CONTAMINATION OF SOIL, SOIL GAS, AND GROUND WATER BY HYDROCARBON COMPOUNDS NEAR GREEAR, MORGAN COUNTY, KENTUCKY

By A. Gilliam Alexander, Douglas D. Zettwoch, and Michael D. Unthank, U.S. Geological Survey, and Robert B. Burns, Kentucky Natural Resources and Environmental Protection Cabinet, Division of Waste Management

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CONVERSION FACTORS, VERTICAL DATUM, AND MISCELLANEOUS ABBREVIATIONS

Multiply	By	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
gallon (gal)	3.785	liter

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

$$°F = 1.8(°C) + 32$$

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

Abbreviation	Definition
mL	milliliters

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ABSTRACT

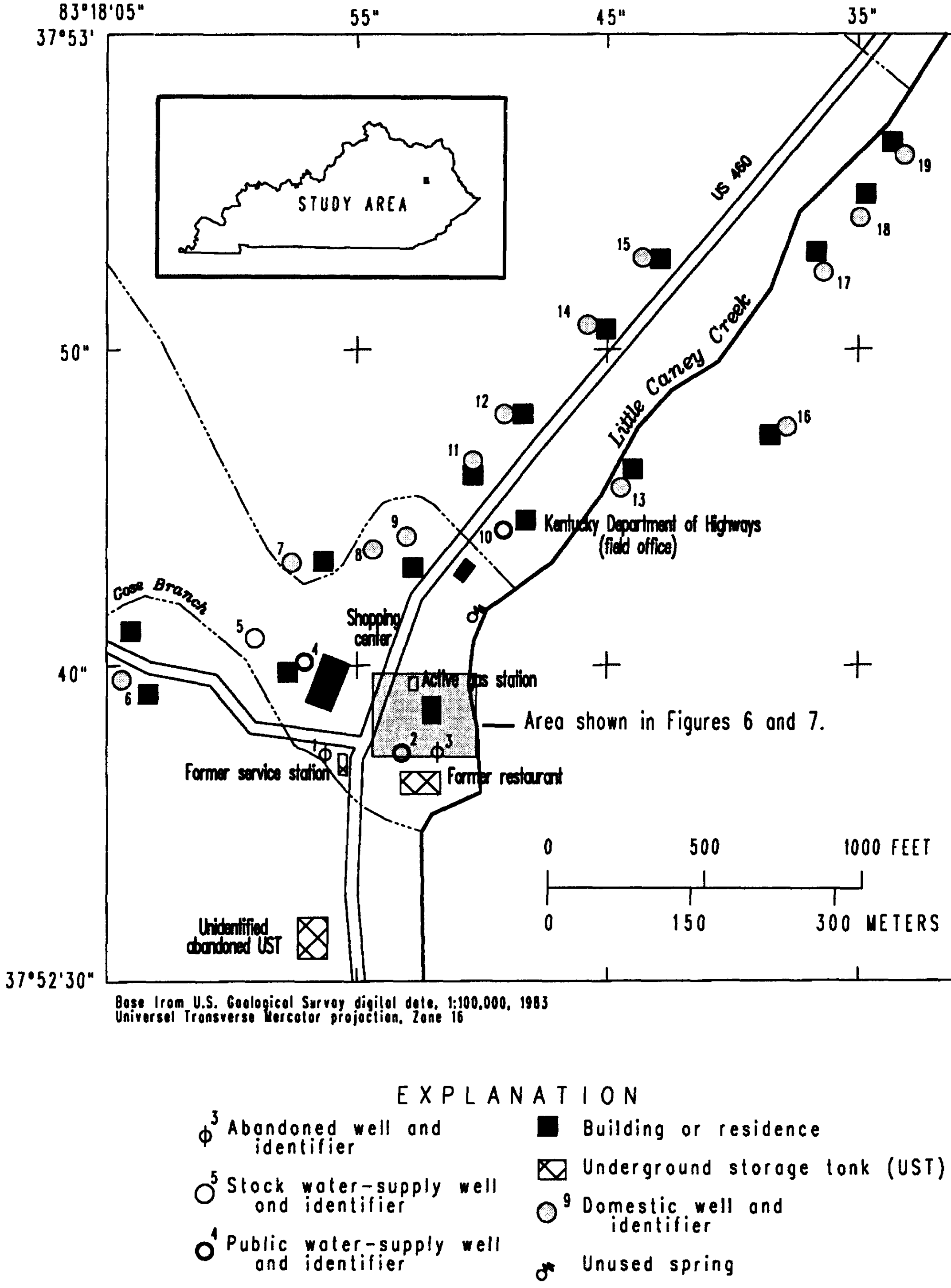
Concentrations of hydrocarbon compounds in ground water from the unconsolidated alluvium and bedrock formations near Greear, Ky., have resulted in the abandonment or restrictive use of several domestic and commercial water-supply wells. Laboratory analyses of water samples from area wells indicated levels of hydrocarbon compound contamination in excess of 1,000 times the U.S. Environmental Protection Agency's Maximum Contaminant Levels for benzene, toluene, and total xylenes.

Examination of the soil, soil gas, and ground-water resources of the study area determined a plume of hydrocarbon compound contamination in the unconsolidated alluvium at and around the active gasoline station. On-site analysis of soil-gas samples using a portable gas chromatograph at and around the gasoline station indicated concentrations of total volatile organic compounds as high as 134 parts per million. Laboratory analysis of water samples from monitor wells, installed during the investigation and screened in the unconsolidated alluvium, confirmed the presence of hydrocarbon compounds in the ground water. Concentrations of benzene (5,800 micrograms per liter) and ethylbenzene (810 micrograms per liter) exceeded the Maximum Contaminant Levels established by the U.S. Environmental Protection Agency. The detection of methyl-tertiary-butyl-ether, an octane-enhancing additive used in unleaded gasolines and only produced commercially since 1979, in several of the ground-water wells indicated that the source of the hydrocarbon compound contamination is associated, in part, with facilities that have stored, used, or spilled unleaded gasoline.

Migration of the hydrocarbon compounds from the alluvium into the bedrock aquifers was probably by natural percolation, induced infiltration caused by the pumping of area water-supply wells, and the mixing of petroleum products with ground water in the well bores during pumping.

INTRODUCTION

Ground water is the sole source of drinking water for the residents of Greear, Morgan County, in east-central Kentucky. Ground-water contamination was first documented in the Greear area in August 1988 when the Kentucky Natural Resources and Environmental Protection Cabinet received a complaint from the Kentucky Transportation Cabinet, Department of Highways, about the quality of water from the well (well 10, fig. 1) supplying its field office



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection, Zone 16

Figure 1.--Location of study area, wells, and underground storage tanks in Greear, Kentucky.

in Greear. Preliminary sampling of the well by the Kentucky Natural Resources and Environmental Protection Cabinet, Kentucky Division of Waste Management (KDWM), indicated the presence of hydrocarbon compounds commonly associated with petroleum products, such as gasoline.

In cooperation with the KDWM, the U.S. Geological Survey (USGS) investigated the extent and probable sources of the hydrocarbon compound contamination in the study area.

Purpose and Scope

The purpose of this report is to present the results of an investigation of hydrocarbon contamination near Greear, Ky. Specifically, the report describes the areal extent and migration of the hydrocarbon contamination in the soil, soil gas, and ground water in the study area. The report also includes a description of the hydrogeologic framework of the Greear area. The application and use of soil-gas surveys, and the on-site analysis of soil gases also are described.

