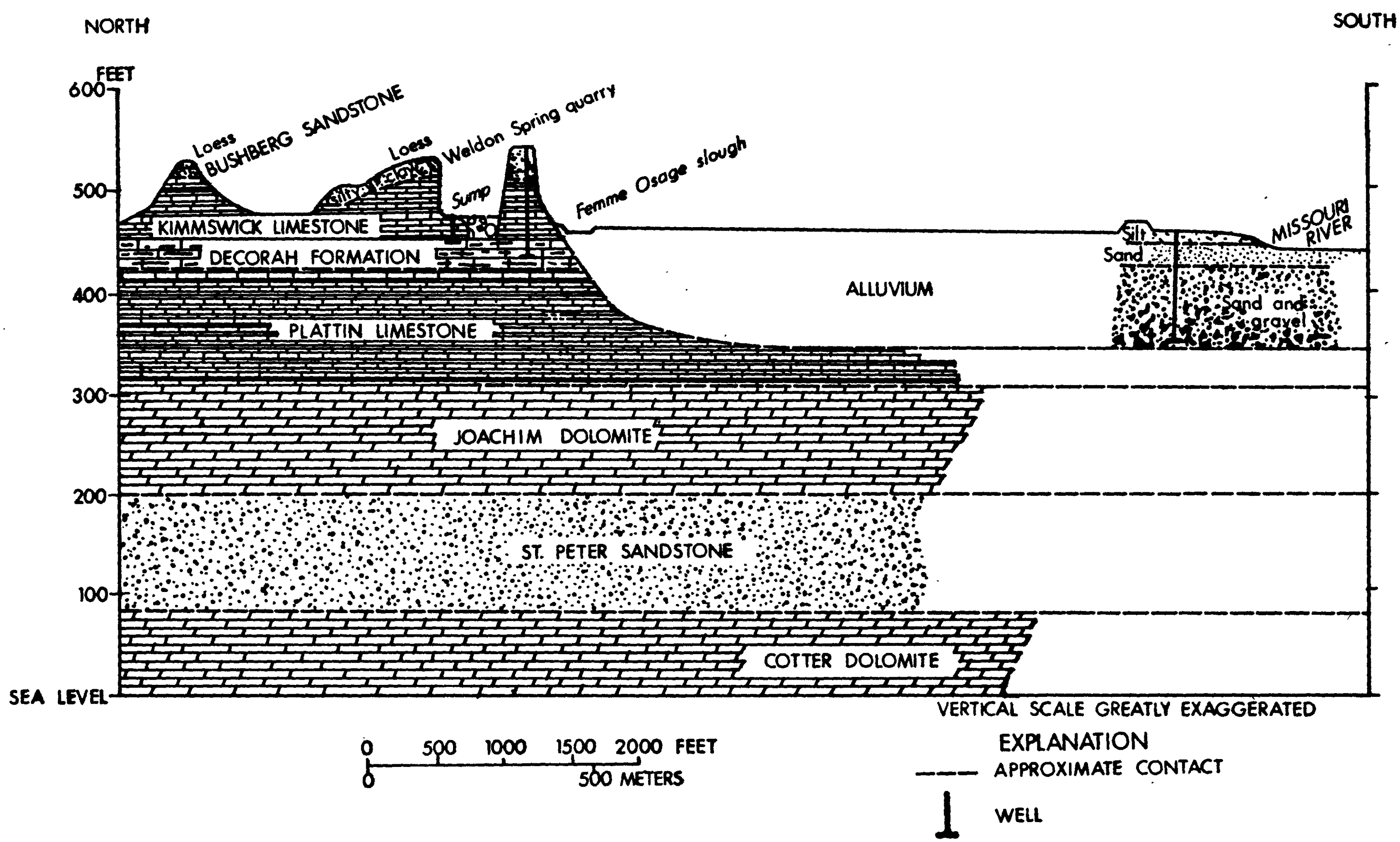

Figure 7.--Generalized north-trending geologic section through the Weldon Spring quarry area (modified from Berkeley Geosciences Assoc., 1984).

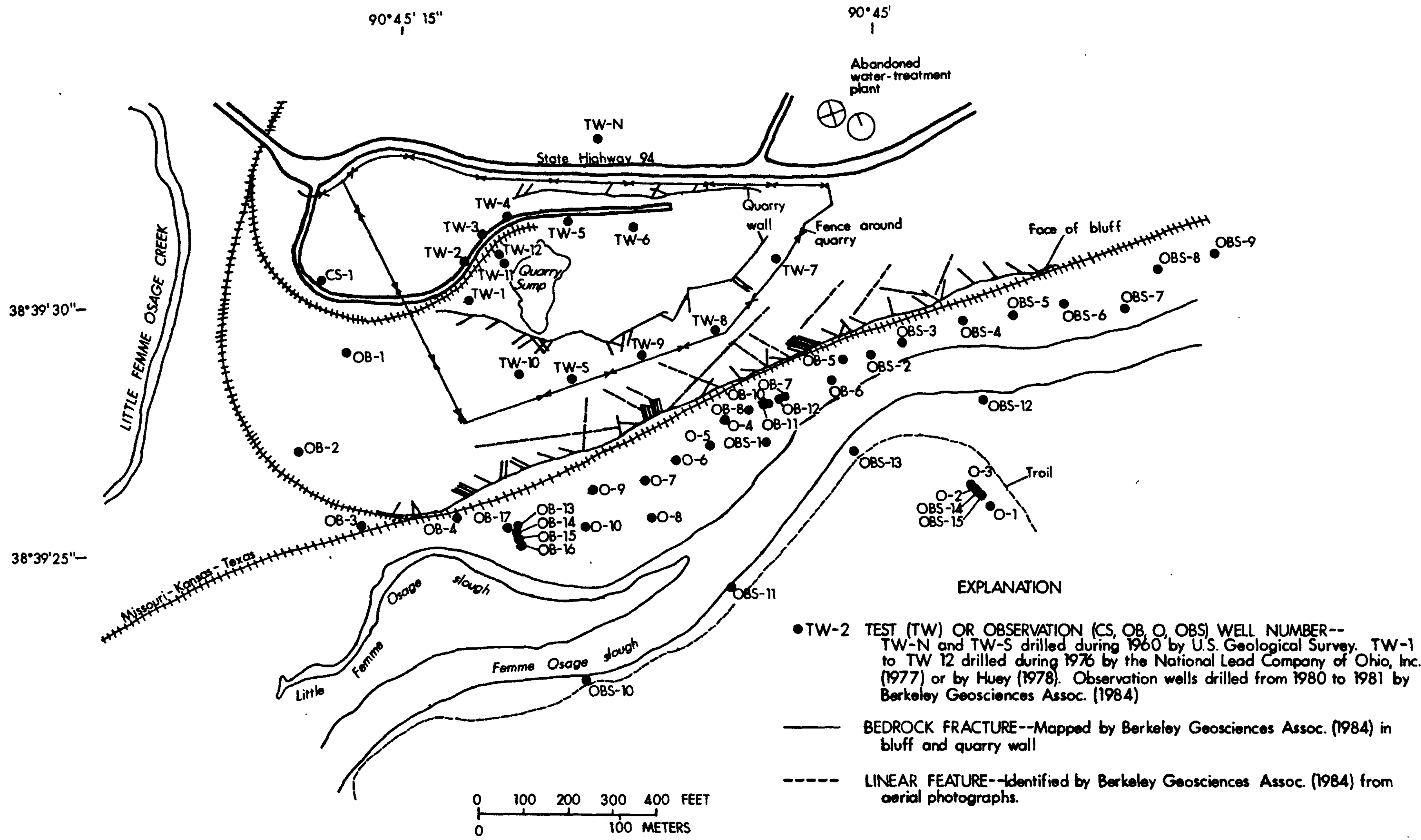

Figure 8.--Surface drainage, location of test and observation wells, bedrock fractures, and linear features in the vicinity of the Weldon Spring quarry (modified from Berkeley Geosciences Assoc., 1984).

Structure

The consolidated rocks in St. Charles County are on the northeast flank of the Ozark uplift and have a regional dip of about 1° northeast. In the study area vertical jointing in rocks is common. The Keokuk and Burlington Limestones, the Chouteau Limestone, and the Kimmswick Limestone have two sets of distinct joints; one set varies from N. 30° E. to N. 72° E. and the other from N. 30° W. to N. 65° W. (Roberts, 1951).

Several tributaries of Dardenne Creek trend from N. 10° E. to N. 45° E. and seem to have developed channels along former fracture lines or solution channels (V.C. Fishel and C.C. Williams, written commun., 1944). Bedding planes and joints in the limestone improve the capability of the rock to transmit water by providing channels for the downward and lateral movement of water.

Berkeley Geosciences Assoc. mapped the location, orientation, and width of the fractures that are in the limestone bluff both on the quarry face and Missouri River face (fig. 8). They observed a major set of fractures oriented N. 70° W. and two minor sets oriented N. 60° E. and north. The joints generally are vertical, and the openings range from less than 1 inch to several feet, some coinciding with gullies, ravines, or other linear features observed on top of the bluffs. Many of the fractures contain partial clay fillings that were either residual material from solution activity or material washed down from overlying soil. They concluded that these fractures extend downward through at least the Decorah Formation, making the Kimmswick Limestone, Decorah Formation, and probably the Plattin Limestone hydraulically connected. Core logging of holes drilled in the fractured limestone also indicated the presence of horizontal fractures (Berkeley Geosciences Assoc., 1984).

HYDROLOGY

An understanding of the hydrology of the study area is necessary to determine the extent and magnitude of contamination from the waste-disposal sites. Surface- and ground-water conditions will be discussed for St. Charles County. The hydrology of the waste-disposal sites will be discussed in more detail.

Surface Water

The capacity of streams to maintain flow and to transport sediment is significant in determining potential surface transport routes of the radionuclide contamination detected at the chemical plant. Flow-duration curves are indicators of hydrologic characteristics of drainage basins. Generally, the small tributary streams in St. Charles County have flow-duration curves that are characteristic of streams that derive most of their flow from direct runoff (Miller and others, 1974). Many streams in the Dissected Till Plains have minimal low-flow potential because of the small permeability of the underlying clay and shale. However, if the streambed fully penetrates the underlying clay or shale, it is possible for the streams to either gain or lose water. This is the case with the unnamed tributary of Schote Creek (fig. 2), which has headwaters on the chemical-plant property and drains the raffinate-pits area. This stream loses water to the streambed (losing stream). Streams can have sustained low flows (gaining streams) because of inflow of water from springs in the carbonate rocks.

Raffinate pits 1 and 2 were built on nearly level ground, but pits 3 and 4 are on terrain that slopes and naturally drains toward the north and west (fig. 9). Runoff from the raffinate-pits area generally flows to the north into one of two forks of an unnamed tributary of Schote Creek. One of these forks contains the locally named Ash pond. Runoff from the chemical plant drains northward to either this tributary or to another unnamed tributary of Schote Creek that contains locally named Frog pond. Drainage from Frog pond flows into August A. Busch Memorial Wildlife Area lake 36, then into Schote Creek that contains lake 35.

Ground Water

The aquifers used for water supply in the study area are the alluvial aquifers along the Missouri and Mississippi Rivers; the aquifer comprised of Mississippian and Devonian rocks, called the "shallow bedrock aquifer" in this report; and the aquifer comprised of Ordovician and Cambrian rocks, called the "deep bedrock aquifer" in this report. A generalized description of the lithologic and hydrologic properties of the aquifers is in table 2. A more detailed description of the ground-water occurrence in the study area is given in Kleeschulte and Emmett, 1986.

Alluvial Aquifers

The saturated sand and gravel in the Missouri and Mississippi River flood plains are the primary alluvial aquifers used in St. Charles County. Because of the proximity of the St. Charles County well field to the Weldon Spring quarry site, only the Missouri River alluvium will be discussed. The Missouri River alluvium typically ranges from 100 to 120 feet thick; however, composition and layering of the deposit can vary considerably in a short distance. The Missouri River alluvium consists of clay, silt, and sand at the surface, with sand and gravel at depth. Wells in the Missouri River alluvium typically are 100 to 110 feet deep. Data from an aquifer test during 1967 by the U.S. Geological Survey in the St. Charles County well field indicated the transmissivity was 36,000 feet squared per day, and specific yield of the alluvial aquifer was 0.2. During this test, the well was pumped at about 2,600 gallons per minute for 47 hours. The average hydraulic conductivity was about 400 feet per day (transmissivity and hydraulic conductivity values were converted from those in Emmett and Jeffery, 1968). Aquifer testing in the St. Charles County well field by Layne-Western Company, Inc. during 1985 indicated the alluvial aquifer had a transmissivity between 50,000 and 60,000 feet squared per day. The transmissivity values were variable throughout the well field; and decreased to the north toward the Femme Osage slough. The storage coefficient was estimated at 0.01 during the test. Hydraulic conductivity of the aquifer was calculated to be 535 to 600 feet per day in the lower, productive part of the aquifer (transmissivity and hydraulic conductivity values were converted from those in Layne-Western Company, Inc., 1986).

Water in the alluvial aquifers normally moves toward, and discharges into, the major streams with which they are hydraulically connected. Water levels measured in wells in the St. Charles County well field and in observation wells around the quarry were used to construct the water-table map in figure 10. This water-table map indicates the potential for ground water in the quarry to move southward toward the slough system. The western part of the slough system was a drain for the ground water on both sides of it during these measurements. Farther east, the water in the slough system conceivably could move south into the well field.

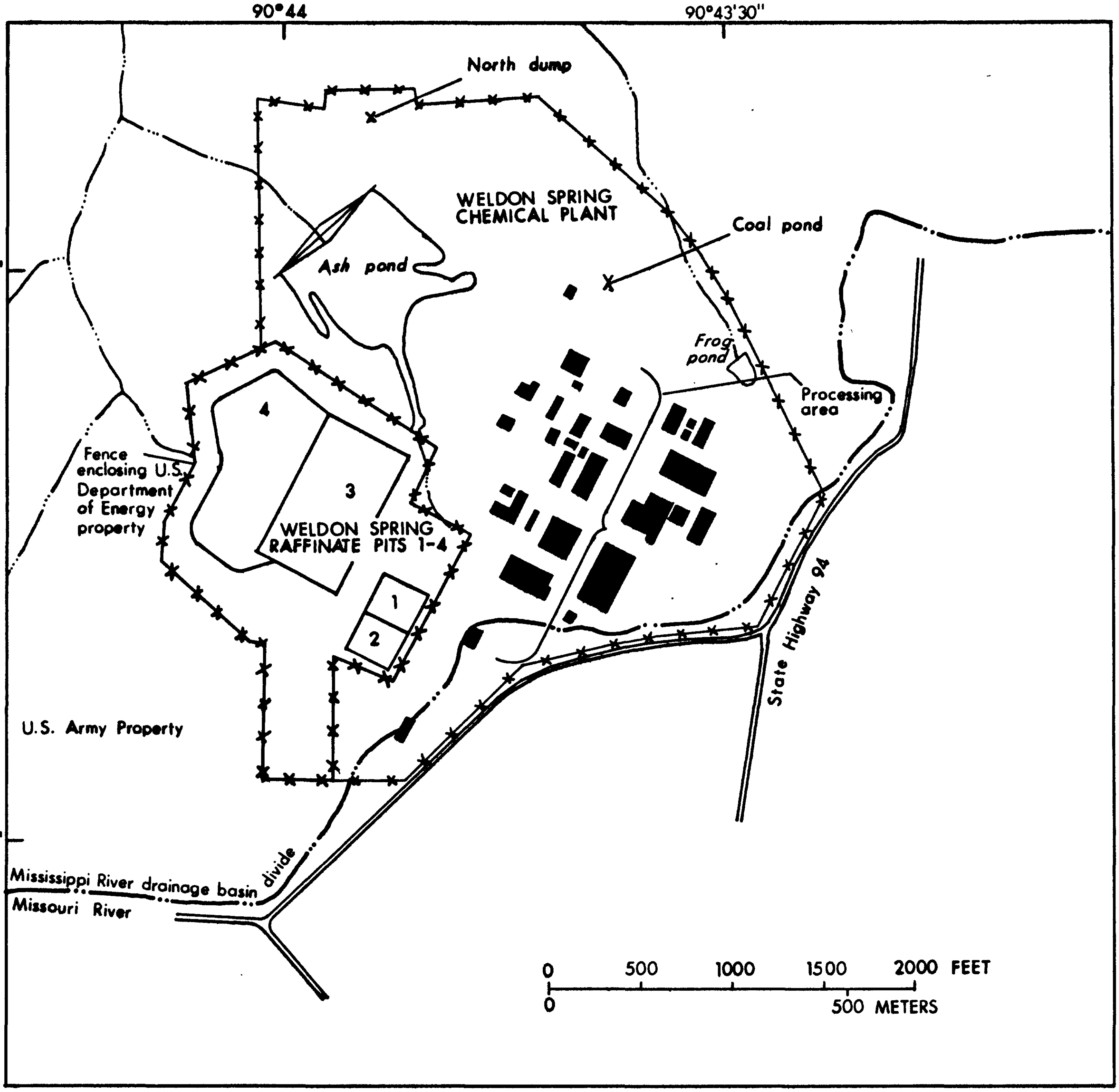

Figure 9.--Weldon Spring Chemical Plant and raffinate pits (modified from Bechtel National, Inc., 1984).