Description of the Study Area

The study area includes the small town of Greear, Morgan County, in east-central Kentucky, approximately 4.5 mi south of the city of West Liberty (fig. 1). Greear is in a reach of the Little Caney Creek valley, in the Kanawha section of the Appalachian Plateaus physiographic province, commonly referred to as the Eastern Coal Field region of Kentucky (Quinones and others, 1981). The area is characterized by narrow, winding ridges and deep, steep-sided valleys. The study area lies in a valley approximately 800 ft above sea level and is bounded by ridges that rise 200 to 400 ft above the valley floor.

Greear consists of several residences, small businesses, and a field office of the Kentucky Transportation Cabinet, Department of Highways. The small businesses include a gasoline station/convenience grocery and a farm-equipment dealership.

The gasoline station is the only currently active business in the study area to report having petroleum products stored in underground storage tanks (UST's). The station uses three fiberglass tanks that were installed in 1986. Operating records maintained by the owner indicated no significant loss of gasoline from leakage or spillage from the tanks.

Several other UST's have been abandoned in the study area. Personnel from the Kentucky Transportation Cabinet, Department of Highways, indicated that three UST's were removed from south of the active gasoline station in 1982 during rerouting of U.S. Highway 460. According to area residents, this was the former site of a restaurant (fig. 1) and gasoline station which was in operation through the late 1950's. Reconnaissance of the study area by the KDWM discovered an abandoned UST west of U.S. Highway 460, across from the active gasoline station. Area residents indicated that this area was the former site of a service station that closed in the 1950's. Magnetometer surveys by the USGS and the KDWM of an area approximately 200-ft south of Gose Branch, west of U.S. Highway 460, indicated the possible location of another unidentified abandoned UST. Area residents confirmed that a grocery store had operated near this site and that it sold heating oil and possibly gasoline. Information on the period of operation of this store was not available, but it has been abandoned for approximately 20 to 25 years.

History of Ground-Water Contamination

Potential contamination problems in the study area were first documented in August 1988 when the Kentucky Transportation Cabinet, Department of Highways, filed a complaint about the quality of water from the well supplying its field office in Greear (well 10, fig. 1). An additional complaint was filed by the owner of well 7 (fig. 1). Preliminary analyses of samples collected from wells 7 and 10 by the KDWM indicated the presence of hydrocarbon compounds commonly associated with petroleum products, such as gasoline. Subsequent sampling by the KDWM revealed that four additional domestic water-supply wells were similarly contaminated.

Well 3 (fig. 1) had previously supplied the gasoline station with potable water but was no longer used because of taste and odor problems. The gasoline station now uses well 2 for its water supply.

On the basis of these results and information, the KDWM initiated a preliminary investigation to determine if active or abandoned UST's were the source of the contamination. Background information was obtained from several sources, including other State agencies, area residents, inventory records of active UST facilities, and tank-installation data.

An abandoned UST was successfully removed from the study area in May 1989 by the Kentucky Transportation Cabinet, Department of Highways. The 550-gal UST at the site of the former service station was badly corroded and pitted. A sample of the liquid remaining in the tank indicated the presence of benzene, toluene, ethylbenzene, xylenes, trimethylbenzenes, and naphthalene, all of which are common constituents of gasoline (table 1). Excavated soils had no noticeable odor and did not register on field organic-vapor detection instruments. Soil samples were collected from the bottom of the excavation basin. Perched water, at a depth of approximately 7 ft, also was sampled. Results of the soil and water sample analyses, done by the Kentucky Division of Environmental Services, indicated no constituents associated with gasoline above limits of detection.

Table 1.--Common constituents of a full-range motor gasoline

[U.S. Environmental Protection Agency, 1975]

Chemical constituent	Composition, by percent weight
Benzene	0.81
Toluene	12.2
Ethylbenzene	1.7
Xylenes (total)	1.58
Isopropyl benzene	.1
n-Propyl benzene	.24
1,3,5- Trimethyl benzene	.39
1,2,4- Trimethyl benzene	1.61
sec- Butyl benzene	.01
Isopropyl toluene	.03
Naphthalene	.1

HYDROGEOLOGIC FRAMEWORK

The Greear area is underlain by unconsolidated alluvial deposits of Quaternary age and rocks of Lower and Middle Pennsylvanian age. Strata are relatively flat lying with no major structural features. The Little Caney coal bed of the Breathitt Formation crops out in parts of the study area and is used as a marker bed. A generalized stratigraphic column is shown in figure 2.

Because all wells in the study area are dug or drilled to depths of 250 ft or less, only the near-surface geology is discussed in this report. Bedrock is overlain by unconsolidated Quaternary alluvium. Bedrock consists of shales, sandstones, siltstones, and limestones of the Breathitt Formation and shales and sandstones of the Lee Formation. Ground water is present in unconsolidated alluvial material and in bedrock.

Alluvium

Throughout the study area, bedrock is overlain by a mantle of unconsolidated alluvium of Quaternary age. Thirty soil borings made during the investigation reveal that the alluvium is mostly unconsolidated silt and clay with small amounts of sand and gravel and is 8 to 30 ft thick.

Water is present in intergranular openings in the alluvium. Shallow, hand-dug wells finished in these sediments can supply enough water for most domestic uses. Ground-water flow is affected by local variations in the character of the unconsolidated material and bedrock topology. The direction

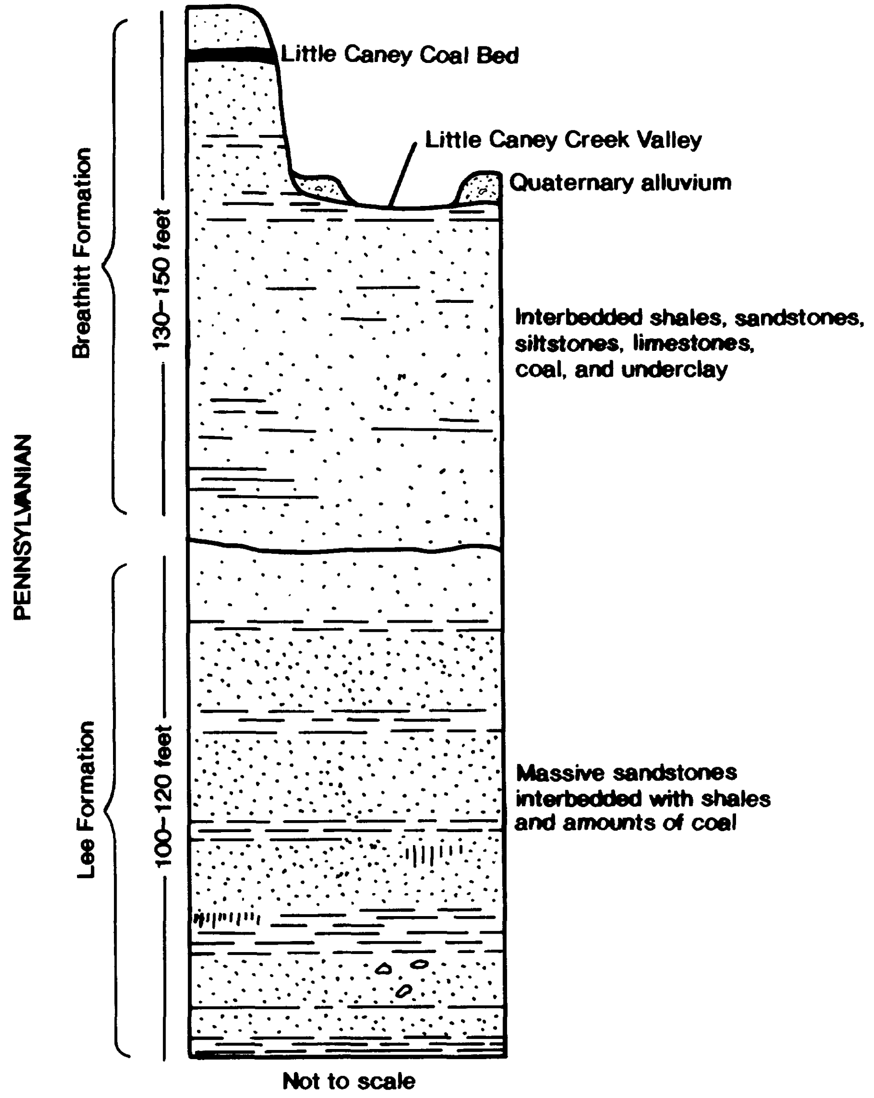


Figure 2.--Generalized stratigraphic column for east-central Kentucky in the area near Greear.

of flow is generally from the valley edges toward Little Caney Creek. Recharge to the unconsolidated material comes directly from precipitation, infiltration of the surface waters, and seepage from the underlying Breathitt Formation (Price, 1956, p. 60).

Breathitt Formation

The Breathitt Formation underlies the alluvium and crops out in road cuts and along the valley walls. The Breathitt Formation consists of interbedded shales, sandstones, siltstones, limestones, and thin coal seams. Well drillers report that the Breathitt Formation is approximately 130 to 150 ft thick in the study area.

Most ground water in the Breathitt Formation is present in openings in the rocks such as joints, fractures, and bedding-plane partings. Wells completed in this formation are usually productive if they intercept a large number of such water-bearing openings (Price, 1956, p. 35).

For this study, nine wells that obtain water solely from the Breathitt Formation were inventoried. The location of each well and altitude of water levels are shown in figure 3. Additional data resulting from the well inventories are listed in table 2.

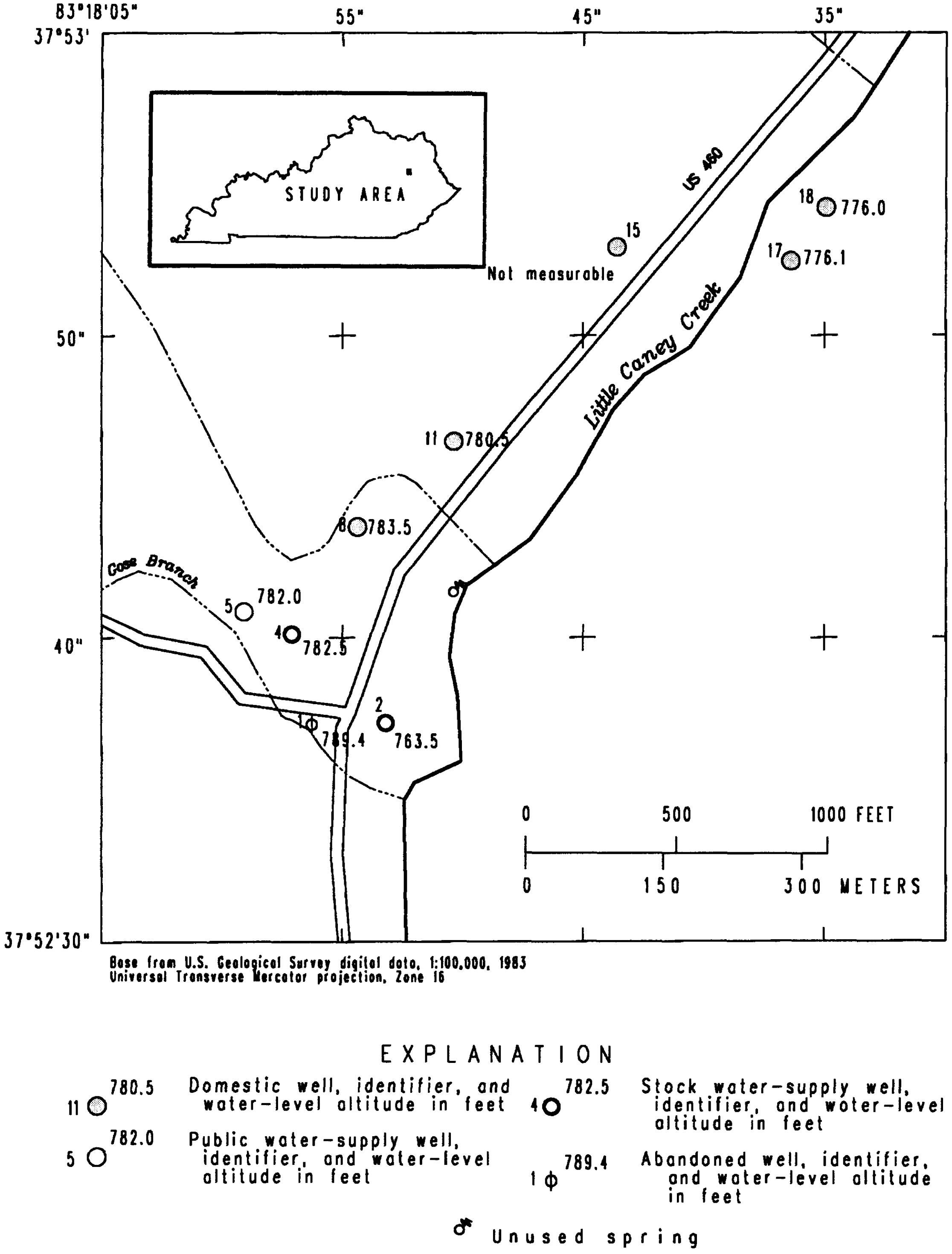
Lee Formation

The Lee Formation is the deepest formation that provides water to existing wells in the study area. The Lee Formation consists primarily of massive sandstones interbedded with minor amounts of shale and coal. A massive sandstone is reported in most drillers' logs as a "white sand." It is typically quartzose and conglomeratic with scattered well-rounded quartz pebbles (Price and others, 1962). Wells as deep as 250 ft do not penetrate the basal units of the formation, indicating that the Lee Formation is at least 100 to 120 ft thick in the study area.

As with the Breathitt Formation, most ground water in the Lee Formation is found in joints, fractures, and bedding-plane partings. According to local drillers, the Lee Formation yields the largest amounts of potable water to drilled wells in the area. The productivity of the Lee Formation is probably due to the increased permeability associated with the massive and in places conglomeratic sandstones of the formation (Price and others, 1962). For this study, five wells that obtain water from the Lee Formation were inventoried (fig. 4 and table 2).

STUDY APPROACH

When released in the subsurface, hydrocarbon compounds, such as gasoline partition between the solid (soil), vapor (soil gas), and aqueous (ground water) phases (Marks and Singh, 1990). Therefore, examination of all three phases was required to delineate the extent of subsurface hydrocarbon compound contamination in the study area. Research has also revealed that field