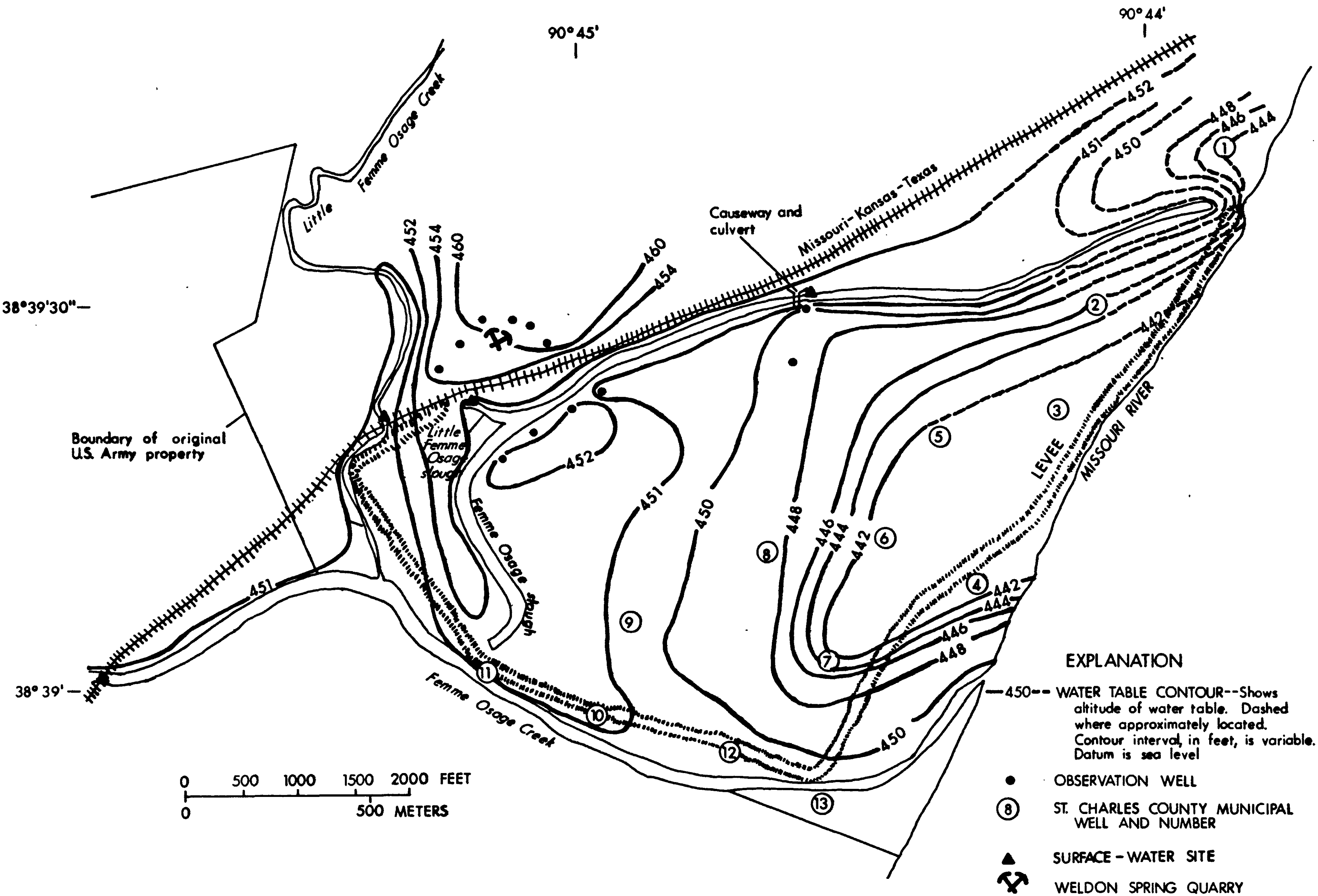

Figure 10.--Altitude of water table for the Weldon Spring quarry and St. Charles County well field, October 30, 1984.

Layne-Western Company, Inc. (1986, p. ix), using an analog model of the St. Charles County well field, concluded "The normal operating mode of the well field is to pump 10.39 million gallons per day (mgd). The model indicates that 66 percent (6.69 mgd) of the water pumped is received directly by infiltration from the Missouri River. When the test well (Well No. 8) pumpage was added to this condition, nearly 100 percent of the additional pumpage was derived from river infiltration. Therefore, as pumpage increases from the system so does the percentage of water derived from river infiltration."

Shallow Bedrock Aquifer

The shallow bedrock aquifer primarily consists of Mississippian and Devonian limestone, with small quantities of sandstone (table 2). This aquifer is absent in the southwestern part of the study area, but gradually thickens to the northeast. Some of the formations comprising the shallow aquifer are more permeable than others, although all seem to be hydraulically connected.

The Keokuk and Burlington Limestones are the formations of primary concern in the shallow aquifer because they are the shallowest formations beneath the Weldon Spring Chemical Plant and may receive recharge from that area. Locally these limestones are fractured, have numerous clay-filled voids, and contain karst features. These features include solution channels that allow conduit-type flow. It is common for ground water to travel thousands of feet per day through these preferred paths.

Infiltration of precipitation on the area where the shallow bedrock formations are near the surface is the principal source of recharge to the aquifer. The precipitation moves through permeable soil and into bedrock along fractures, bedding planes, and solution openings. Another source of recharge is water entering the aquifer through losing streams. An example of such recharge is the unnamed tributary of Schote Creek that drains the raffinate-pits area and Ash pond. Water flows in the headwaters of this tributary during and after precipitation events, but some, if not all of this flow, is lost by infiltration to the ground-water system before it reaches the main stem of Schote Creek.

During the summer of 1984, the depth to water was measured in about 75 wells that were completed in the shallow bedrock aquifer to determine the direction of water movement through the study area. The water-level data are presented in a report by Kleeschulte and Emmett (1986). These data were used to prepare the potentiometric map in figure 11. The chemical plant is on a ground-water divide. When the water-level data were collected, ground-water flow was through the raffinate-pits area toward the north. Dardenne Creek is a primary drain for the area north of the ground-water divide. Several local areas of higher ground-water levels are in St. Charles County. Ground water south of the divide moves southward towards the Missouri River.

Discharge from the shallow bedrock aquifer occurs as springs, seeps, evapotranspiration, discharge to the alluvium, and underflow. Some water may move downward through the leaky confining layer into the underlying deep bedrock aquifer at locations where the potentiometric surface of the shallow bedrock aquifer is higher than that of the deep bedrock aquifer. Discharge also occurs from pumpage of wells completed in the aquifer.

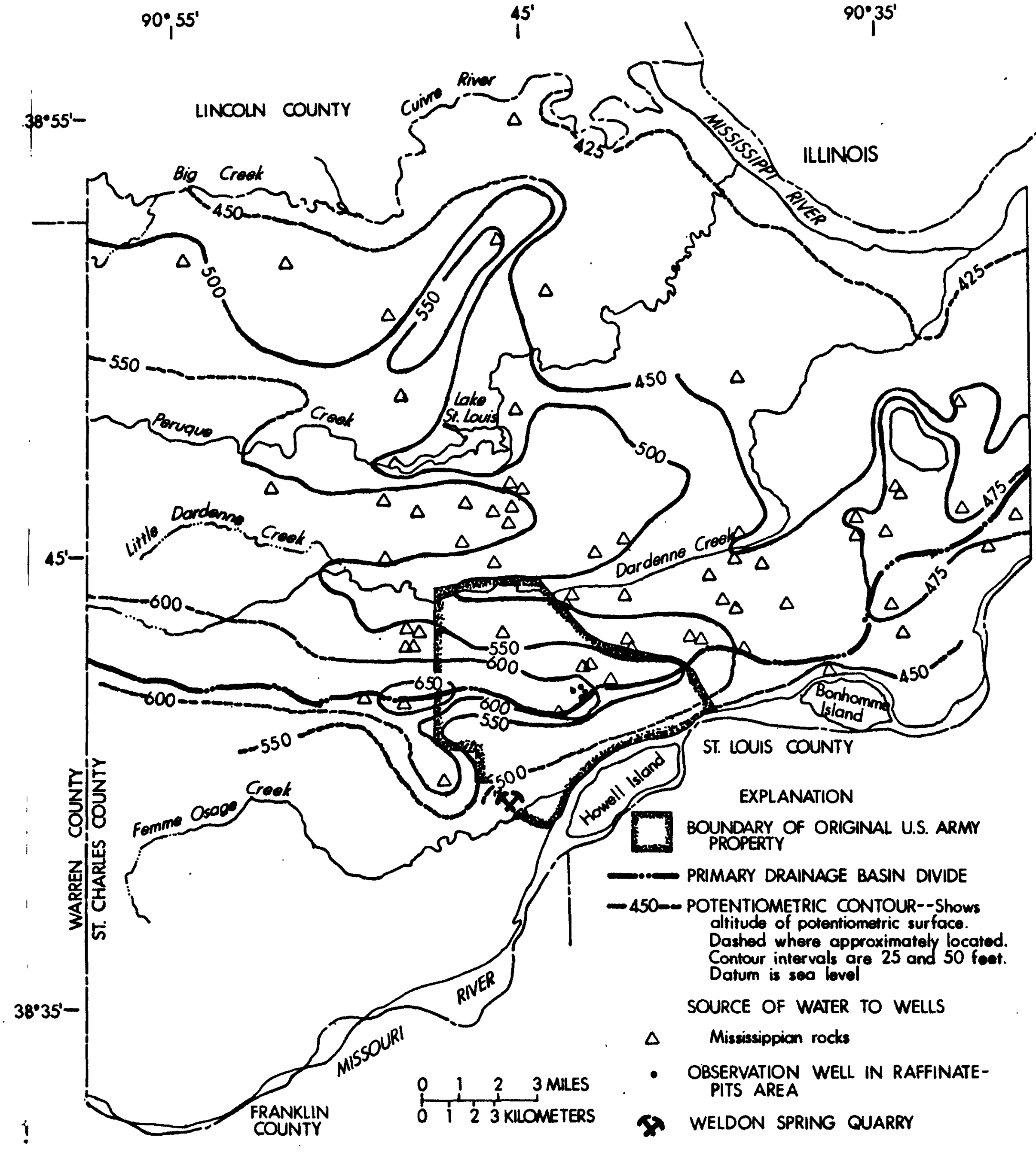

Figure 11.--Potentiometric surface of the shallow bedrock aquifer, summer 1984.

Confining Layer and Deep Bedrock Aquifer

The confining layer and underlying deep bedrock aquifer in this report include Ordovician shale, limestone, dolomite, and sandstone and Cambrian dolomite from the Maquoketa Shale to the base of the Potosi Dolomite (table 2). The oldest formation typically used in the study area for public-water supply is the Gasconade Dolomite. The formations from the Maquoketa Shale through the Joachim Dolomite form a less permeable part of the aquifer and are a leaky confining layer for the more permeable underlying formations. The confining sequence generally is about 300 feet thick on the western side of the study area and increases to about 400 feet thick on the eastern side.

The more permeable rocks comprising of the deep bedrock aquifer are about 1,000 feet thick, and this thickness is uniform throughout St. Charles County where all of these formations are complete. The deep aquifer is a source of water for the public-water supplies that do not use alluvial aquifers.

A source of recharge for the deep bedrock aquifer is precipitation on areas where the aquifer is near the surface, as in the southern part of the study area. Recharge also occurs from downward leakage from the alluvial or shallow bedrock aquifers where the confining sequence is too thin, fractured, or where wells are open to both the shallow and deep aquifers.

Depth-to-water measurements were made during the summer of 1984 and were used to draw a potentiometric-surface map of the deep bedrock aquifer (fig. 12). Field data for these measurements are in Kleeschulte and Emmett (1986). Femme Osage Creek, which is in the outcrop area of Ordovician rocks, seems to be a primary drain for the deep bedrock aquifer. A large drawdown cone in the northern part of the study area extends from the Wentzville area to the city of St. Peters and is caused by pumpage from public-supply wells. The ground-water divide for the deep aquifer corresponds to that of the shallow aquifer. Ground water north of the divide flows northeasterly except where the large cone of depression interferes with the flow. South of the divide where the aquifer crops out, the water levels tend to be influenced by topography.

Discharge from the deep bedrock aquifer principally occurs as underflow. Other sources of discharge are seepage to springs and streams where the aquifer is exposed and evapotranspiration. Discharge occurs artificially as pumpage from wells.

Chemical-Plant and Raffinate-Pits Area

Concern exists that seepage from the raffinate pits may contaminate the ground-water system. A water-balance study was made at the raffinate pits for the U.S. Department of Energy from 1983 through 1985 (Bechtel National, Inc., 1986). During the 3-year study, 10 meteorological parameters were monitored. These included wind direction, wind speed, air temperature, dew point, solar radiation, precipitation, evaporation, and water temperature. Water levels also were recorded at each of the four pits. The method used in the water-balance study was to calculate the change in water volume expected from the meteorological data and compare it with the change in water volume measured in the four pits. Calculations using the three years of meteorological data indicated an expected net gain in the water volume of the pits. The measured water levels in the pits showed a loss. According to Bechtel National, Inc.

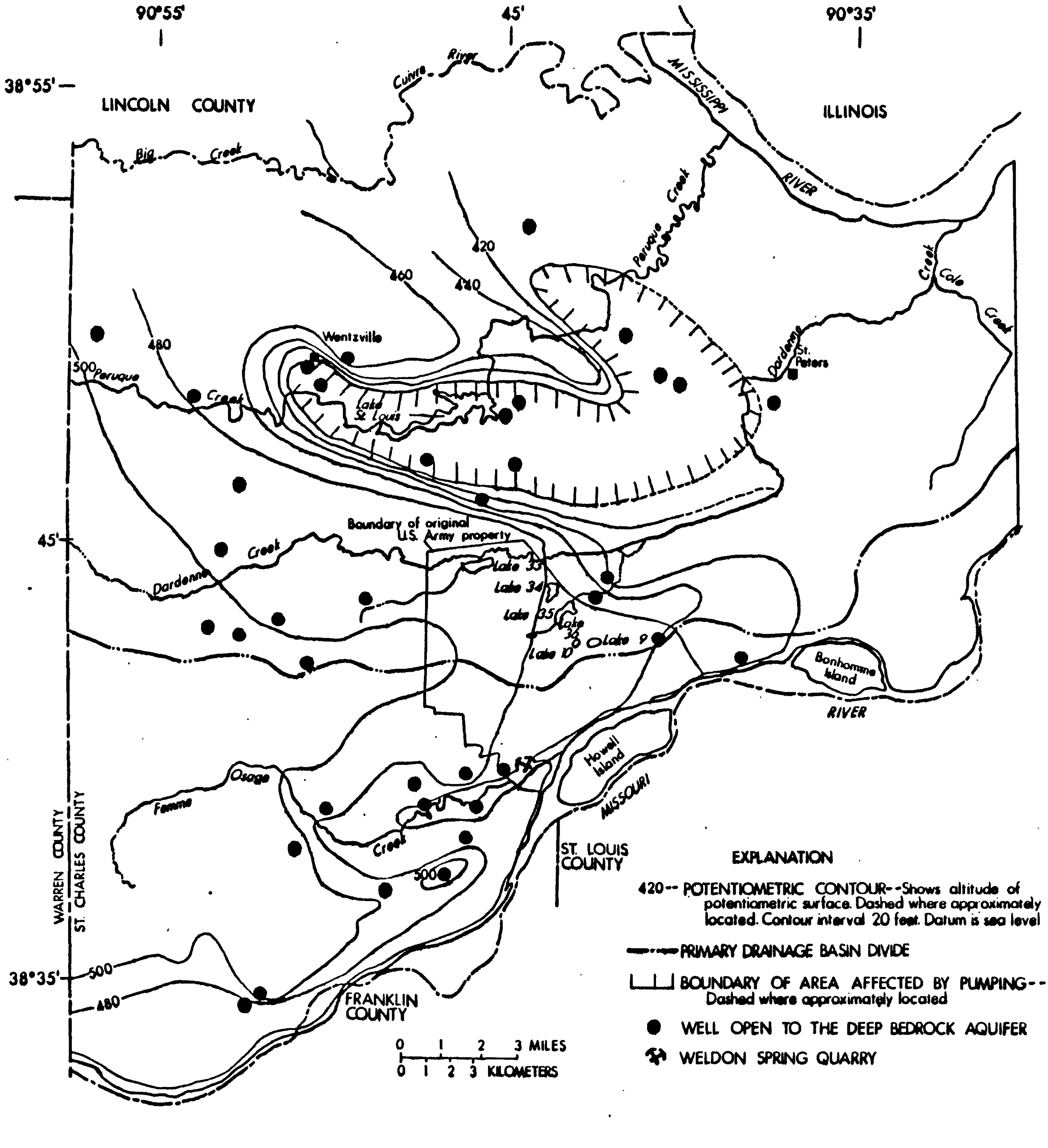

Figure 12.--Potentiometric surface of the deep bedrock aquifer, summer 1984.

(1986), all four pits had a loss that could not be attributed to the meteorological conditions. The loss was calculated to be equivalent to a 0.04 to 0.08 inch per day decrease in the water level in the pits. Evapotranspiration for the pits could not be measured with the precision of the other meteorological components and was not used in the water-balance study. Therefore, the actual unattributable water loss from the raffinate pits was less than reported. The reported loss of water corresponds to a daily volumetric loss of 216 to 324 cubic feet from pit 1 and pit 2, and a daily volumetric loss of 3,240 cubic feet from pits 3 and 4, which were considered together because of an overflow pipe connecting the two.

The calculated water loss from the raffinate pits implies a soil permeability rate consistent with permeability tests made on the overburden at the site. Results of the permeability tests at the site ranged from 1.6×10^{-9} to 3×10^{-6} centimeters per second. A 0.08 inch per day drop in water level implies with a soil permeability rate of 10^{-7} centimeters per second. "It appears from the magnitude of the loss in water depth from the pits and the conservative basis upon which the determination of this loss was based that the loss most probably results from natural seepage into the underlying clays." (Bechtel National, Inc., 1986, p. 12). This statement may indicate why seismically detected areas of saturated overburden were discovered in 1983 by Weston Geophysical Corp., which was doing contract work for Bechtel National, Inc., at the raffinate-pits area. A steep-sided ground-water mound seemed to be centered beneath pit 3 and extended under unsaturated soils to the east and west of the pit. Water levels were slightly higher to the south of pit 3 and appeared to be higher than the bottom elevation of pit 3 (Bechtel National, Inc., 1984b). During a water-sampling trip at the raffinate-pits area in 1986, U.S. Geological Survey personnel observed seepage of about 0.01 cubic feet per second from the base of pit 4 at the west levee. This seep coincides with the base of a drain that relieves pore pressure at the downstream toe of the west levee of pit 4 (Bechtel National, Inc., 1984b).

In May 1984, water-level measurements were made by the U.S. Geological Survey in four observation wells surrounding raffinate pits 3 and 4. These measurements indicated the overburden was not saturated and the water-table altitude was in the Keokuk and Burlington Limestones. The local water-table gradient was about 32 feet per mile toward the north.

The bottoms of raffinate pits 3 and 4 at their lowest altitudes are about 638 and 628 feet above sea level (Bechtel National, Inc., 1984b). The water-level measurements made in May 1984 indicate 22 to 34 feet of unsaturated overburden and bedrock are beneath pit 3 and 12 to 24 feet beneath pit 4. Bechtel National, Inc. (1984b, p. 43) states "* * * the overburden is unsaturated beneath pit 4 and portions of pit 3 and generally outside the pits, especially in the western half of the site around pit 4. Seismically detected areas of saturation exist beneath the center of pit 3 and as thin, shallow layers (south and east of pit 3) * * *. The [thin saturated] layer appears to be a naturally occurring perched water table that is possibly receiving some recharge from pit 3 * * *." Another possible area of overburden saturation is near the toe of the north levee of pit 3 where the ground has been disturbed by dumping, landfilling, or both since pit 3 was constructed.

Anomalously high water-level altitudes have been measured in an observation well at the toe of the west levee of pit 4. Water-level altitudes measured in this well are above the limestone bedrock, but geophysical data indicate the overburden beneath and around pit 4 is not saturated. Field-radiation tests on water from this well did not indicate concentrations larger than background (Bechtel National, Inc., 1984b).

On June 17, 1986, water-level measurements were made using the observation wells on the chemical-plant site and the wells on the August A. Busch Memorial Wildlife Area. These measurements indicated a general northward direction of local ground-water flow. Also, they indicated that the ground-water divide was beneath pits 1 and 2 and that ground water beneath pits 1 and 2 possibly may flow south toward the Missouri River during certain times of the year (fig. 13). This ground-water divide seems to be a dynamic hydrologic feature that fluctuates with climatic conditions or in response to other recharge. For example, an estimated 200,000 gallons of water per day were discharged to the chemical-plant site through broken underground water lines (Rod Nelson, U.S. Department of Energy, oral commun., 1987). The leak has been corrected (1987); however, the results of this corrective action have not been determined. This added recharge to the ground-water system may possibly have affected ground-water levels on the site and thereby affected the location of the drainage divide.

Quarry Area

R.M. Richardson (written commun., 1960) made one of the first studies on the ground-water hydrology at the quarry. He reported ground-water movement was south through the quarry. He also stated that the results of pressure injection in core holes indicated that the permeability of the quarry walls above an altitude of 467 feet above sea level was large enough to permit equilibrium conditions between surface runoff into the sump and ground-water outflow. This was because fracturing and solution had increased the permeability of the limestone wall above this level. From 1960 to 1963, the water level in the sump was kept at a predetermined level of 445 feet above sea level (Lenhard and others, 1967) by pumping excess water into Little Femme Osage Creek (in 1961 this became Little Femme Osage slough). Pumping ceased in 1963 and the water level in the sump was allowed to reach equilibrium. The uranium concentration in the sump water increased during the period it was pumped. Ground water that was in contact with the waste stored on the quarry floor was thought to leach uranium from the waste, before discharging into the sump. In 1964, after the water level in the sump was in equilibrium with the surrounding ground water, analysis of the water in the sump indicated the uranium concentration had decreased (Lenhard and others, 1967). The decrease in uranium concentration may have been caused by recharge of ground water containing smaller concentrations of constituents north of the sump moving down gradient into the sump.

The U.S. Department of Energy (1987) states that uranium concentrations in the quarry sump increased from 1 pCi/L (picocurie per liter) in 1960 to a peak value of 17,000 pCi/L in 1967 and then decreased to 620 pCi/L in 1985. The buildup from 1960 to 1967 may represent increasing quantities of uranium available for leaching, as waste was added to the quarry during that period. The decline after 1967 may represent a slow leaching and depletion of uranium from the waste, or it may be caused by water sampling at different depths in the quarry sump (U.S. Department of Energy, 1987).

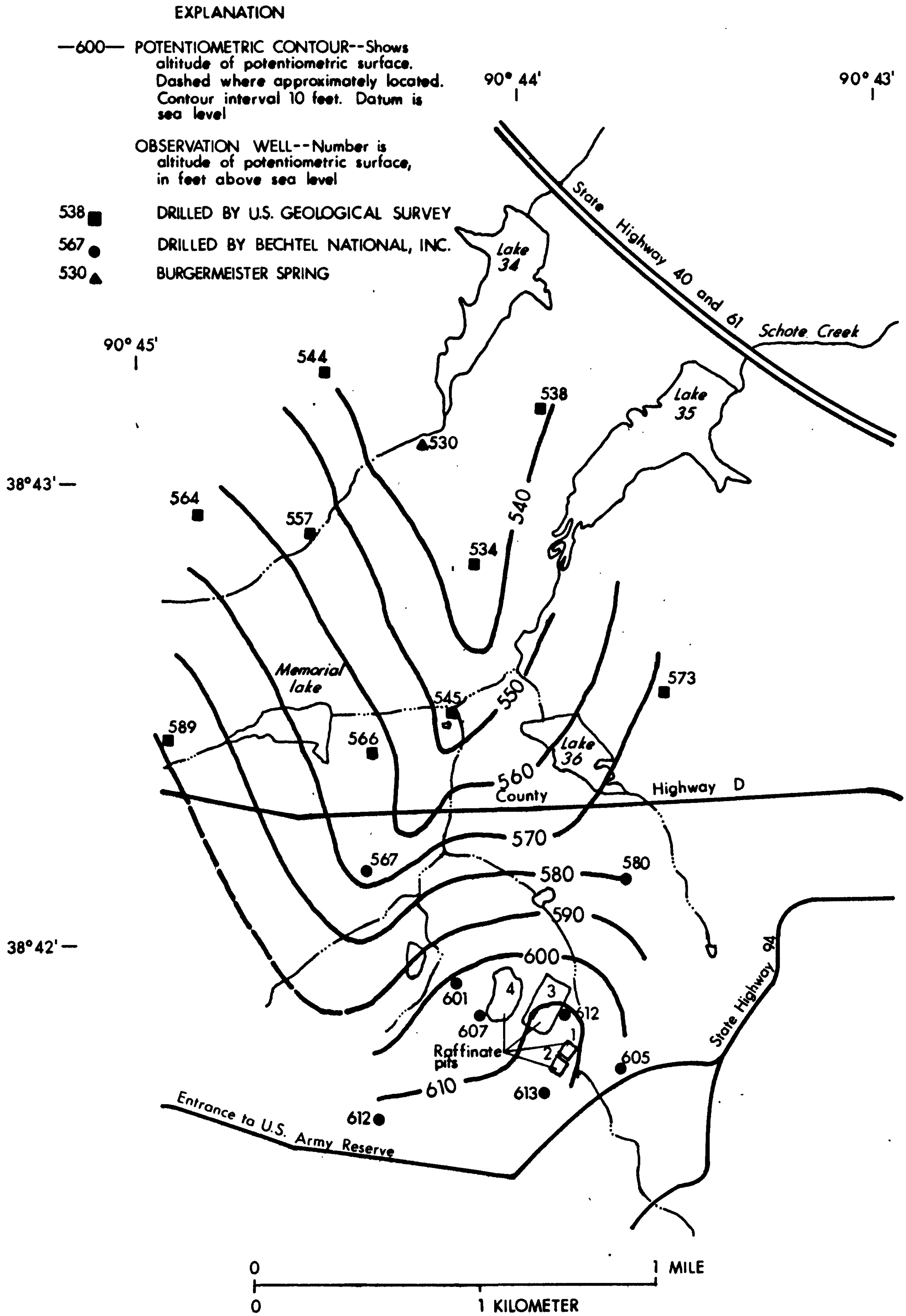

Figure 13.--Potentiometric surface of the shallow bedrock aquifer in the vicinity of the Weldon Spring Chemical Plant, June 17, 1986.

Berkeley Geosciences Assoc. (1984) concluded that the larger fractures and solution openings in the quarry face provided a primary pathway for ground-water movement from the quarry. However, when water was pumped from boreholes in the alluvium between the slough system and the quarry, the permeability of the alluvium in this area was concluded to be minimal. This was based on observations of rapid dewatering of the wells and long projected recovery times.

On October 30, 1984, U.S. Geological Survey personnel made water-level measurements in observation wells in the vicinity of the quarry and in the St. Charles County well field (fig. 10). They concluded the slough system was a drain at that time for the land adjacent to both banks at the western end of the slough system. At the central and eastern part of the slough, however, the potential exists for the water in the slough system to infiltrate the alluvium and flow southward and eastward. The general direction for ground-water flow in the well field is toward the east. Water also may be induced to move from the Missouri River toward the well field, depending on the stage of the river (Kleeschulte and Emmett, 1986).

SURFACE- AND GROUND-WATER RELATIONS

Seepage Run on Tributaries to Dardenne Creek

Because of the interaction between the surface- and ground-water systems, a seepage run was made on six north-flowing Dardenne Creek tributaries from Kraut Run to Crooked Creek from April 1 to 4, 1985 (fig. 14). A seepage run is a series of discharge measurements along a stream reach made in a short time to identify where gains or losses in flow occur. The streamflow measurements identified stream reaches where surface flow was lost to the shallow aquifer or water was discharged from the aquifer to the stream. Streamflow was measured at 102 sites, and water temperature and specific conductance were measured at selected sites. During the 2 days preceeding the seepage run, about 3 inches of rainfall occurred (National Oceanic and Atmospheric Administration, 1985). The seepage run was begun at this time so gaining and losing stream reaches could be identified, as well as the location of wet-weather springs. Surface drainage of pasture land was still occurring, but flow from these areas was minimal. The results of the seepage runs are tabulated in Kleeschulte and others (1986).

Kraut Run gained flow throughout its entire length. The upstream reach of the creek, the area west of County Road DD, was investigated entirely, and a few small draws draining pasture land in the basin were flowing. These draws only added a small quantity of discharge to the total flow, which was usually between 0.01 and 0.05 cubic foot per second. The tributaries in this upstream reach, which are large enough to appear on the topographic map, also were flowing. However, after investigating these tributaries, most of the discharge was determined to come from sources other than surface drainage. No springs were found, but ground water apparently was seeping into the stream. The tributaries that contain lakes had more flow coming out of the lakes than flowing into them. This was to be expected because of the earlier intense rain and consequent release of water from storage in the lakes. In the downstream reach of Kraut Run, the area east of County Road DD, the flow significantly increased; however, this reach was not investigated entirely because another storm was coming into the area. The area south of August A. Busch Memorial Wildlife lake 33 was marshy, with several springs and wet-weather seeps flowing into the lake. The area in the vicinity of lake 33 therefore appears to be a ground-water discharge zone.

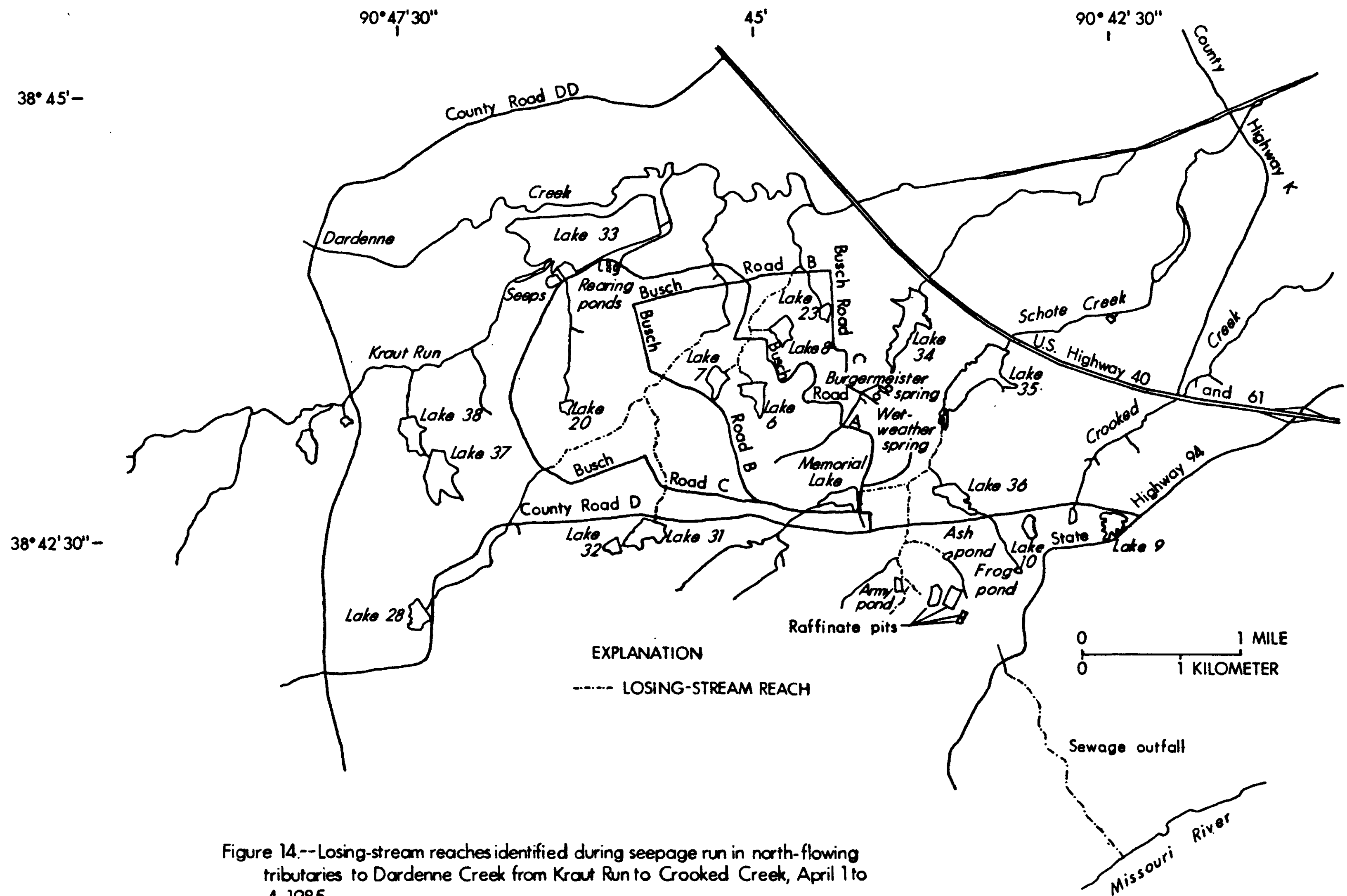

Figure 14.--Losing-stream reaches identified during seepage run in north-flowing tributaries to Dardenne Creek from Kraut Run to Crooked Creek, April 1 to 4, 1985.

The unnamed tributary of Dardenne Creek to the east of Kraut Run was an interrupted stream at the time of the seepage run. This stream was investigated in its entirety except for the dry reach, which only was checked at selected locations. The outflow from lake 28 was measured at the headwaters, and flow increased downstream, primarily from surface-water sources. Downstream from where the tributary crosses the August A. Busch Memorial Wildlife Area road C (Busch road C) to the junction with the stream that drains lake 31 (fig. 14), flow was lost, and eventually the stream became dry. The tributary that received the outflow from lake 31 also lost flow gradually. The water from this stream flowed into the main stem, but the tributary again was dry before reaching August A. Busch road B. The main stem of the tributary remained dry until about 1,200 feet upstream from August A. Busch road B. In places through this dry reach, the streambed consisted of bedrock with a minimal quantity of gravel. Upstream from the location at which the main stem began flowing again, water was found ponded in scattered locations. Flow gradually increased downstream to the mouth of the tributary. A cluster of wet-weather springs were found along a rock bluff between roads B and C.