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection, Zone 16

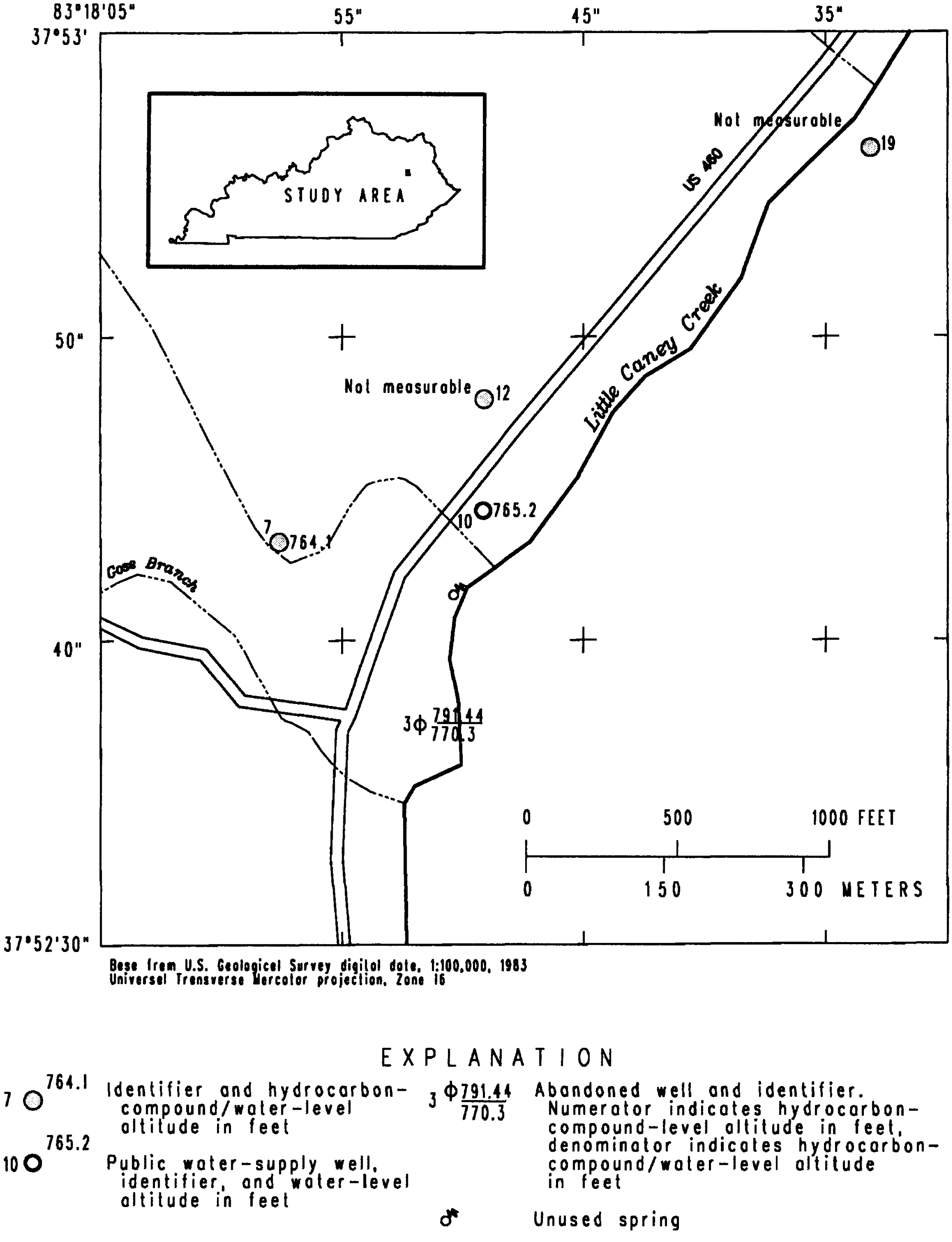
Figure 3.--Altitudes of water levels in wells completed in the Breathitt Formation in Greear, Kentucky.

Table 2.--Selected data for wells in Greear, Kentucky

[LSD, land-surface datum; --, no information available; R, reported value; water-level measurements are in feet above sea level]

Well number	Land-surface datum	Depth of well below LSD	Water level below LSD (07-25-89)	Altitude of water level (07-25-89)	Deepest formation penetrated
1	804.94	91.9	15.56	789.38	Breathitt
2	799.85	--	36.68	763.17	Breathitt
3	800.12	127.5	[a]8.68	791.44	Lee
3	800.12	127.5	29.8	770.3	Lee
4	807.86	--	25.40	782.46	Breathitt
5	818.79	115	36.8	782.0	Breathitt
6	--	--	--	--	--
7	826.25	250	62.18	764.07	Lee
8	804.08	73	20.57	783.51	Breathitt
9	803.68	22	4.5	799.2	Alluvium
10	796.77	110R	31.54	765.23	Lee
11	797.29	--	16.8	780.5	Breathitt
12	--	115R	--	--	Lee
13	--	--	--	--	--
14	--	--	--	--	--
15	--	60R	--	--	Breathitt
16	807.84	23	9.0	798.8	Alluvium
17	790.67	75	14.6	776.1	Breathitt
18	788.83	45	12.8	776.0	Breathitt
19	--	200R	--	--	Lee

[a] Petroleum product observed in well; level reported is that of the product and not the depth to ground water.



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection, Zone 16

Figure 4.--Altitudes of water and hydrocarbon-compound levels in wells completed in the Lee Formation in Greear, Kentucky.

screening for benzene, toluene, and total xylenes (BTX) compounds can successfully be used to delineate the presence of such hydrocarbon compounds for the following reasons:

1. The aromatic BTX compounds are common constituents of fuel hydrocarbons.
2. BTX compounds have a high water solubility and, thus, tend to partition preferentially into the aqueous phase rather than into the vapor phase.
3. As nonaromatic constituents of hydrocarbons eventually diffuse into the atmosphere in the vapor phase, the mass of the aromatic BTX compounds relative to the nonaromatic compounds increases (Baehr, 1987).

Field studies began in July 1989 with a reconnaissance survey and well inventory and were completed in May 1990. During this investigation, semiquantitative field screening of soil gas, headspace gas from soil samples, and water samples by means of a portable gas chromatograph (PGC) was done to (1) determine the extent of any areas where BTX compounds were present, and (2) select soil and water samples for quantitative analysis for the volatile organic compounds (VOC's) listed in table 1. The analyses were made by the USGS National Water Quality Laboratory in Arvada, Colo.

Soil Sampling, Screening, and Analysis

Soil samples were collected for field screening and laboratory analysis. The depth at which soil samples were collected was based on the depth to saturated soils and bedrock at each site. The target zone for soil sampling was the 2-ft interval directly above saturated soil. At selected sites where hydrocarbons were present, soil samples were collected from two horizons--one in the unsaturated soil and another in the deeper, saturated soil--to determine if a concentration gradient of hydrocarbon compounds was present.

Soil borings were made by use of a truck-mounted auger-drill rig. Each borehole was drilled by use of a 4-in. outside-diameter (O.D.) solid-stem auger flight to the desired depth above bedrock. The augers were then removed and a split-spoon sampler (24-in. long, 1.5-in. inside diameter (I.D.)) attached to the proper length of A-rod was lowered into the open hole. After the bottom of the hole was reached, the split spoon was advanced by hydraulic pressure to the desired sampling depth or to the top of bedrock. If bedrock was reached before a sufficient volume of soil could be collected, an adjacent hole was augered to an adjusted depth to enable the collection of an adequate sample volume.

For samples to be screened by the PGC, a section of the soil core was immediately removed from the split-spoon sampler with stainless-steel utensils and placed in a 120-mL borosilicate glass jar fitted with a Teflon septum cap. The jar was brought to a temperature of approximately 30 °C and allowed to stabilize for at least 20 minutes. A 1.0-mL sample of the gas in the headspace above the soil sample was withdrawn and injected into the PGC by use of a gas-tight glass syringe. Compounds were tentatively identified by comparison of instrument response to the retention time of a prepared BTX standard at the same temperature.

On the basis of results from the field screening, soil samples were collected for laboratory analysis as described above except that 6-in. lengths of stainless-steel liners were inserted into the split-spoon sampler. Use of the liners enabled the removal of an undisturbed sample, which was immediately capped with Teflon tape and plastic end caps, chilled, and shipped by overnight delivery to the USGS laboratory. Samples were prepared and analyzed according to U.S. Environmental Protection Agency (USEPA) method SW8240, gas chromatograph/mass spectrometer analysis for VOC's in solid-waste matrices with medium levels of contamination (U.S. Environmental Protection Agency, 1983). An estimation of the practical quantification limit is 75 milligrams per kilogram for the target compounds listed in table 1 (D.L. Rose, U.S. Geological Survey National Water Quality Laboratory, written commun., 1990).