The unnamed tributary of Dardenne Creek which receives water from August A. Busch Memorial Wildlife lakes 6, 7, 8, and 23, had both gaining and losing reaches. The headwaters of the tributary were dry from lake 6 to the junction of the stream draining lake 8. The flow from lake 8 gradually decreased to the junction of the stream draining lake 23. The combined flow from lake 23 and that measured in the main stem of the tributary at the junction with the stream draining lake 23 was less than the flow measured in the main stem at its junction with Dardenne Creek, indicating a gaining-stream reach. No surface-water sources were determined between these sites.

The unnamed tributary of Dardenne Creek containing lake 34 is significant because its drainage area includes Burgermeister spring. Flow in this tributary gradually increased downstream to the area where the wet-weather springs were concentrated. Flow from these springs enters the main stem of the tributary by a spring branch. During wet weather, three known springs discharge in this branch; however, only Burgermeister spring is perennial. These three springs are all believed to be hydrologically connected. Flow increased in the tributary downstream from lake 34 until the tributary entered the Dardenne Creek flood plain, where flow was lost.

Schote Creek was an interrupted stream during the seepage run. The main stem gained discharge throughout its length downstream to Memorial Lake on the August A. Busch Memorial Wildlife Area. Downstream from Memorial Lake the creek became a losing stream. The unnamed tributary of Schote Creek, which enters from the south, is of concern because it contains the tributaries that drain the raffinate-pits area. The west fork of the unnamed tributary lost no water. The middle fork and the east fork, which drains Ash pond, lost water throughout most of their length. Six hundred feet downstream from County Road D (fig. 14), the main stem of the unnamed tributary was dry and remained dry to its mouth. Flow in the main stem of Schote Creek, downstream from Memorial Lake, continued to lose water for the next 0.7 mile. The water flowed into a large pool at this point, but no outflow was determined from the pool. Schote Creek remained dry to its junction with the tributary that drains Frog pond and lake 36. Flow in the main stem of Schote Creek, supplied by the tributary that contains lake 36 was observed to continue downstream until backwater conditions about 1,000 feet upstream from lake 35 interfered, and discharge measurements could not be made. The tributary that drains Frog pond was not a losing stream.

Crooked Creek, the easternmost stream measured, did not have any losing reaches throughout its length. In June 1987, flow in the upstream two-thirds of Crooked Creek again was measured. No losing reaches were measured; however, gravel was piled at places in the stream, and the entire flow (0.03 to 0.06 cubic feet per second) traveled through the gravel to only emerge 10 to 30 feet downstream. Flow remained nearly constant in the headwaters of Crooked Creek, and north of U.S. Highway 40 and 61, flow increased downstream primarily because of surface-water inflow.

Several losing-stream reaches were determined in the six tributaries of Dardenne Creek that were measured. Losing-stream reaches were measured in the unnamed tributary to the east of Kraut Run and west of Schote Creek on the August A. Busch Memorial Wildlife Area. Losing-stream reaches also were in the unnamed tributary of Schote Creek that drains the chemical plant and raffinate-pits area and in the main stem of Schote Creek downstream from the mouth of this unnamed tributary.

Dye Traces

Some springs on the August A. Busch Wildlife Memorial Area have radionuclide concentrations larger than background concentrations. In an attempt to correlate the surface runoff from the chemical plant that flows through losing-stream reaches with flow from the contaminated springs, the Missouri Department of Natural Resources, Division of Geology and Land Survey made three dye-tracer studies and the U.S. Geological Survey made one. The results of these four dye traces are shown on figure 15 as straight lines.

Before the start of each study, activated charcoal packets, which adsorb and concentrate water-tracer dye, were placed in the streams at the monitoring sites to determine the background concentrations of fluorescein and rhodamine dyes. The packets were recovered after a week, then analyzed after elution with a solution of 5 percent ammonia hydroxide in 95 percent ethyl alcohol by a synchronously scanning spectrofluorometer for concentrations of fluorescein and rhodamine dyes.

The first dye trace was made on the surface drainage west of raffinate pit 4 in a losing reach of the unnamed tributary of Schote Creek. On February 9, 1984, one-half gallon of rhodamine-WT dye was injected in the stream. On February 14, 1984, the charcoal packets were recovered, replaced, then collected again on February 17. The Missouri Department of Natural Resources concluded that the northward drainage of this tributary and the drainage through Ash pond, which is on the east fork of the same unnamed tributary of Schote Creek, can be expected to flow underground before leaving the U.S. Army property and emerge at or in the vicinity of Burgermeister spring in an adjoining drainage basin to the northwest. The straight line flow distance is about 6,500 feet. The time of travel was estimated to be 48 to 72 hours but was dependent on rainfall conditions (Dean, 1984a).

The second dye trace was made to help define the ground-water divide and to determine if surface water lost to the subsurface south of the chemical-plant area reverses flow direction and moves to the north following the natural dip of the bedrock. On June 28, 1984, one-half gallon of rhodamine-WT dye was placed south of the outfall-sewer discharge point from the chemical plant in the outfall drainage basin. All of the flow at this point was lost to the

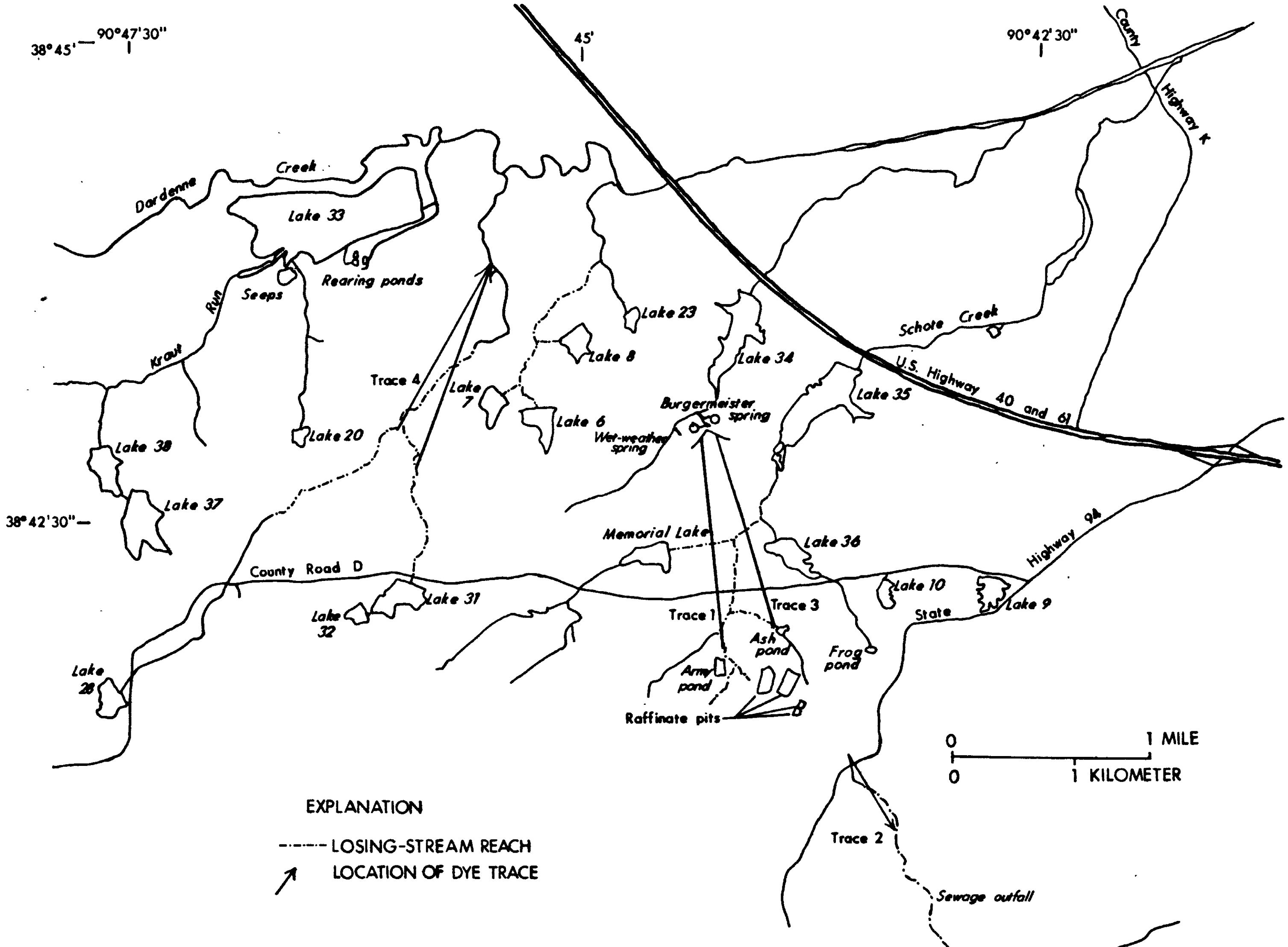

Figure 15.--Dye traces near the Weldon Spring Chemical Plant.

subsurface at, and just upstream from, the south boundary of the U.S. Army property. It was concluded from this dye test that "* * * surface runoff from the southern part of the Weldon Spring Ordnance Works that enters the outfall drainage valley as well as water discharging from the outfall sewer line enters the subsurface on the Army property, and emerges in at least two springs to the south. The water does not appear to move north downdip with the bedrock but rather stays within the confines of the valley * * * with probable emergence in the Missouri River * * *" (Dean, 1984b). Therefore, there is no evidence for interbasin transfer of water in this drainage basin.

A third dye trace was made to determine the emergence point for the surface flow lost in the losing reach downstream from Ash pond in the east fork of the unnamed tributary of Schote Creek, inside the U.S. Department of Energy fenceline. On March 21, 1985, one-half gallon of rhodamine-WT dye was placed in a flowing reach of the tributary downstream from Ash pond. The surface flow continued about 90 feet past the fence where the entire flow was lost to the subsurface. Four days later the charcoal packets were recovered, and positive traces of dye were detected at Burgermeister spring and the wet-weather spring. "In summary, a subsurface connection exists between the stream drainage downstream of Ash pond and the Burgermeister Spring area" (Dean, 1985).

A fourth dye trace was made by the U.S. Geological Survey to determine where the water emerged from a losing stream reach in the unnamed tributary east of Kraut Run and west of Schote Creek on the August A. Busch Wildlife Memorial Area. This stream does not drain the chemical plant property, but the information was needed to help define the hydrology of the area. The Missouri Department of Natural Resources, Division of Geology and Land Survey analyzed the charcoal packets on their spectrofluorometer. On February 14, 1986, one liter of rhodamine-WT dye was injected into the losing reach of the unnamed tributary. The packets were collected 4 days later, and the results indicated dye emerged in one of a cluster of springs along a rock bluff in the same basin in which the dye was injected, but 1.3 miles downstream. The water that was lost remains in the same drainage basin but travels through the subsurface. The charcoal packets were collected and replaced for the next 3 weeks. One replacement packet had a faint indication of rhodamine-WT dye at the rearing-pond spring in an adjacent drainage basin to the north. This connection, however, is not conclusive. This dye trace did help to limit the boundary for the recharge area of Burgermeister spring to the west. It appears that water lost in this losing stream does not affect Burgermeister spring.

Discharge of Burgermeister Spring and Wet-Weather Spring

Because of the connection between the losing-stream reaches draining the raffinate-pits area and Burgermeister spring, the daily flow of Burgermeister spring was monitored. On March 20, 1985, a weir was installed across the Burgermeister spring branch with a continuous gage-height recorder. A continuous gage-height recorder also was installed on a nearby wet-weather spring. The daily discharges for Burgermeister spring and the wet-weather spring are tabulated for the period March 20, 1985, through April 30, 1986, in Kleeschulte and others (1986).

The daily discharge of Burgermeister spring ranged from 0.72 cubic feet per second, following an intense storm, to 0.07 cubic feet per second during base flow. The spring was perennial during the period of record, continuing to flow even during the dryest conditions. Burgermeister spring discharge responds rapidly to precipitation, as shown in figure 16. A short lag time is noted between the rainfall and an increase in discharge. The spring discharge also becomes turbid during storms.

The wet-weather spring, similar to Burgermeister spring, quickly responded to precipitation and became turbid during storms. The primary difference is that the discharge from the wet-weather spring exceeded discharge from Burgermeister spring by as much as five times during intense storms. This spring is thought to be a reversible sinkhole or estavelle that is hydrologically connected to Burgermeister spring. When the flow at Burgermeister spring becomes excessive for the capacity of the spring orifice, water backs up in the solution opening supplying the spring and emerges at a higher altitude, the orifice of the wet-weather spring. The resurgence of the wet-weather spring often is short lived; the spring stops flowing before the discharge of Burgermeister spring can reach base flow after a storm. The daily discharge for the period of record at the wet-weather spring ranged from no flow to 3.7 cubic feet per second.

WATER QUALITY

A general concern in the study area is whether or not operation of the chemical plant and disposal of radioactive waste in the raffinate pits and quarry has caused contamination of the water resources. Maximum permissible contaminant levels for gross-alpha particle radioactivity, radium-226, and radium-228 in community water systems are (1) 15 pCi/L for gross-alpha particle activity (including radium-226 but excluding radon and uranium) and (2) 5 pCi/L for combined radium-226 and radium-228 (U.S. Environmental Protection Agency, 1986). More than 30 public drinking-water supplies have been identified throughout Missouri where the background water quality exceeds maximum contaminant level for radioactivity. It is believed the source of the large radionuclide concentration in these wells is naturally occurring. Five of these sites are in St. Charles County (Missouri Department of Natural Resources, Division of Environmental Quality, written commun., 1983).

Radioactive substances often are adsorbed on clay particles. Consequently, radioactivity may be depleted from the ground water if the water has percolated through a clay layer. Under these conditions, radioactive substances are inadequate indicators of contamination, and other chemical indicators must be used. These may be substances that are not normally detected in the native water, or if normally present, are in abnormally large quantities or unusual ratios.

Background Surface-Water Quality in the Area

The study area is bounded on the south by the Missouri River and on the northeast by the Mississippi River. Because of their large flows, these rivers make available an almost unlimited water supply and can dilute large quantities of waste. The water-quality data for the Missouri River were obtained from water samples collected by the U.S. Geological Survey at Hermann, Missouri, 47 miles upstream from the U.S. Highway 40 and 61 bridge over the Missouri

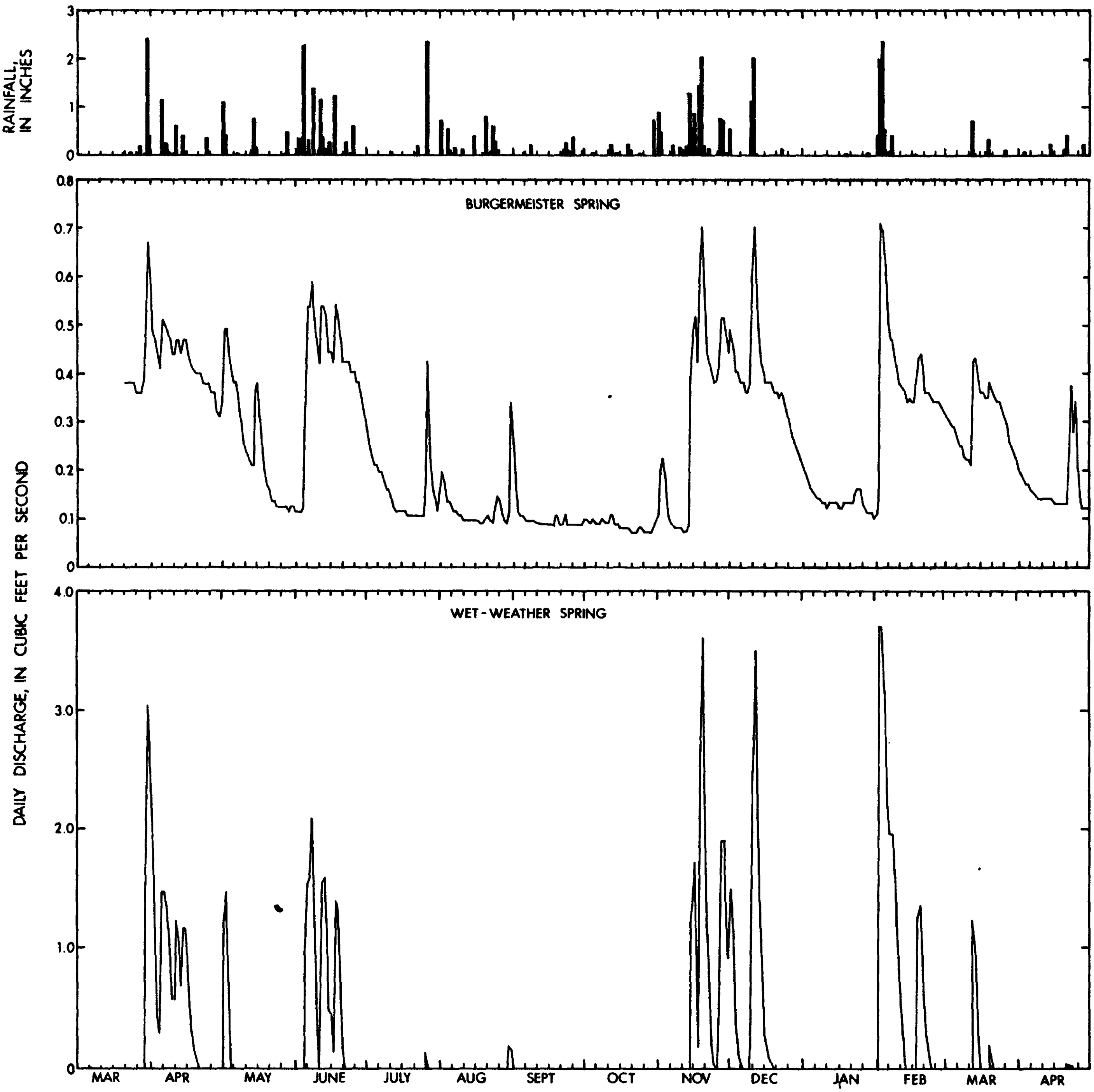

Figure 16.--Hydrographs of Burgermeister spring and a nearby wet-weather spring, March 1985 to April 1986, showing response to rainfall.