To prevent cross-contamination, field personnel thoroughly steam cleaned all drilling equipment before the start of soil boring, between borings, and after each day of field work. Before the collection of soil samples for field screening or laboratory analysis, the split-spoon sampler and stainless-steel liners (when used) were thoroughly decontaminated; equipment was washed with laboratory-grade detergent and tap water, rinsed first with deionized water, then with hexane, and allowed to air dry.

Quality assurance and quality control (QA/QC) measures included the analysis of duplicate soil samples, equipment blanks, spiked samples, and standards to ensure proper analytical technique and operation of the PGC and to detect any cross-contamination. Duplicate samples were analyzed to ensure that proper analytical procedures were maintained and cross-contamination was not occurring. Likewise, spiked samples--water blanks contaminated with 1 mL of regular-grade gasoline--were analyzed each day. Standards were analyzed periodically to ensure calibration of the PGC throughout the analyses. Changes in breakthrough times--the time required for the volatilization of compounds--for the BTX compounds were documented.

Soil-Gas Sampling and Screening

Soil-gas surveys--the sampling of gases contained in the voids between soil particles--can be an effective means of quickly identifying areas of hydrocarbon contamination. The effectiveness of the investigative technique, however, is limited by the characteristics of the soil matrix, such as mineral content, clay content, moisture content, and permeability (Devitt and others, 987). Therefore, an initial assessment of soil-gas sampling to determine its feasibility as an investigative tool in the study area was done before the technique was used.

The soil-gas sampling system consists of a collection probe, fitting, vacuum hose, electric vacuum pump, pressure gage, septum, and syringes. The collection probe is constructed of stainless steel with threaded components including a drive point, a slotted screen (12-in. long, 0.5-in. O.D., 0.25-in. I.D.), and extension rods (30-in. long, 0.5-in. O.D., 0.25-in. I.D.). The number of extension rods used is based on the desired sampling depth. A stainless-steel, threaded four-way fitting that accommodates a vacuum-pump hose, a vacuum gage, and a septum is screwed into the uppermost extension rod. The vacuum pump supplies the necessary suction to draw soil gases through the probe, the vacuum gage monitors the pressure exerted by the vacuum pump, and the septum provides a sampling point for the collection of soil gases by use of syringes before soil gases come in contact with the vacuum hose or pump.

To sample soil gas, the field technician drives the collection probe into the soil to the desired sampling depth by use of an electric roto-hammer. A vacuum is applied using the vacuum pump. The soil-gas sampling system must initially be tested by closing a shutoff valve on the vacuum hose side of the four-way fitting, which keeps the system pressurized. The vacuum pump is then shut off, and the system is checked for leaks by monitoring the pressure. A sustained reading of elevated pressure indicates the integrity of the sampling system. If the system fails to maintain an elevated pressure, the probe may need to be repositioned or reinserted. Once the system is proven airtight, the valve is opened, and the system is purged by evacuation of the probe for 1 to 2 minutes.

After system evacuation, a volume of soil gas is withdrawn by a 1-mL gas-tight glass syringe equipped with a Teflon locking device that is inserted into the septum. Two soil-gas samples were collected at each sampling location to ensure reproducibility and validity of the sampling procedure and field analysis. Each soil-gas sample was allowed to stabilize at approximately 20 °C, and the sample was then injected into the PGC. Compounds were tentatively identified by a comparison of instrument response to the retention time of a prepared BTX standard at the same temperature. Calculations of benzene concentrations, in parts per million, were normalized to the response of the PGC to a benzene standard at the time of analysis.

Before each sampling, the soil-gas collection probe, fitting, and septum were thoroughly decontaminated; equipment was washed with laboratory-grade detergent and tap water, rinsed first with deionized water and then with hexane, and allowed to air dry.

QA/QC measures, as outlined for soil sampling, included the analysis of duplicate soil-gas samples, equipment blanks, spiked samples, and standards to ensure proper analytical technique and operation of the PGC and to detect any cross-contamination.

Monitor-Well Construction

Shallow ground-water monitor wells were installed by use of the truck-mounted auger rig equipped with hollow-stem augers (3.75-in. I.D. and 7-in. O.D.). The boreholes were augered to refusal in bedrock. The nature of the unconsolidated material above the bedrock was noted during augering. Threaded, flush-jointed casing and well screen (2-in. I.D.), constructed of stainless steel, were installed inside the auger stem. The threaded joints enabled well construction without the use of glues. The slot size of the screen was 0.010 in. The screened interval extended upward from the bedrock contact to include the anticipated vertical extent of the shallow aquifer at each well site, thus enabling the sampling of hydrocarbons that may be floating on the ground-water surface. The minimum screen length was 2.5 ft. A filter pack of clean, inert silica sand was inserted (tremied) from the bottom of the borehole to approximately 2 ft above the top of the well screen. As the augers were removed, a 2-ft thick bentonite seal was placed on top of the filter pack, and the remainder of the hole was filled with a cement-bentonite grout to a point just below the top of casing. A 6-in. I.D. cast-iron well protector was placed over the casing, and a concrete surface pad was poured around the protector to finish the well at land surface. A watertight, lockable well cap was placed on the well to prevent surface-water infiltration and tampering. Diagrams of each shallow well installed during the study (figs. 13 and 14) are provided in the "Supplemental Data" section of this report.

Before sampling, the monitor wells were developed by pumping until the discharged ground water appeared clear. Water levels, temperature, and specific conductance were measured and recorded before and after the development of each well. After development, water levels in the wells were allowed to stabilize for at least one day before measuring and sampling.

To prevent cross-contamination, field personnel thoroughly steam cleaned the drill rig, augers, and other tools before the start of well drilling, between boreholes, and after each day of field work. The well screens and casings were thoroughly decontaminated; equipment was washed with laboratory-grade detergent and tap water, rinsed first with deionized water and then with hexane, and allowed to air dry before installation.

Ground-Water Sampling, Screening, and Analysis

Ground-water samples were collected for field screening and laboratory analysis. When samples were collected from a well used for a water supply, the water-supply system was initially purged for at least 15 minutes or until the water temperature and specific conductance had stabilized. Newly constructed monitor wells were purged by use of a peristaltic pump equipped with disposable Tygon tubing, were allowed to recover, and were sampled with a stainless-steel bailer. The monitor wells were purged of three well volumes of water before a sample was collected. The existing wells not equipped with a pump were sampled with a disposable polyvinyl-chloride bailer suspended from a disposable nylon cord by which an unpurged or "grab" sample was collected. The ground-water sample was then collected by overfilling a 40-mL amber vial with a Teflon septum cap, which prevented the entrapment of air in the sample and minimized volatilization losses. A wet-weather spring in the study area was sampled upstream from its confluence with Little Caney Creek by overfilling and capping a 40-mL amber vial.

Preservation of water samples for field screening was unnecessary because of the limited holding time (approximately 30 minutes) between sample collection and PGC analysis. After the sample was collected, the target constituents (BTX) were extracted by means of an organic solvent; 10 mL of sample were removed with a clean syringe and replaced with an equal volume of hexane. The vial was then agitated to ensure proper mixing and then allowed to stabilize for a minimum of 10 minutes at ambient temperature. A clean syringe was used to remove 1.0 mL of the organic-phase extract from the vial, which was then injected into the PGC.

Ground-water samples collected for laboratory analysis were preserved with the addition of 1 mL of hydrochloric acid and 10 mL of ascorbic acid. This procedure required that the vials be opened after sample collection, which increased the potential for volatization of organic compounds and sample degassing. All samples were placed in plastic storage bags, chilled on ice, and shipped by overnight delivery to the laboratory for VOC analysis.

To prevent cross-contamination, field personnel thoroughly decontaminated any reused stainless-steel bailers; equipment was washed with laboratory-grade detergent and tap water, rinsed first with deionized water and then with hexane, and allowed to air dry. Teflon cords were not reused.

QA/QC measures, as outlined for soil sampling, included the analysis of duplicate ground-water samples, equipment blanks, spiked blanks, and standards to ensure proper analytical technique and operation of the PGC and to detect any cross-contamination.

Surface-Water Sampling and Screening

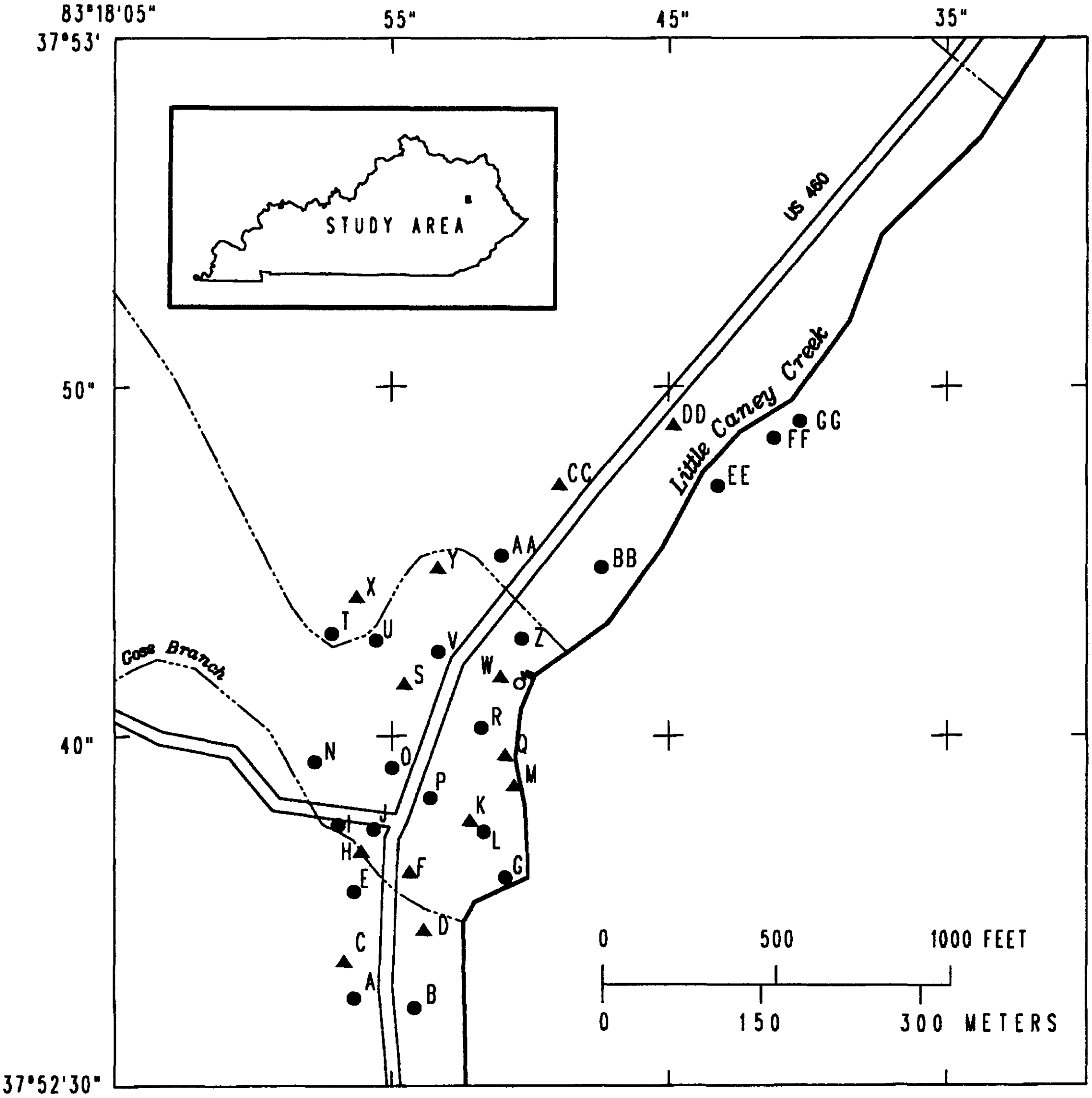
Surface-water samples were collected from Little Caney Creek throughout its reach in the study area to determine if hydrocarbon compounds might be discharging to the creek from the alluvium. All samples were screened in the field for BTX compounds by use of the PGC. Screening procedures were the same as those described for ground-water samples. All results were negative, and no further discussion of surface-water quality is presented in this report.

CONTAMINATION BY HYDROCARBON COMPOUNDS

As stated in the study approach, hydrocarbon compounds partition between the solid (soil), vapor (soil gas), and aqueous (ground water) phases when released in the subsurface. An examination of all three phases was necessary to delineate the extent of subsurface hydrocarbon compound contamination in the study area.

Soil

Soil sampling was done to aid in the determination of the areal extent and possible source(s) of the hydrocarbon contamination and to determine if hydrocarbons were migrating toward the deeper formations. Samples were collected from soil borings at 33 different sites throughout the study area (figs. 5 and 6). The distribution and location of soil borings were based on results from the initial field screening of ground-water samples from existing wells, the location of wells that had reportedly produced water contaminated with hydrocarbons, the location of potential hydrocarbon sources, and the need for background data.



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection, Zone 16

EXPLANATION

▲ F Soil-boring sample and identifier analyzed with a portable gas chromatograph

● A Soil-boring sample and identifier analyzed by the United States Geological Survey National Water-Quality Laboratory

♂ Unused spring

Figure 5.--Soil-sampling sites, Greear, Kentucky.