River. The Mississippi River data were obtained from water samples collected by the U.S. Geological Survey at Alton, Illinois, which is adjacent to St. Charles County. These data were compared with data from the city of St. Louis Howard Bend Water Plant, adjacent to St. Charles County (fig. 17). Data from the Howard Bend Water Plant (Miller and others, 1974) were obtained from water samples collected between 1951 and 1970.

Water-quality analyses from the Missouri River at Hermann, Missouri, are used in this report because it is the closest station to St. Charles County with current available data. Twelve water samples collected from October 1984 to September 1985 were used. These analyses indicate the predominant chemical constituents were calcium, magnesium, sodium, bicarbonate, and sulfate. The water typically was hard to very hard with calcium carbonate concentrations ranging from 160 to 250 mg/L (milligrams per liter). Sulfate concentrations ranged from 66 to 200 mg/L, dissolved-solids concentrations ranged from 231 to 499 mg/L, nitrate as nitrogen concentrations ranged from 0.43 to 2.90 mg/L, and lithium concentrations ranged from 20 to 41 ug/L (micrograms per liter; Waite and others, 1986). A water sample collected by Lawrence Berkeley Laboratory in 1979 from the Missouri River in the vicinity of the St. Charles County well field had a uranium concentration of 1 ug/L. This is considered background concentration for surface water in the study area (Berkeley Geosciences Assoc., 1984).

Miller and others (1974) compiled annual average values of several water-quality characteristics of the Missouri River at the Howard Bend Water Plant during 1951 to 1970. These analyses indicated the water at the Howard Bend Water Plant was similar to the water sampled at Hermann, Missouri, in 1984 and 1985. The predominant chemical constituents were calcium, magnesium, sodium, bicarbonate, and sulfate. The water typically was very hard, calcium carbonate concentrations ranged from 183 to 238 mg/L, and dissolved-solids concentrations ranged from 313 to 479 mg/L. A water sample collected by National Lead Company of Ohio, Inc. in 1980 at the intake of the Howard Bend Water Plant had a nitrate concentration of 5.8 mg/L and a uranium concentration of less than 2 ug/L.

Six water samples from the Mississippi River at Alton, Illinois, collected between November 1984 and September 1985, indicated the water was a calcium bicarbonate type with significant quantities of magnesium. The water typically was hard to very hard with calcium carbonate concentrations ranging from 160 to 230 mg/L. Sulfate concentrations ranged from 28 to 51 mg/L. Dissolved-solids concentrations in the water ranged from 206 to 307 mg/L. Nitrate as nitrogen concentrations ranged from 0.47 to 4.0 mg/L, and lithium concentrations ranged from 8 to 11 ug/L (Waite and others, 1986). National Lead Company of Ohio, Inc. collected a water sample from the intake at the Chain of Rocks water plant in 1980. The uranium concentration of this water was less than 2 ug/L (Weidner and Boback, 1982).

Dardenne Creek, Femme Osage Creek, and Little Femme Osage Creek are the streams in the vicinity of the raffinate-pits area and quarry that are of primary concern. Data reported by Berkas and Lodderhose (1985) during two 48-hour water-quality studies on Dardenne Creek indicate that between August 1 and 3, 1983, specific conductance ranged from 380 to 420 us/cm (microsiemens per centimeter at 25 °Celsius) near Cottleville. Between September 26 and 28, 1983, specific conductance ranged from 425 to 450 us/cm near Cottleville and increased downstream from 690 to 740 us/cm near the mouth of Dardenne Creek.

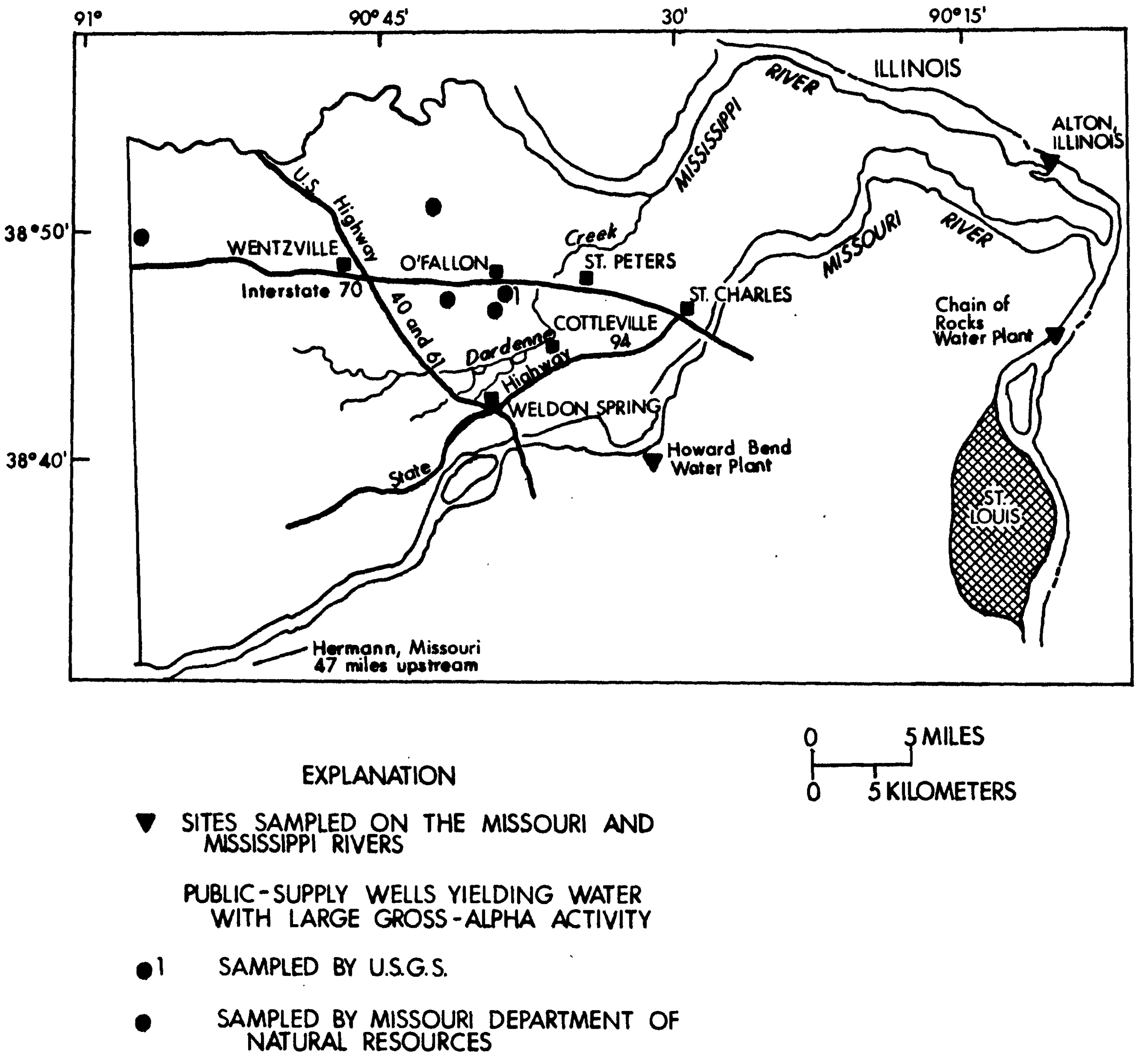

Figure 17.--Sites on the Missouri and Mississippi Rivers and public-supply wells with large gross-alpha activities.

Total nitrate as nitrogen in the water ranged from 0.46 to 1.3 mg/L near Cottleville and increased to 3.8 to 4.1 mg/L near the mouth of the creek. The increase in nitrate probably was caused by two sewage-treatment facilities that were discharging waste into Dardenne Creek and one of its tributaries at that time (Berkas and Lodderhose, 1985). Specific conductance data for Dardenne Creek were reported by Miller (1977) during reconnaissance studies on tributary streams in 1967 and 1970. These data indicate the specific conductance values of Dardenne Creek in the vicinity of Weldon Spring ranged from 340 to 400 us/cm.

Limited water-quality data are available for Femme Osage Creek. Miller (1977) reported the specific conductance near the headwaters was 370 us/cm on September 13, 1967. On the same day, the specific conductance was 490 us/cm downstream at the State Highway 94 crossing. A water sample collected by Lawrence Berkeley Laboratory in 1979 from Femme Osage Creek in the vicinity of the St. Charles County well field had a uranium concentration of 2 ug/L (Berkeley Geosciences Assoc., 1984).

Four water samples collected by National Lead Company of Ohio, Inc. from 1979 to 1980 from Little Femme Osage Creek upstream from the quarry had nitrate concentrations that ranged from 1.0 to 1.7 mg/L and uranium concentrations that ranged from 2 to 5 ug/L. Four samples collected downstream from the quarry had nitrate concentrations ranging from 0.7 to 2.8 mg/L and uranium concentrations ranging from less than 3 to 4 ug/L (Weidner and Boback, 1982). Lawrence Berkeley Laboratory collected samples from Little Femme Osage Creek in the vicinity of the quarry in 1979. They reported a bicarbonate concentration of 126 mg/L, a sulfate concentration of 45 mg/L, a lithium concentration of 10 ug/L, and a uranium concentration of 2 ug/L (Berkeley Geosciences Assoc., 1984).

Background Ground-Water Quality in the Area

Ground-water quality varies in the study area, depending on the aquifer sampled and the well location. Water from wells in the Missouri River alluvium has a slightly different composition than water from wells in the Mississippi River alluvium. Water samples from the Missouri River alluvium at the St. Charles County well field near Weldon Spring indicate the water is predominantly a calcium bicarbonate type. The Census of Missouri Public Water Supplies (Missouri Division of Environmental Quality; 1977, 1980, 1982, and 1985) reports dissolved-solids concentrations ranged from 184 to 338 mg/L and nitrate concentrations ranged from 0.6 to 2.1 mg/L. Four water samples collected from 1979 to 1984 from different wells in the city of St. Peters well field in the Mississippi River alluvium indicate the dominant cations were either calcium, sodium, or both, with increased magnesium concentrations. The dominant anions were bicarbonate and chloride. Dissolved-solids concentrations ranged from 312 to 611 mg/L, nitrate concentrations ranged from less than 0.05 to 0.2 mg/L.

Locally, some water samples from alluvial aquifers contain significant quantities of sulfate. The water is hard and characterized by variable dissolved-solids concentration and a large iron concentration.

Water samples from St. Charles County well field and the city of St. Peters well field were used to define the range for background radionuclide concentrations for the alluvial aquifers in the study area. All of the water samples from the Missouri River alluvium were collected from four St. Charles

County wells in 1985 (data on file at the Missouri Division of Geology and Land Survey office, Rolla, Missouri). The water samples from the Mississippi River alluvium were collected from three City of St. Peters wells between 1979 and 1984 (table 3).

The Missouri River alluvium has been sampled more frequently and thoroughly because of its proximity to the Weldon Spring quarry site (table 3). Gross-alpha activity in water from the wells in the Mississippi River alluvium has been within the specified limits of the U.S. Environmental Protection Agency, and additional sampling has not been required.

Water in the shallow bedrock aquifer generally is a calcium bicarbonate type with locally large concentrations of magnesium in the western part of St. Charles County and is a sodium chloride type toward the eastern part of St. Charles county. Variations in the chemical characteristics between the calcium bicarbonate type water and the sodium chloride type are thought to be related to geologic structure affecting upward movement of more mineralized water from underlying formations. Water with large sulfate concentrations is limited to the area underlain by Pennsylvanian shale, sandstone, and siltstone (Miller, 1977). Analyses of water samples collected during 1986 from 12 wells, open only to the shallow bedrock aquifer in the vicinity of the chemical plant were used to characterize the water in the shallow aquifer. These included 10 wells drilled by the U.S. Geological Survey on the August A. Busch Memorial Wildlife Area and two privately owned wells. The water from these wells predominantly was a calcium bicarbonate type. However, water from one of the privately owned wells was a calcium magnesium bicarbonate type, and water from the other privately owned well was a magnesium bicarbonate type. The dissolved-solids concentrations ranged from 251 to 393 mg/L and nitrate as nitrogen concentrations ranged from less than 0.10 to 4.60 mg/L. Lithium concentrations ranged from less than 4 to 13 ug/L (Kleeschulte and others, 1986).

Table 3.--Background radionuclide activities and concentrations in alluvial aquifers

[All values are in picocuries per liter; <, less than; --, data not available; data on file at the Missouri Division of Geology and Land Survey office, Rolla, Missouri]

	Missouri River alluvium	Mississippi River alluvium
Gross-alpha activity	1.7-4.6	<1.0-4.3
Gross-beta activity	4.2-5.9	--
Radium-226 concentration	0.5-0.7	--
Radium-228 concentration	<1.0-1.4	--

These same 12 wells open to the shallow aquifer were sampled during 1986 to obtain background radionuclide concentrations in the water. Background gross-alpha activities ranged from less than 1.0 to 3.2 pCi/L, radium-226 concentrations were less than 0.4 pCi/L, and uranium concentrations ranged from less than 0.4 to 3.8 ug/L (Kleeschulte and others, 1986). The raw, untreated water analyzed for radionuclide concentrations was collected in polyethylene bottles that previously had been rinsed with nitric acid. This was the method used by the U.S. Geological Survey personnel for radionuclide sampling throughout the study.

Analyses of water collected from three multiaquifer public-supply wells in the study area between 1977 and 1985 were used to characterize water from wells that penetrate the shallow and deep aquifer and obtain water from both. Analyses of water from these wells indicate the water is a calcium magnesium bicarbonate type that locally has large concentrations of sodium or sulfate. In 20 analyses from these multiaquifer wells from 1961 to 1982, dissolved-solids concentrations ranged from 290 to 500 mg/L and nitrate concentrations ranged from 0 to 2.3 mg/L (data on file at the Missouri Division of Geology and Land Survey office, Rolla, Missouri). Most of this water probably came from the deep aquifer because it generally yields more water.

Selected water analyses reported between 1966 and 1985 from 12 public supply wells throughout the study area indicate the water from the deep aquifer predominantly is a calcium magnesium bicarbonate type that locally can have large concentrations of sodium or sulfate. In the O'Fallon area, wells yield water containing moderate quantities of sodium, chloride, or sulfate. Dissolved-solids concentrations ranged from 276 to 642 mg/L, but typically ranged from 300 to 400 mg/L. Nitrate concentrations ranged from almost 0 to 4.4 mg/L, but generally were less than 1.0 mg/L (data on file at the Missouri Division of Geology and Land Survey office, Rolla, Missouri). According to Miller (1977), the eastern part of St. Charles County generally yields excessively mineralized sodium chloride water from the St. Peter Sandstone and older formations where they are deeply buried. The western part of the county yields moderately mineralized calcium magnesium bicarbonate water from these formations.

Radionuclide concentrations in water from the deep aquifer varies both spatially and with depth. Water from 13 public supply wells open only to the deep aquifer were sampled and analyzed for radionuclide concentrations between 1981 and 1985 by the Missouri Department of Natural Resources, Division of Environmental Quality. Some wells were sampled more than once. Gross-alpha activity ranged from 3.4 to 49.9 pCi/L, gross-beta activity ranged from 2.8 to 20.6 pCi/L, radium-226 concentrations ranged from 2.0 to 12.5 pCi/L, and radium-228 concentrations ranged from less than 1.0 to 2.7 pCi/L (data on file at the Missouri Division of Geology and Land Survey office, Rolla, Missouri).

Five public supply wells in the study area had gross-alpha activities larger than the 15 pCi/L standard set by the U.S. Environmental Protection Agency (1986). The U.S. Geological Survey sampled one of the five wells that was in the possible flow path of ground water from the chemical plant to determine the possible connection, if any, between the large radionuclide concentration in the well and the radioactive waste stored at the chemical plant (fig. 17). The tritium concentration in the water from the well was 1.5 tritium units (Kleeschulte and others, 1986). The quantity of tritium in the atmosphere was greatly increased by nuclear-weapons testing. As a result, beginning in 1954, precipitation in the northern Hemisphere contained larger concentrations of tritium. The value of 1.5 tritium units thus dates the bulk of the water from the well as being pre-1954, indicating the source of the large radionuclide concentration in the well is naturally occurring.

Water from 21 wells was collected by the Missouri Division of Health in December 1982 and January 1983. These wells encircle the chemical plant area and are all within 9 miles of the plant. These samples represent water from wells open to the shallow aquifer, the deep aquifer, or both. Reported depths for these wells ranged from 16 to 700 feet. Gross-alpha activities ranged from less than 1.0 to 5.7 pCi/L. Gross-beta activities ranged from 0 to 5.1 pCi/L (D.R. Dodson, Missouri Division of Health, written commun., 1983). These values represent background concentrations of radioactivity in water from wells in the study area. The Missouri Division of Health has expanded their monitoring program to include 39 wells and has increased the number of constituents analyzed to include sulfate, dissolved solids, nitrate, and lithium. In 1986, water from four of the sampled wells had increased gross-alpha activities. When these wells were resampled, radium-226 concentrations in water from three of the wells were within the U.S. Environmental Protection Agency (1986) standards. The Missouri Division of Health believes the one well that had radium-226 concentrations larger than permissible standards is contaminated by the natural radioactivity in the deep aquifer from formations penetrated by the well (John Crellin, Missouri Division of Health, oral commun., 1987).

In January 1983 the Missouri Department of Natural Resources, Division of Environmental Quality, sampled water from 14 private wells in northern St. Charles County. The depths of these wells were not reported, but the wells are in areas of thick Mississippian limestone. The gross-alpha activities of water in these wells ranged from less than 1.0 to 4.5 pCi/L, except for one well which had a gross-alpha activity of 10.0 pCi/L. The well was resampled in March 1983 for radium-226, and the concentration was 3.1 pCi/L (R.G. Burgess, Missouri Department of Natural Resources, Division of Environmental Quality, written commun., 1983).

Quality of Water at the Chemical Plant and Vicinity

The chemical-plant area encompasses about 200 acres. This includes the raffinate-pits area and the process buildings that remain on the site. The property in the vicinity includes the U.S. Army Reserve Area and the two Missouri Department of Conservation wildlife areas. The relation of the chemical plant and vicinity to the surrounding area is shown in figure 18.

Raffinate Pits

In August 1979, water sampling of the raffinate pits (fig. 9) was done by the Oak Ridge Y-12 Plant and the Oak Ridge National Laboratory. At the time of the sampling, pits 1 and 2 were dry, so only pits 3 and 4 were sampled. Water was collected both from near the surface and near the bottom in the pits about 10 feet from shore. Eight samples were collected from pit 3 and six were collected from pit 4. The analyses indicated the water in each pit was well mixed and similar in composition, regardless of the location from which it was collected. The water in pit 3 had a significantly larger dissolved-solids concentration. The values reported are average values of all samples taken from each pit (Taylor and others, 1979). Water-quality data collected by different agencies from the raffinate pits are listed in table 4.

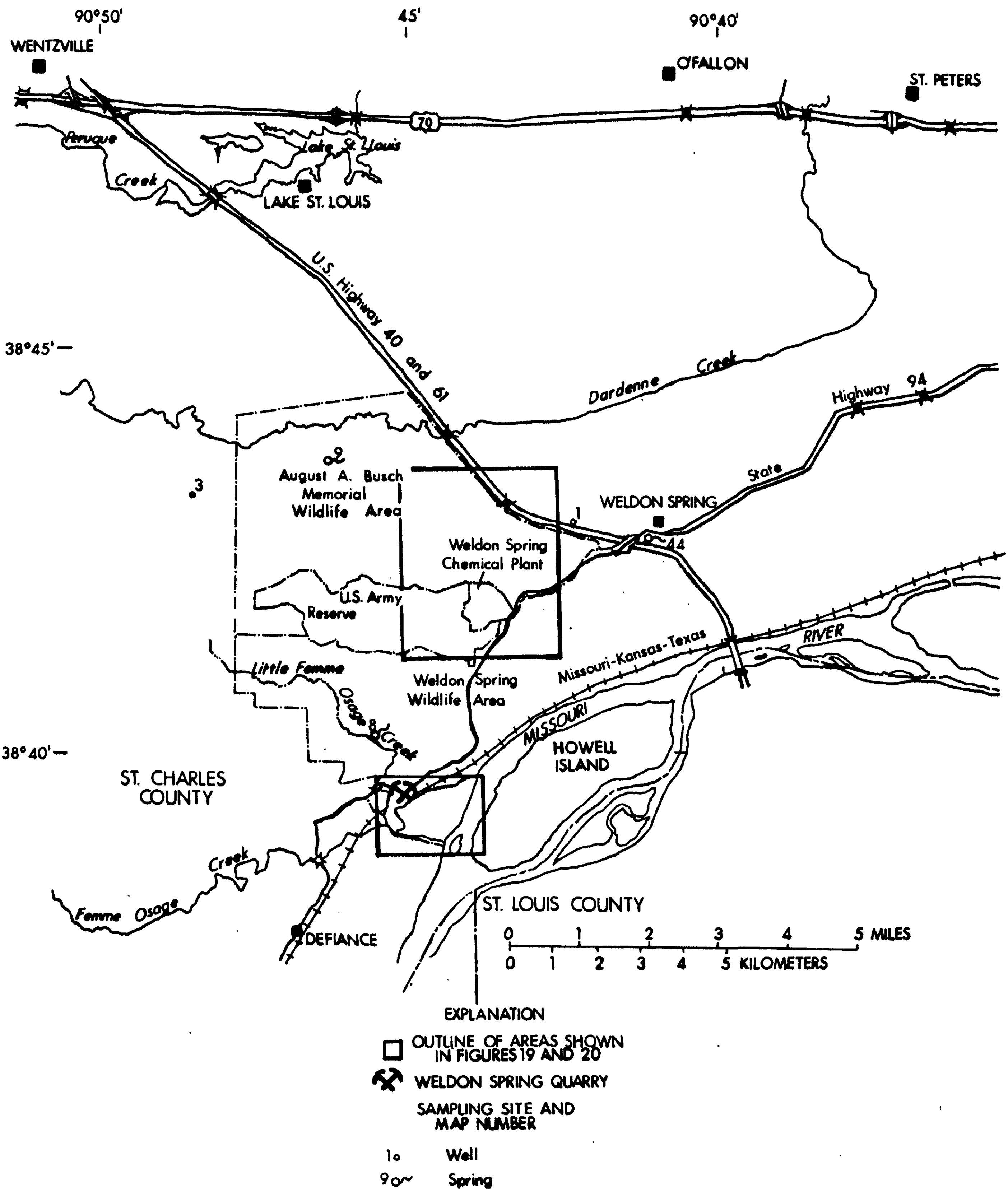

Figure 18.--Selected water-quality sampling sites.

Table 4.--Water quality in the four raffinate pits

[BCHT, Bechtel National, Inc.; USGS, U.S. Geological Survey; mg/L, milligrams per liter; --, no data available; ug/L, micrograms per liter; <, less than; W&B, Weidner and Boback; ORNL, Oak Ridge National Laboratory; pCi/L, picocuries per liter]

Constituent (unit)	Raffinate pit 1 BCHT 1983	Raffinate pit 1 USGS 1984	Raffinate pit 1 USGS 1986	Raffinate pit 2 BCHT 1983	Raffinate pit 2 USGS 1984	Raffinate pit 2 USGS 1986
Calcium, mg/L	--	560	340	--	380	140
Magnesium, mg/L	--	26	21	--	66	47
Sodium, mg/L	--	520	390	--	180	120
Potassium, mg/L	--	48	29	--	33	17
Alkalinity, mg/L	--	34	40	--	37	41
Sulfate, mg/L	100	400	280	460	990	580
Chloride, mg/L	15	17	13	6	5.7	4.4
Flouride, mg/L	1.1	2.5	2.0	1	2.7	2.2
Silica, mg/L	--	5.4	5.4	--	2.2	2.8
Nitrite, dissolved as nitrogen, mg/L	--	32	3.8	--	5.4	2.9
Nitrite plus nitrate, dissolved as nitrogen, mg/L	[a]710	668	416	[a].1	205	50
Aluminum, ug/L	--	30	--	--	40	--
Arsenic, ug/L	100	6	--	90	15	--
Barium, ug/L	<100	90	--	<100	72	--
Beryllium, ug/L	<1	12	--	1	8	--

Constituent	Raffinate pit 3 W&B 1979-80	Raffinate pit 3 ORNL average 1979	Raffinate pit 3 BCHT 1983	Raffinate pit 3 USGS 1984	Raffinate pit 3 USGS 1986	Raffinate pit 4 W&B 1979-80	Raffinate pit 4 ORNL average 1979	Raffinate pit 4 BCHT 1983	Raffinate pit 4 USGS 1984	Raffinate pit 4 USGS 1986
Calcium, mg/L	1,400	1,396	--	880	510	--	14.9	--	17	18
Magnesium, mg/L	440	480	--	320	290	--	34.1	--	52	49
Sodium, mg/L	1,460	1,187	--	1,500	970	--	122	--	190	190
Potassium, mg/L	--	181	--	150	80	--	17.8	--	23	18
Alkalinity, mg/L	--	--	--	37	52	--	--	--	240	259
Sulfate, mg/L	--	[b]625	260	640	410	--	140	70	150	130
Chloride, mg/L	29.3	37	20	25	22	12	10	7	7.7	7.4
Flouride, mg/L	7.4	6	2.7	8.9	6.9	8.7	13	5.8	7.8	6.3
Silica, mg/L	--	--	--	2.8	2.9	--	--	--	1.7	.4
Nitrite, dissolved as nitrogen, mg/L	--	[a]40	--	15	6.7	--	[a]<5	--	3.4	.6
Nitrite plus nitrate, dissolved as nitrogen, mg/L	[a]13,300	[a]13,000	[a]1,500	1,880	1,190	[a]55	[a]56	[a]100	91.6	78.4
Aluminum, ug/L	--	31	--	30	--	--	27	--	10	--
Arsenic, ug/L	--	--	140	4	--	--	--	20	2	--
Barium, ug/L	--	186	<100	170	--	--	125	100	100	--
Beryllium, ug/L	--	<1	1	<5	--	--	<4	<1	--	--

Table 4.--Water quality in the four raffinate pits--Continued

Constituent (unit)	Raffinate pit 1 BCHT 1983	Raffinate pit 1 USGS 1984	Raffinate pit 1 USGS 1986	Raffinate pit 2 BCHT 1983	Raffinate pit 2 USGS 1984	Raffinate pit 2 USGS 1986
Boron, ug/L	<100	--	--	<100	--	--
Cadmium, ug/L	.4	<3	--	.2	<3	--
Chromium, ug/L	<1	<1	--	<1	<1	--
Cobalt, ug/L	28	<9	--	32	<9	--
Copper, ug/L	111	4	--	5	4	--
Iron, ug/L	12	15	--	5	<9	--
Lead, ug/L	<1	<1	--	2	<1	--
Lithium, ug/L	--	140	10	--	140	26
Manganese, ug/L	28	9	--	33	9	--
Mercury, ug/L	<1	<.1	--	<1	<.1	--
Molybdenum, ug/L	--	3,000	--	--	7,100	--
Nickel, ug/L	<10	<1	--	20	<1	--
Selenium, ug/L	10	<1	--	<10	<1	--
Silver, ug/L	<1	<1	--	<1	<1	--
Strontium, ug/L	--	1,400	1,000	--	780	380

Constituent	Raffinate pit 3 W&B 1979-80	Raffinate pit 3 ORNL average 1979	Raffinate pit 3 BCHT 1983	Raffinate pit 3 USGS 1984	Raffinate pit 3 USGS 1986	Raffinate pit 4 W&B 1979-80	Raffinate pit 4 ORNL average 1979	Raffinate pit 4 BCHT 1983	Raffinate pit 4 USGS 1984	Raffinate pit 4 USGS 1986
Boron, ug/L	--	183	<100	--	--	--	91	<100	--	--
Cadmium, ug/L	--	--	<.1	<10	--	--	--	.3	<1	--
Chromium, ug/L	--	<4	<1	<1	--	--	<4	<1	<1	--
Cobalt, ug/L	--	<8	40	<30	--	--	<4	13	<3	--
Copper, ug/L	<1	27	11	7	--	<1	<4	<1	1	--
Iron, ug/L	--	56	11	<30	--	--	<4	74	<3	--
Lead, ug/L	--	--	2	11	--	--	--	4	17	--
Lithium, ug/L	--	6,240	--	460	2,700	--	689	--	660	590
Manganese, ug/L	--	93	9	35	--	--	<4	7	7	--
Mercury, ug/L	--	--	<1	<.1	--	--	--	<1	<.1	--
Molybdenum, ug/L	--	3,940	--	3,600	--	--	1,040	--	670	--
Nickel, ug/L	--	7	<10	<1	--	--	<4	<10	<1	--
Selenium, ug/L	--	--	80	<1	--	--	--	<10	<1	--
Silver, ug/L	--	3	<1	<1	--	--	<3	<1	<1	--
Strontium, ug/L	--	5,460	--	2,800	1,600	--	122	--	190	180

Table 4.--Water quality in the four raffinate pits--Continued

Constituent	Raffinate pit 1 BCHT 1983	Raffinate pit 1 USGS 1984	Raffinate pit 1 USGS 1986	Raffinate pit 2 BCHT 1983	Raffinate pit 2 USGS 1984	Raffinate pit 2 USGS 1986
Vanadium, ug/L	--	3,200	--	--	2,000	--
Zinc, ug/L	70	45	--	40	25	--
Radium-226, pCi/L	500	290	--	480	120	--
Uranium, ug/L	[c]6	26	46	[c]43	28	180
Cyanide, ug/L	<20	--	--	30	--	--

Constituent	Raffinate pit 3 W&B 1979-80	Raffinate pit 3 ORNL average 1979	Raffinate pit 3 BCHT 1983	Raffinate pit 3 USGS 1984	Raffinate pit 3 USGS 1986	Raffinate pit 4 W&B 1979-80	Raffinate pit 4 ORNL average 1979	Raffinate pit 4 BCHT 1983	Raffinate pit 4 USGS 1984	Raffinate pit 4 USGS 1986
Vanadium, ug/L	--	484	--	810	--	--	181	--	79	--
Zinc, ug/L	--	--	50	66	--	--	--	10	5	--
Radium-226, pCi/L	--	195	200	180	--	--	10	14	8.4	--
Uranium, ug/L	150	[b]148	[c]60	350	170	4,000	[b]3,780	[c]1,133	3,500	2,400
Cyanide, ug/L	--	--	50	--	--	--	--	<20	--	--

Note: A gamma spectrometer scan on water from each of the four raffinate pits by the U. S. Geological Survey detected no artificial isotopes present in the water.

[a] Reported as nitrate. No determination if total or dissolved nitrate; or if reported as milliequivalents of nitrate or nitrogen.

[b] Value reported in text different from value reported in table (Taylor and others, 1979).

[c] Value in picocuries per liter.

Weidner and Boback (1982) listed typical values for various properties and constituents in the water in the pits for 1979 to 1980. However, sample collection techniques were not described. The values given are comparable to concentrations reported by other agencies, except for the nitrate concentrations reported for pits 1 and 2.

Results of water sampling by Bechtel National, Inc. for the U.S. Department of Energy were reported in June 1983. The sampling procedure used was not described (R.C. Hengerson, Missouri Department of Natural Resources, written commun., 1983).

In September 1984, the U.S. Geological Survey collected water samples from the four raffinate pits (fig. 9). The water in pits 1 and 2 was estimated to be from 1 foot to 3 feet deep. Samples from both pits were collected about 15 feet from the shore. Pit 3 was uniformly 3 to 5 feet deep when sampled about 100 feet from shore. The pit was green with algae. Pit 4 varied in depth from 8 to 15 feet and had a sparse algal growth. Water temperature and dissolved oxygen were checked at different depths. The water in pit 4 was not stratified. In June 1986, the U.S. Geological Survey sampled water from the four raffinate pits to verify values of several of the constituents sampled for in 1984. The sampling indicated that the concentrations of constituents in the pits vary seasonally. Included with this sampling was an organic-compound scan using the gas chromatograph-flame ionization method. The scan indicated no significant concentrations.

Generally the data collected and analyzed by the different agencies are within an order of magnitude of each other. The discrepancies can perhaps be attributed to differences in sample-collection techniques, differences in laboratory analytical methods, and possibly in climatic conditions at the time of sampling. In summary, water in the raffinate pits has a large dissolved-solids concentration and a different chemical composition from the natural surface and ground water. This is reflected by the increased concentrations of some of the commonly occurring ions, especially calcium, sodium, sulfate, fluoride, and nitrate and by the presence in large concentrations of several trace elements, such as lithium, molybdenum, strontium, vanadium, and uranium.

In February 1986, the U.S. Geological Survey sampled eight observation wells within 2,100 feet of, and completely surrounding, the raffinate pits (fig. 19, sites 15 to 22). Seven of these wells are completed in the Keokuk and Burlington Limestones and have well casing extending through the overlying soil and glacial till. The remaining well (site 19) is completed in the residuum. The casing was grouted in all these wells.

One annular volume of water was pumped from the wells with a 1 3/4-inch diameter pneumatic pump before sampling. The results from the sampling indicated the specific conductance in these wells ranged from 430 to 6,600 us/cm. Site 20 had the largest specific conductance value and also had increased concentrations of calcium, 800 mg/L; magnesium, 320 mg/L; sodium, 330 mg/L; sulfate, 190 mg/L; molybdenum, 33 ug/L; and strontium, 1,700 ug/L. The nitrate concentration was 920 mg/L and the lithium concentration was 1,700 ug/L. Site 21 had an increased uranium concentration of 54 ug/L (Kleeschulte and others, 1986).