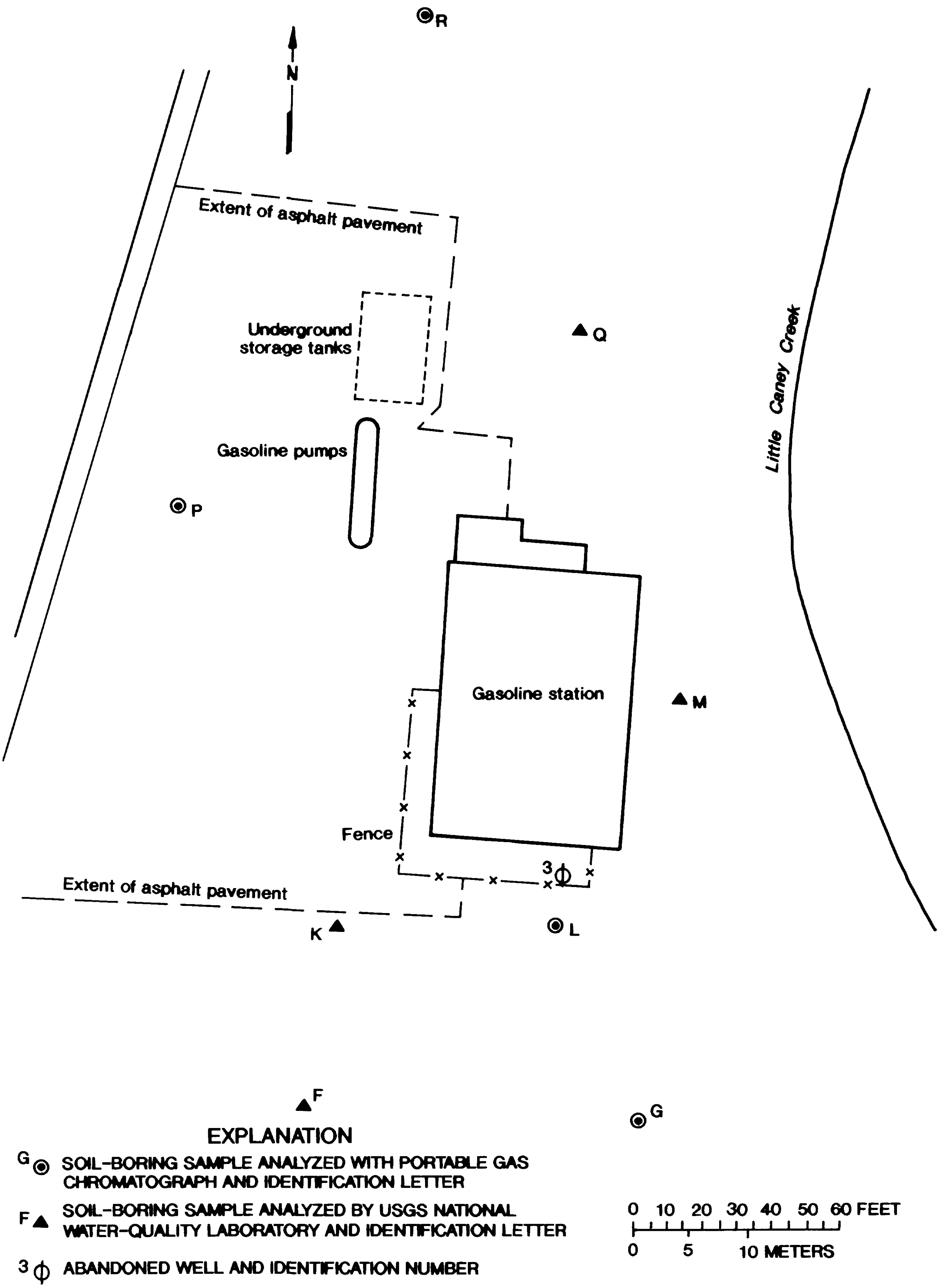


Figure 6.--Soil-sampling sites near active gasoline station.

Soil samples from 20 sites were initially screened in the field for BTX compounds. Only one sample screened positive; the sample was collected from the soil boring at site L (sample B collected from a depth interval of 10.2 to 10.6 ft) (fig. 6). Bedrock at this site was 10.6 ft below land surface, and soils were saturated with water in the bottom 0.2 ft of the boring. Soil samples from 13 other sites were analyzed in the laboratory for VOC's. Several of the soil samples were collected near site L, the boring site that screened positive for BTX. The samples were collected at similar depths (10.2 to 10.6 ft); however, none of the samples analyzed in the laboratory contained detectable concentrations of VOC's.

Soil Gas

The feasibility of using soil-gas surveys as a screening method to identify areas of hydrocarbon contamination was tested in the immediate vicinity of well 3 (fig. 1). On July 19, 1989, a discernible hydrocarbon layer was present in the well. The immediate area around well 3 also included the soil sample from site 12 that had screened positive for the presence of BTX compounds. The soil-gas survey began near well 3 and continued radially outward with seven samples collected at sites that ranged from 2 to 125 ft from well 3 (fig. 7). All but the most distant sample (SV 7) indicated the presence of several BTX compounds in the soil gas.

After the feasibility of soil-gas surveys in the study area was proven, 63 additional soil-gas samples were collected in three focused areas (fig. 8)--an area at and around well 7, an area at and around a reportedly abandoned UST, and an area at and around the active gasoline station. The selection of the sampling depth at each site was based on the physical character of the site, such as the depth to bedrock, the depth to saturated soils, and the physical character of the soil matrix. The target zone for sampling was a 1- to 2-ft interval of unsaturated soil immediately above the water table in the alluvium. At selected sites where BTX compounds were determined to be present, soil-gas samples were collected from two horizons--one in the unsaturated soil and another in the deeper saturated soil--to determine if a concentration gradient of BTX compounds was present.

A soil-gas survey was done near well 7 because the well water was known to contain hydrocarbon compounds even though it did not contain a discernible floating hydrocarbon layer in the well. This well produces water from the Lee and Breathitt Formations. Six sample points were selected from 5 to 10 ft from the well with sampling depths ranging from 5.5 to 7.3 ft. Results of screening with the PGC were negative. The negative results indicated that the unconsolidated material near the well was not a source of hydrocarbon contamination in the well.

A soil-gas survey also was done in the area of a reportedly abandoned UST in the southern part of the study area. A magnetometer survey confirmed the presence of a small buried tank (500 gal or less). Several area residents reported that the tank was last used to store heating oil--and, possibly, gasoline--20 to 25 years ago at a small grocery store. Eight soil-gas sampling points were selected in a grid ranging from 7 to 20 ft from what was