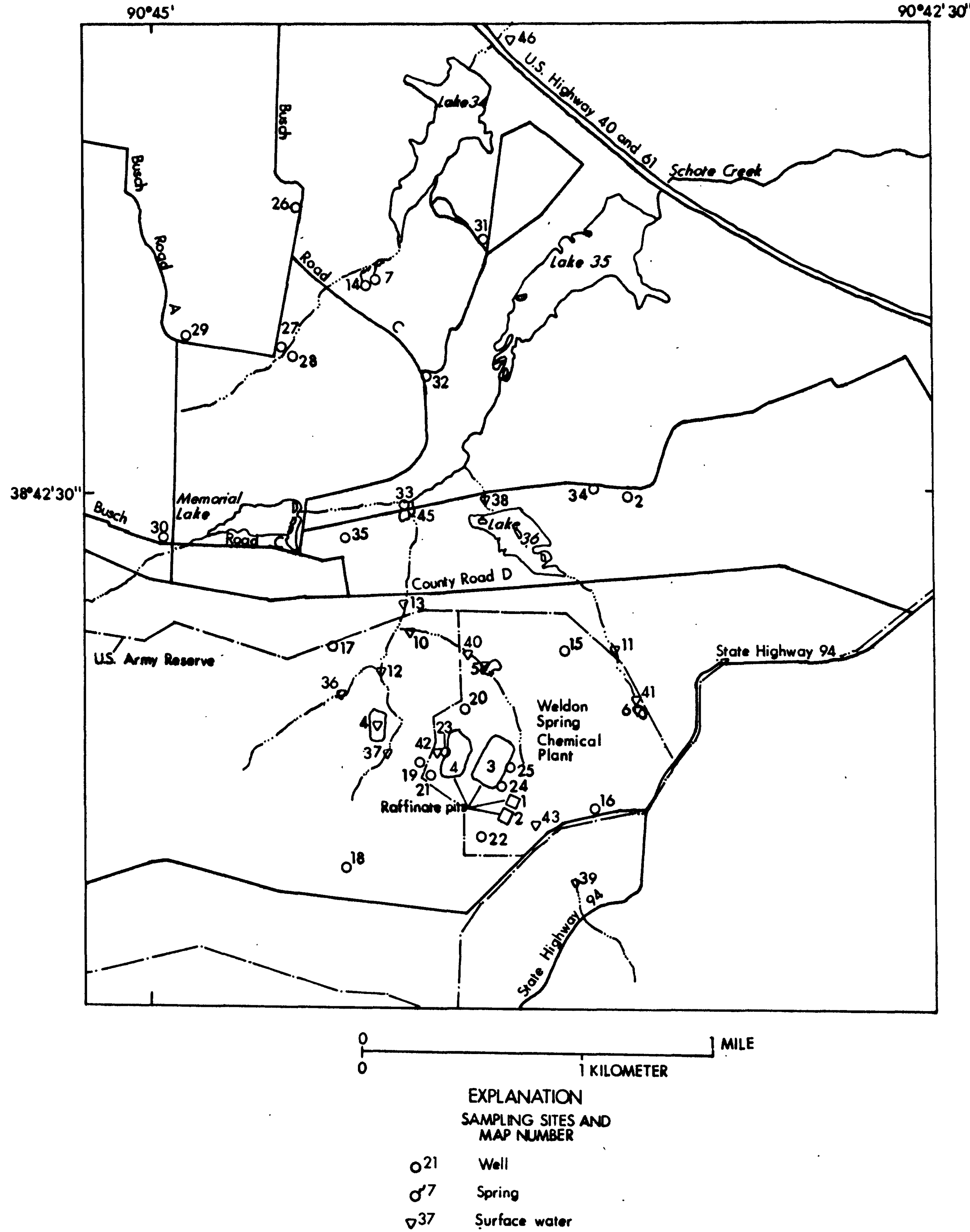

Figure 19.--Water-quality sampling sites in the vicinity of the Weldon Spring Chemical Plant.

In June 1986, seven of these wells were resampled to verify the results of the February sampling. Three other observation wells located onsite were added to the list to be sampled (fig. 19, sites 23 to 25). Two of these wells (sites 23 and 24) were completed in glacial till. The other well was completed in the Keokuk and Burlington Limestones. Dissolved-solids concentrations ranged from 841 to 5,900 mg/L in water from five of these wells. This sampling verified that, in most cases, water from these same five wells with the large dissolved-solids concentrations also had increased concentrations of calcium, magnesium, sodium, sulfate, nitrate, lithium, and strontium. Nitrate concentrations ranged from 53 to 990 mg/L in five wells. Lithium concentrations ranged from 40 to 1,700 ug/L in water from four wells. Uranium concentrations were increased in water from site 16 (49 ug/L) and site 21 (86 ug/L; Kleeschulte and others, 1986).

The onsite sampling indicated that contaminated water had entered the ground-water system and was present in the underlying bedrock. The sampling also indicated a possible source for the large nitrate and lithium concentrations in the water discharging from Burgermeister spring. The anomalous constituent during the sampling, however, was uranium. It was detected in large concentrations in the raffinate pits, but increased concentrations were detected in only two of the sampled wells. As previously stated, five wells contained water that had anomalously large concentrations of one or more constituents that are known to be present in large concentrations in one or all of the raffinate pits. A possible explanation for the small values of uranium is selective adsorption of the uranium by the clay particles in the glacial-till overburden. The clay may be inhibiting the migration of the uranium from the immediate area around the pits.

Soil Samples

During 1978, an assessment was made of radiological contamination at the Weldon Spring Chemical Plant for the U.S. Army (Ryckman, Edgerley, Tomlinson, and Assoc., 1978). As part of this study, 160 soil samples were collected from 30 boreholes and analyzed for uranium. The boreholes were in four general areas: the process-building area, Ash pond area, the north dump area, and the Coal pond area (fig. 9). Sediment samples were collected from several streams and impoundments and analyzed for uranium. The assessment indicated that an estimated 5,000 cubic yards of soil and sediment were contaminated with uranium contents of more than 500 milligrams per kilogram. Eighty percent of this material is near Ash pond or the north dump area. Both of these sites are in the drainage basin of the unnamed tributary of Schote Creek that contains Ash pond. This same tributary has been shown to be a losing stream downstream from Ash pond (fig. 15).

A radiological survey of the area surrounding the raffinate pits was made for the U.S. Department of Energy during 1982 to 1983 (Bechtel National, Inc., 1984a). As part of the study, 120 surface and 34 trench-sidewall soil samples were collected. Uranium-238 contents in surface soil ranged from 2 to 34,090 pCi/g. The largest radium-226 content was 261.8 pCi/g, but the content of a follow-up sample was 8.3 pCi/g, indicating the variation of the contamination in the area. The largest thorium-230 concentration, 370 pCi/g, and the largest thorium-232 content, 459.9 pCi/g, were from the same sample (Bechtel National, Inc., 1984c). This sampling was done on land owned by the U.S. Department of Energy in the drainage basin of the unnamed tributary of Schote Creek that has been determined to be a losing stream.

Wells, Springs, and Ponds

The water-quality data collected by the U.S. Geological Survey during 1984 through 1986 is reported in Kleeschulte and others (1986). In September 1985, the U.S. Geological Survey sampled three private wells open to the shallow aquifer, three springs, and three ponds, all of which are in the vicinity of the chemical plant (figs. 18 and 19, sites 1 to 9). The wells and springs were sampled to determine the extent of ground-water contamination in the shallow bedrock aquifer. The ponds were sampled to characterize the chemical composition of the water in each.

In relation to the raffinate pits, one well (fig. 18, site 1) is 1.8 miles to the northeast, one well (fig. 19, site 2) is 0.8 miles to the north, and the third well (fig. 18, site 3) is 4.4 miles to the west-northwest. The properties or constituents that were analyzed as possible tracers were specific conductance, calcium, magnesium, sodium, sulfate, nitrate, lithium, radium-226, and uranium. No significant concentrations of these were detected in the wells, and the concentrations are assumed to represent background values.

The three springs were sampled because contaminants from the chemical-plant area that enter the ground-water flow system may not be following the normal dispersive flow paths that occur in unconsolidated or granular material. Ground-water movement in a karst environment often is through fractures, joints, or solution openings. Springs are points to which ground water converges in a catchment basin, so discharge from springs should represent the water quality in the catchment basin.

The weather during the 2 weeks before the sampling was dry. This insured the source of outflow from the springs primarily was from ground-water storage and not runoff. The rearing-pond spring (fig. 18, site 9) is about 2.8 miles northwest of the raffinate pits. This spring emerges from a small bluff of the Keokuk and Burlington Limestones. Lost Valley spring (fig. 18, site 8) is 2.7 miles southwest of the raffinate pits and emerges from a bluff of the Kimmswick Limestone. Neither of these two springs had anomalous concentrations of any of the parameters sampled. Burgermeister spring (fig. 19, site 7) was sampled to determine the water composition during dry weather. Burgermeister spring had increased concentrations of nitrate, lithium, and uranium.

Ash pond and Frog pond (fig. 19, sites 5 and 6) were sampled to characterize the water in each. Ash pond did not have increased concentrations of the common constituents or trace metals. The sampling indicated increased concentrations of sodium, 74 mg/L, and chloride, 83 mg/L, in Frog pond. However, in both ponds the dissolved uranium concentrations were large; the concentration in Ash pond was 820 ug/L and in Frog pond was 140 ug/L. The unnamed pond on the U.S. Army property, hereafter referred to as Army pond (fig. 19, site 4) was sampled because the pond possibly was used as a waste-storage site when the Department of the Army used the facilities as an ordnance plant. Water from the pond had a small dissolved-solids concentration of 69 mg/L and did not have large concentrations of other common constituents, nitrate, trace metals, or radionuclides.

To summarize water samplings completed in 1985, samples from the three private, shallow wells did not indicate contamination. These nearby wells are in possible flow paths of ground water from the site. The water samples from the springs indicated that contamination existed in the catchment basin of Burgermeister spring. The sampling of the three ponds indicated that outflow from Ash pond and Frog pond are possible sources of uranium contamination.

In February 1986, the U.S. Geological Survey drilled 10 wells in the August A. Busch Memorial Wildlife Area. Most of the wells were between the raffinate pits and Burgermeister spring (fig. 19, sites 26-35). The wells were drilled to locate a possible contamination plume from the raffinate pits. The wells were drilled about 50 feet into the Keokuk and Burlington Limestones with casing through only the glacial till. The wells were completed at an altitude lower than the orifice at Burgermeister spring, a known outlet for water with larger-than- background concentrations of nitrate, lithium, and uranium. Because of the low permeability of the glacial till, ground-water movement through the glacial till was assumed to be negligible; however, the residuum below the glacial till and above the Keokuk and Burlington Limestones possibly could be conducive to ground-water movement.

Water-quality data from the wells in March 1986 did not indicate a contamination plume. Constituents used as possible tracers were nitrate, lithium, strontium, and vanadium. None of these values exceeded the typical concentrations detected in water from Burgermeister spring. These data thus indicate that contaminants from the chemical plant are not forming a plume in the ground-water system. Instead, the data imply that the contaminants emerging from Burgermeister spring may be in a conduit-type system while being transported through the bedrock. In a karst environment, this phenomenon is common. This hypothesis also is supported by two of the Missouri Department of Natural Resources dye traces that were made in the losing reaches of the tributaries that border the raffinate pits. This type of ground-water transport system confines the water to narrow lateral channels. Thus, it is difficult to obtain water samples representative of drainage from the chemical-plant area from randomly located monitoring wells. These wells were sampled again in June 1986, and the results were similar.

Wildlife Areas

The unnamed tributaries to Schote Creek that contain Ash pond and Frog pond flow into the August A. Busch Memorial Wildlife Area lakes 35 and 36. The Missouri Department of Conservation sampled water and sediment from seven sites in the August A. Busch Memorial and Weldon Spring Wildlife Areas during the spring of 1983. These samples were analyzed for gross-alpha and gross-beta radioactivity. Samples were collected from lakes 9 and 10 (fig. 14) that are unaffected by runoff from the chemical-plant or raffinate-pits area and are presumed to represent background activities. Gross-alpha activity in water samples from lakes 9 and 10 was less than 1 pCi/L for both lakes, and in sediment samples of both lakes was less than 1 pCi/g. Gross-beta activity in these water samples was less than 4 pCi/L in both lakes, and in both sediment samples gross- beta activity was 13 pCi/g. Gross-alpha and gross-beta activity from the water and sediment samples from lakes 35 and 36 were larger than background activities (J.R. Whitely, Missouri Department of Conservation, written commun., 1983). Gross-alpha activity in water from these lakes had a maximum concentration of 6.0 pCi/L and gross-beta activity ranged up to 18 pCi/L. In the lake sediment, gross-alpha activity had a maximum content of 1.3 pCi/g, and gross-beta activity was as large as 55 pCi/g. Previous sediment sampling by Ryckman, Edgerley, Tomlinson, and Assoc. (1978) also indicated increased uranium content in lake 35 from 11 to 44 ug/g and in lake 36 from 13 to 287 ug/g, in Ash pond from 70 to 1,145 ug/g, in Frog pond from 473 to 858 ug/g, and in the sewage-outfall tributary of as much as 900 ug/g. This indicates that radioactive-contaminated sediment has been washed into the local streams.

Between July 1984 and September 1985, Oak Ridge Associated Universities made a radiological assessment of the August A. Busch Memorial Wildlife Area and the Weldon Spring Wildlife Area at the request of the U.S. Department of Energy. As part of the assessment, water and sediment samples were collected from several lakes and ponds on the chemical-plant and wildlife areas. Boerner (1986) reported increased uranium-238 concentrations in the water from lake 34 (16 pCi/L) and lake 36 (18 pCi/L). Contents of uranium-238 in the sediment from lake 34 was 2 to 120 pCi/g, from lake 35, from less than 2 to 37 pCi/g, from lake 36, less than 2 to 94 pCi/g, from the drainage of Frog pond, 2 to 65 pCi/g, from the drainage to lake 36, 39 pCi/g, and from the sewage-outfall tributary, less than 1 to 65 pCi/g.

Storm Runoff

On November 19, 1985, approximately two inches of rain fell on the Weldon Spring area from a localized thunderstorm. The U.S. Geological Survey sampled the runoff at three locations in the unnamed tributary of Schote Creek, which drains the chemical-plant and raffinate-pits area. Runoff in the tributaries containing Frog pond, Burgermeister spring, and the wet-weather spring near Burgermeister spring also were sampled (fig. 19, sites 7 and 10 to 14). These tributaries were sampled to determine if the source of nitrate, lithium, and uranium concentrations at Burgermeister spring came from runoff from the chemical-plant area entering the ground-water system from losing-stream reaches.

The two forks of the unnamed tributary of Schote Creek and the tributary containing Frog pond are the three primary transport routes for runoff draining the chemical-plant and raffinate-pits areas. Along with water samples collected from both forks of the unnamed tributary, a water sample also was collected 150 feet downstream from where these two forks converge, which allowed runoff from both forks sufficient distance to mix.

The analyses indicate the runoff from both forks of the unnamed tributary are similar in chemical composition. The most notable difference is that the fork of the tributary that contains Ash pond had large concentrations of uranium and the middle fork does not. Runoff from the Frog pond tributary had large concentrations of sodium, 460 mg/L, chloride, 740 mg/L, manganese, 110 ug/L, and uranium, 60 ug/L. The source of the large sodium and chloride concentrations has been traced to a Missouri State Highway Maintenance shed about 1,000 feet east of Frog pond on State Highway 94. Salt is stockpiled on the maintenance-shed lot for use on the highways during the winter months; runoff during storms washes the salt into Frog pond tributary.

The water samples from Burgermeister spring and the nearby wet-weather spring were similar in chemical composition. These samples also were similar to the three samples from the unnamed tributary of Schote Creek with the exception of the uranium concentration. The uranium concentration in the water discharging from the springs was less than concentrations detected in the tributary and was less than uranium concentrations discharged during base-flow periods from the springs. The large sodium, chloride, and manganese concentrations that were in the water from Frog pond tributary were not detected at Burgermeister spring or the wet-weather spring.

The sampling indicated some constituents in the water of the runoff leaving the U.S. Department of Energy property by Ash pond tributary and the water quality of Burgermeister spring are correlated. It also indicated runoff or outflow from Ash pond and Frog pond could be a source of uranium washing into the local surface-water system, and contaminants in Ash pond tributary also could be washed into the ground-water system. The sampling did not, however, explain the source of large nitrate or lithium concentrations detected in the local ground water that emerges from Burgermeister spring during low flow.

Base Flow

Seven surface-water sites were sampled from March 10 to 12, 1986 (fig. 19, sites 7 and 36 to 41). No measurable precipitation was recorded in the area for at least 11 days before the sampling, but in late winter the base flow of streams usually is high. Base flow is sustained, or fair-weather, flow. However, during the night of March 11 and early morning of March 12, 0.70 inch of rain fell on the area in 9 hours (National Oceanic and Atmospheric Administration, 1986), causing slight runoff to mix with the base flow.

The sampling was conducted to determine if ground-water outflow from the chemical-plant area when the ground is saturated leaches contaminants from the soil into the streams in the area. These data are tabulated in Kleeschulte and others (1986). The sampling data indicated that water in the two forks of the unnamed tributary of Schote Creek that drains the chemical-plant and raffinate-pits area does not contain concentrations of uranium larger than background concentrations. The outflow from August A. Busch Memorial Wildlife lake 36 and discharge of the sewage-outfall tributary had uranium concentrations of 45 and 390 ug/L. The sewage-outfall tributary also had a nitrate as nitrogen concentration of 10 mg/L. The Ash pond outflow had increased nitrate as nitrogen concentration of 9 mg/L. The water samples collected from the Ash pond and Frog pond outflows had increased uranium concentrations of 4,000 and 88 ug/L. These water samples may have been affected by runoff. The water from Burgermeister spring had a nitrate as nitrogen concentration of 26 mg/L and a uranium concentration of 210 ug/L.

This sampling indicated that uranium does not enter the surface-water system by seepage from the aquifer in the two forks of the unnamed tributary of Schote Creek. Instead this indicates uranium enters the ground-water system through the losing streams during runoff. The sewage-outflow tributary has increased uranium concentrations during base-flow conditions.

Miscellaneous Sampling

In June 1986, five sites that had not been sampled previously were sampled by the U.S. Geological Survey . These miscellaneous sites included two small seeps, one spring, a sewage lagoon, and a stream (fig. 18, site 44 and fig. 19, sites 42, 43, 45, and 46).

While the onsite observation wells were being sampled, a small seep was noticed at the base of the levee on the west side of raffinate pit 4 (site 42). Water from this seep had increased concentrations of calcium, 210 mg/L; magnesium, 72 mg/L; sulfate, 720 mg/L; and dissolved-solids, 1,190 mg/L when compared to local ground water. Uranium was at background concentration. Another small seep was noticed upstream from the sewage treatment facility at the chemical plant (site 43). Water from this seep had background concentrations of the common constituents, but had an increased uranium concentration of 110 ug/L. Weldon Spring (site 44) was sampled and the water had background concentrations of all constituents. The August A. Busch Memorial Wildlife Area sewage lagoon (site 45) was sampled to determine if nitrate was being discharged in large enough concentrations to be a possible source of the nitrate detected in Burgermeister spring (site 7). This lagoon discharges into the losing-stream reach that has been determined to be hydraulically connected to Burgermeister spring. However, the nitrate as nitrogen concentration in the sewage lagoon was less than 1 mg/L. The stream that contains Burgermeister spring branch was sampled downstream from where it discharges from August A. Busch Memorial Wildlife Area lake 34 (site 46). The common constituents and nitrate were at background concentrations, but the uranium concentration was slightly increased at 13 ug/L.

Quarry Area

Water sampling by Berkeley Geosciences Assoc. (1984) from the Missouri River, Femme Osage Creek, and Little Femme Osage Creek indicated that background concentrations of uranium in the streams ranged from 1 to 2 ug/L. Background concentrations of radioactivity in water from wells in the study area were determined by the Missouri Division of Health. Gross-alpha activity ranged from 1.0 to 5.7 pCi/L, and gross-beta activity ranged from 0 to 5.1 pCi/L (Missouri Division of Health, written commun., 1983).

Berkeley Geosciences Assoc. (1984) sampled water and sediment from the quarry property during 1979 to 1980. Water from the quarry sump had uranium concentrations ranging from 3,000 to 5,000 ug/L. Water samples from auger holes on the quarry property had uranium concentrations ranging from 3,000 to 11,000 ug/L. An 18-inch sediment sample from below the water surface had a uranium content of 69 ug/g near the water surface, and the uranium content decreased to 3 ug/g with depth. Another set of samples from four locations in the quarry sump consisted of mud and organic sediment. Uranium contents ranged from 84 to 660 ug/g. Berkeley Geosciences Assoc. (1984) suggests the large contents in these last samples indicated uranium had precipitated out of solution because of the reducing environment caused by the decaying organic matter at the bottom of the sump.

National Lead Company of Ohio, Inc. determined that the water in the slough system south of the quarry had uranium concentrations 200 times larger than those detected in Little Femme Osage Creek during 1975. This implied a hydraulic connection between the quarry and the slough system (National Lead Company of Ohio, Inc., 1977) and this prompted the drilling of monitoring wells in the quarry floor, around the quarry sump, and in the limestone bluff south of the quarry. The water from the wells in the bluff had uranium concentrations ranging from 10 to 13,000 ug/L.

Berkeley Geosciences Assoc. (1984) sampled the low permeability clays in the alluvium between the Missouri-Kansas-Texas Railroad line and the slough system (fig. 8). Uranium contents ranged from 1.8 to 177 ug/g from 21 borehole soil samples. The largest contents were detected in the boreholes opposite a large fracture zone in the limestone bluff (fig. 8, OB-7, OB-8, OB-10, and O-4). Further soil sampling of the top 1/8 to 1/4 inch layer indicated that the uranium content rapidly decreased towards the slough system. Soil samples collected from the south side of the slough system had a uranium content of about 3 ug/g at all depths (Berkeley Geosciences Assoc., 1984).

Water samples also were collected from boreholes in the alluvium between the slough system and railroad line. Berkeley Geosciences Assoc. (1984) indicated variable uranium concentrations. Some of these wells were sampled as many as six times, and all the samples from each well were averaged. Average uranium concentrations in water from one well was 4 ug/L. However, concentrations ranged from 20 to 970 ug/L in 6 wells, and 1,200 to 9,900 ug/L in 11 wells. Water samples from five wells south of the slough system and east of the quarry had uranium concentrations ranging from less than 2 to 8 ug/L (Berkeley Geosciences Assoc., 1984).

Water samples from Femme Osage slough were collected from two locations by Berkeley Geosciences Assoc. (1984). Water from the section west of the causeway and culvert (the section nearest the quarry) had a uranium concentration of 70 ug/L, and the water east of the culvert had a uranium concentration of 30 ug/L. A water sample collected by the U.S. Geological Survey during 1984 from the western section of the slough had a uranium concentration of 77 ug/L (Kleeschulte and others, 1986). Sediment samples collected by Berkeley Geosciences Assoc. (1984) from below the water surface in the slough had uranium contents ranging from 2 to 10 ug/g. Water from Little Femme Osage slough had a uranium concentration ranging from 160 to 310 ug/L. Sediment samples from Little Femme Osage slough had uranium contents as large as 30 ug/g. Five of the seven sediment samples from both of the sloughs had more than the 2.5 to 3.8 ug/g uranium content determined by Berkeley Geosciences Assoc. (1984) to be background content in the surficial soil and clay of the area.

Seven bedrock wells were sampled north of the Missouri-Kansas-Texas Railroad line (fig. 20, sites 46 to 52) by the U.S. Geological Survey during 1985 and 1986. Uranium concentrations in water from these wells ranged from 8.9 to 14,000 ug/L. The two wells (sites 51 and 52) with the largest uranium concentrations in the water (4,700 and 14,000 ug/L) are southeast of the quarry sump and within 200 feet of each other. Another well (site 50), about 200 feet northeast of these two wells, had a uranium concentration of 410 ug/L. Water from six wells in the Missouri River alluvium north of the slough system also was collected (fig. 20, sites 53-58). Two of these wells were completed in bedrock (sites 56 and 57). The uranium concentrations in these six samples

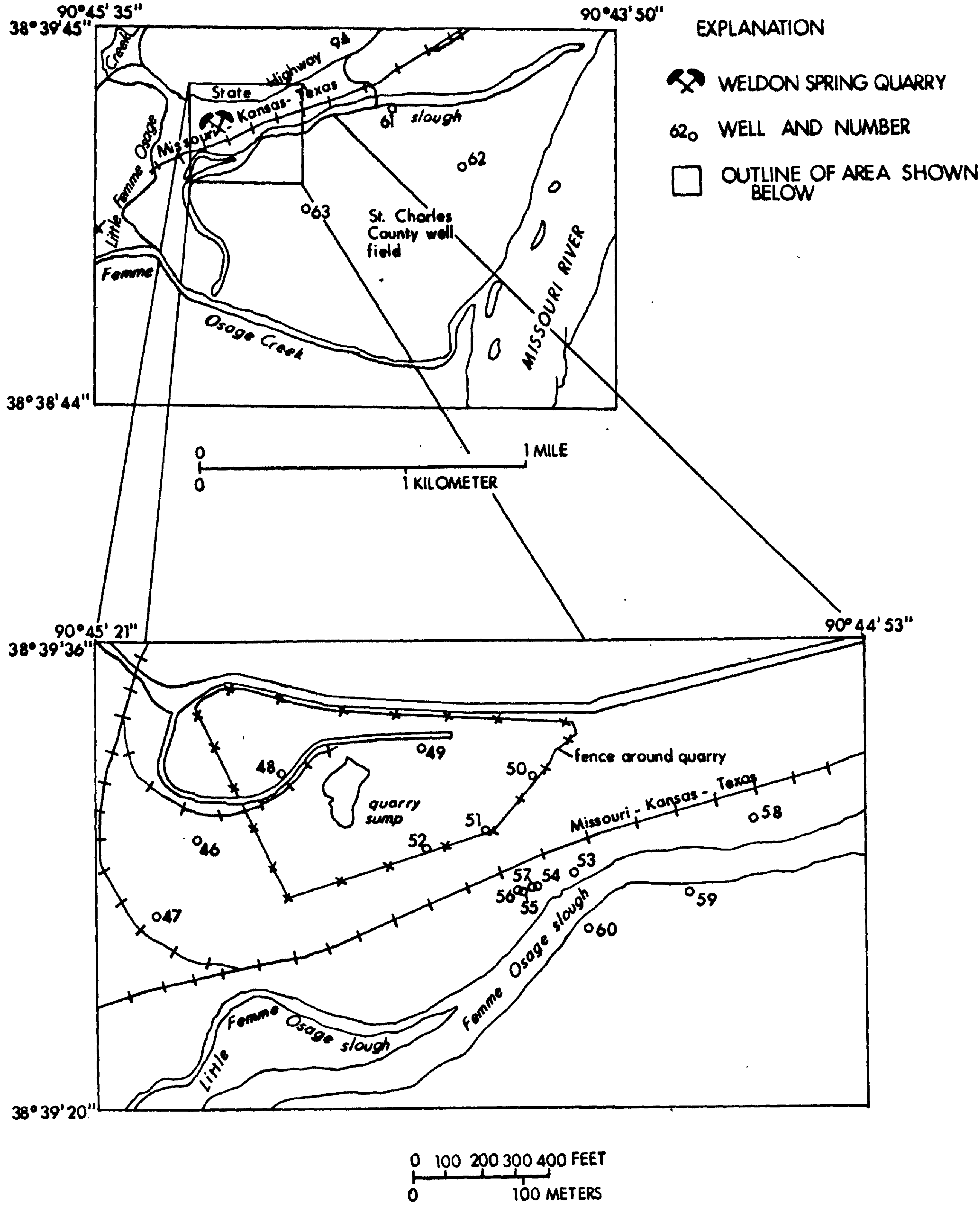

Figure 20.--Water-quality sampling sites in the vicinity of the Weldon Spring quarry (modified from Berkeley Geosciences Assoc., 1984).

ranged from 47 to 4,500 ug/L. One of the bedrock wells (site 57) had a uranium concentration of 3,900 ug/L, whereas the other (site 56), which is about 30 feet away, had a concentration of 100 ug/L. An alluvial well (site 55) between the two bedrock wells had a uranium concentration of 4,500 ug/L. It is not likely that the uranium is moving in a plume from the quarry; instead it seems to move in preferred paths and is not limited to the bedrock or alluvium, but is detected in both. Water from five wells in the alluvium south of the slough system (fig. 20, sites 59 to 63) had uranium concentrations ranging from 0.4 to 4.2 ug/L.

Uranium from the quarry probably has migrated as far as the alluvium north of the slough system. Sample data from the slough system indicate increased concentrations of uranium in both the water and the sediment. The radioactive contamination in the slough system could have been caused from 1960 to 1961, before the completion of the levee, when water was pumped from the quarry sump into Little Femme Osage Creek. Another possibility is that ground-water movement through fractures in the limestone is transporting uranium from the quarry (Berkeley Geosciences Assoc., 1984). This reasoning is supported by analyses of data from test holes that indicate the largest uranium concentrations are opposite the fractures in the limestone bluff.

Water samples from several test wells around the quarry sump and from alluvial wells north of the slough system had uranium concentrations larger than the concentrations detected in the quarry sump. This indicates either the uranium concentrations in the quarry-sump water previously were larger or uranium is being leached by precipitation infiltrating through the waste stored on the main quarry floor. Near-background concentrations of uranium were detected in water from boreholes south of the slough system. The clay at the bottom of the slough system possibly extends down to the bedrock and forces the ground water to move through the fractured bedrock under the slough system, rather than through the alluvium (Berkeley Geosciences Assoc., 1984). An alternative explanation can be derived by an analysis of water levels in the area (fig. 10). The water levels in some of the observation wells on the western end of and south of the slough system were higher when measured than the altitude of the water in the slough system. This indicates that the direction of water movement was from these wells northward toward the slough system, not from the slough system to the wells.

ADDITIONAL STUDIES NEEDED

The ground-water divide in the shallow bedrock aquifer in the vicinity of the chemical plant and raffinate pits is not sufficiently defined. An improved definition of the ground-water divide is needed because of its proximity to the chemical plant and raffinate pits and the control the divide may exert on the direction of ground-water movement. Installation of several monitoring wells south of the divide would aid in the better definition of ground-water movement and ground-water quality in an area where sparse data exist.

The relation of the hydraulic head in the shallow bedrock aquifer to the hydraulic head in the deep aquifer is not well substantiated. Limited data indicate that some water from the shallow bedrock aquifer may move downward to the deep aquifer. At least two nests of wells installed to various depths could provide information on vertical-flow patterns. One nest of wells near the chemical-plant and raffinate-pits area and one nest of wells near Dardenne Creek may provide this information. These wells could be used to determine vertical-head differences and difference in ground-water quality. The wells could be used to understand the three-dimensional components of ground-water flow in the consolidated rocks beneath and near the waste-disposal sites and would therefore be useful in evaluating concepts about the ground-water movement.

SUMMARY AND CONCLUSIONS

The Weldon Spring Chemical Plant is in an area characterized by dissected till deposits that range from 0 to 50 feet thick, karst geology, and gently undulating topography. The overburden in the area of the four raffinate pits primarily consists of clay, silty clay, and clayey silt ranging from 10 to 25 feet thick. A residuum layer ranging from 0 to 22 feet thick lies beneath the glacial till deposits. The permeability of this layer is variable but is substantial in places. The bedrock is locally fractured, gradationally weathered, and has solution channels.

The fork of an unnamed tributary of Schote Creek that contains Ash pond and the middle fork of this same unnamed tributary drain the raffinate-pits area and have both been determined to be losing streams that are hydraulically connected to Burgermeister spring. Water in Ash pond has a large uranium concentration ranging from 820 to 1,000 ug/L; a possible source may be contaminated soil that has washed into the pond. During periods of rainfall, the water in the pond may reach the altitude of the spillway. This contaminated water may then flow into local streams, and part or all of the surface flow is lost to the ground-water system. Part of this water may emerge at Burgermeister spring. Frog pond also has increased uranium concentrations (140 ug/L); however, water flowing from Frog pond does not enter a losing stream until it reaches Schote Creek downstream from August A. Busch Memorial Wildlife Area lake 36.

A 3-year water balance made on the four raffinate pits supported the conclusion that the 0.04 to 0.08 inch-per-day decrease in the water level of the pits could not be attributed to meteorological conditions (Bechtel National Inc., 1986). Water samples from observation wells completed in the bedrock near the raffinate pits indicate the ground water in the area has increased concentrations of calcium (900 mg/L), magnesium (320 mg/L), sodium (340 mg/L), sulfate (320 mg/L), dissolved solids (6,040 mg/L), nitrate (990 mg/L), lithium (1,700 ug/L), molybdenum (33 ug/L), and strontium (1,900 ug/L). Uranium in these wells generally were near background concentrations, except in two wells where the uranium concentrations were 49 and 86 ug/L (Kleeschulte and others, 1986). The uranium may be adsorbed onto clay particles in the glacial till, and therefore is not detected in concentrations comparable to that of the water in the raffinate pits or Burgermeister spring.

Water from Burgermeister spring has increased nitrate (54 mg/L), lithium (77 ug/L), and uranium (250 ug/L) concentrations, an indication of contamination from the chemical plant. Much of the uranium probably is transported to the spring from surface-water sources and losing streams, and nitrate and lithium probably enter the ground-water system near the raffinate pits. Surface-water flow into August A. Busch Memorial Wildlife Area lakes 34 and 36 has contaminated these lakes with radionuclides. Increased contents of uranium-238 also were detected in sediments of lake 34, 2 to 120 pCi/g; lake 35, less than 2 to 37 pCi/g; and lake 36, less than 2 to 94 pCi/g (Boerner, 1986).

The Weldon Spring quarry site is in fractured limestone on a bluff adjacent to the Missouri River alluvial flood plain. Water in the quarry sump contains large sulfate and uranium concentrations of 120 mg/L and 2,100 ug/L. Water samples in test wells in the limestone bluff and in observation wells in the alluvium north of the Femme Osage slough, indicate uranium has migrated southward from the quarry area. The wells with the largest uranium concentrations of 3,900 to 5,100 ug/L are opposite a large fracture zone in the bluff. Some of these wells are completed in bedrock, and some are completed in the alluvium.

In 1984, water samples from Femme Osage slough near the quarry had increased uranium concentrations of 77 ug/L. Water samples in the slough (Berkeley Geosciences Assoc., 1984) indicated the western section of the slough has a larger uranium concentration, 70 ug/L, than the concentration of 30 ug/L in the eastern section. Two possible sources of the radiologic contamination in the slough are pumpage of water from the quarry sump into Little Femme Osage Creek in the early 1960's or from migration of radioactive-contaminated ground water from the quarry through fractures in the bedrock. Water samples from south of the slough in the St. Charles County well field have been at or near background concentrations for uranium of 0.4 to 4.2 ug/L.

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