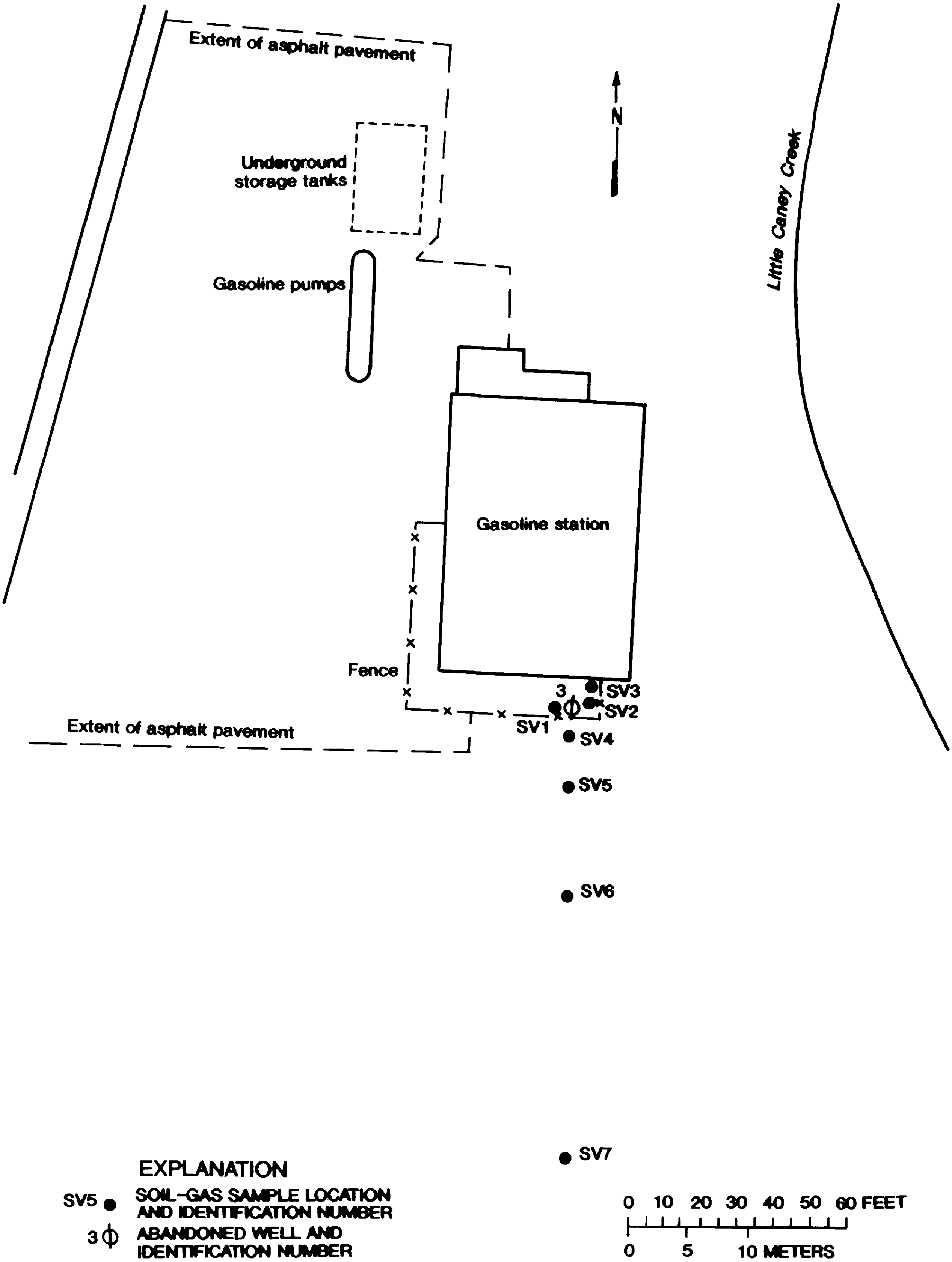
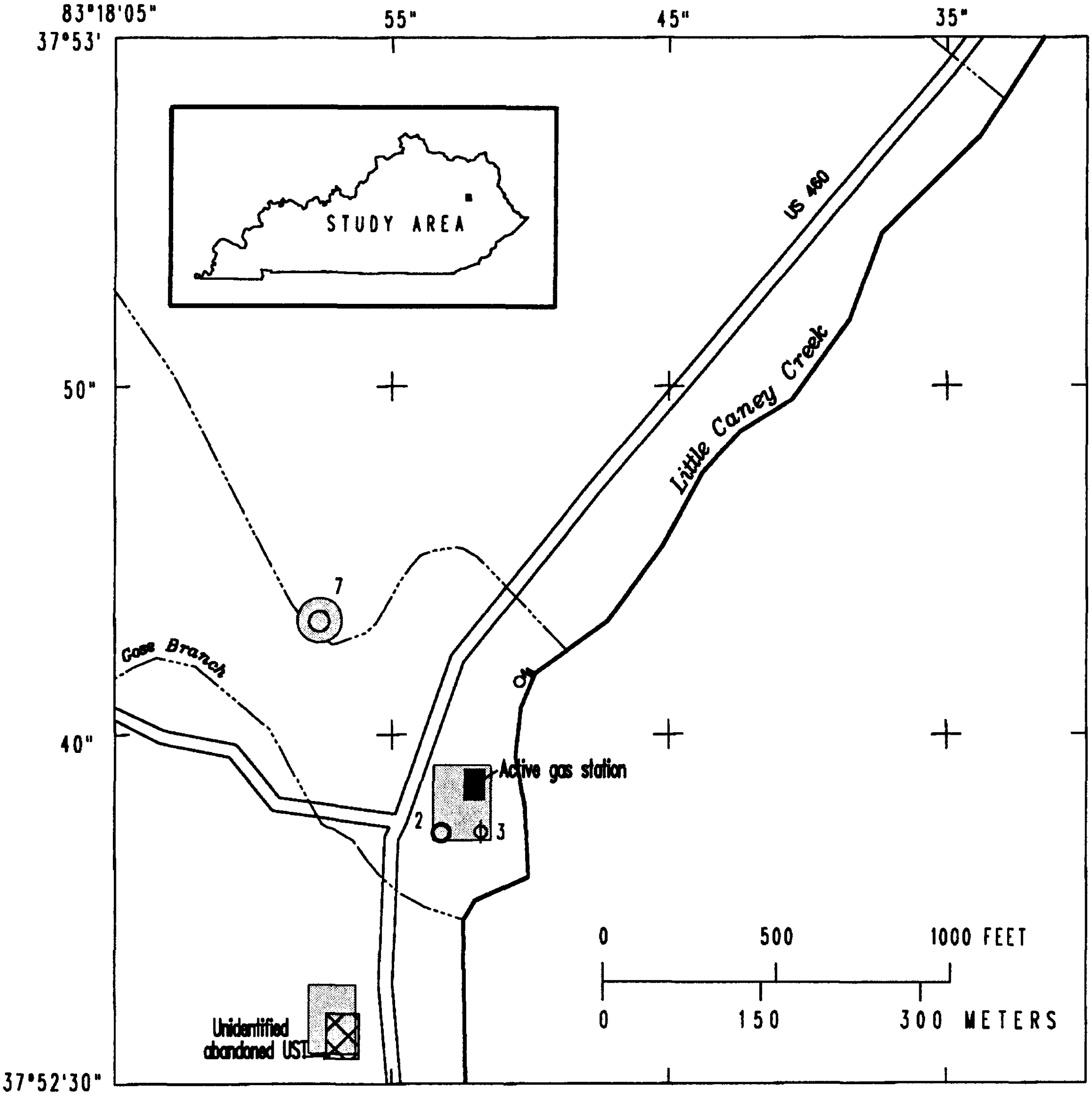


Figure 7.--Soil-gas sampling sites near well 3.



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection, Zone 16

EXPLANATION

▨ Area of soil-gas survey

ϕ 3 Abandoned well and identifier

○ 2 Public water-supply well and identifier

◎ 7 Domestic well and identifier

♂ Unused spring

Figure 8.--Soil-gas survey areas, Greear, Kentucky.

thought to be the center of the abandoned UST. Sample-collection depths ranged from 3.8 to 5.5 ft below land surface. All samples screened negative for the presence of BTX compounds.

An extensive soil-gas survey was done in the area of the active gasoline station. The presence of a discernible hydrocarbon layer in well 3 and the results of the soil-gas method assessment near the well warranted an extensive survey. Sampling was done under similar weather conditions during the 5 days of the survey to minimize the effects of temperature and barometric pressure on the volatilization of the VOC's in the unsaturated zone. In addition, an attempt was made to compensate for the variation of concentration gradients resulting from differences in soil-matrix characteristics and physical features (paved as opposed to graveled surfaces). Sampling depths ranged from 4.5 to 7.0 ft depending upon site characteristics. The location of soil-gas sampling sites and the results from the PGC screening, reported as total VOC's, in parts per million, are shown in figure 9.

The soil-gas survey began in the vacant lot north of the gasoline station with three east-west transects (sampling sites 1-12, fig. 9). PGC screening revealed that several of the samples contained low concentrations of unidentified VOC's, and, except for the sample from site 11, did not contain BTX compounds. The sample from site 11 contained BTX and other unidentified organic compounds (fig. 10). A possible explanation for the presence of the unidentified organic compounds in the samples is that they were collected near the approximate location of the septic tank leach field for the gasoline station.

Additional soil-gas survey transects were done in a north-south orientation on both sides of the gasoline-station building. The highest concentrations of BTX compounds were measured near the UST installations, the delivery system to the gasoline pumps, and around well 3, which produces water from the Lee and Breathitt Formations. Example chromatograms for samples from these two areas also are shown in figure 10. The location of the two areas of high BTX concentrations, the apparent trend of increased concentration, and the discernible hydrocarbon layer in well 3 indicate that high levels of hydrocarbons are present in the alluvium and in the ground water from the bedrock formations in this area.

Ground Water

Early in the investigation, a field-reconnaissance/well-inventory survey was done to locate existing wells, assess typical well-construction practices, collect selected water-quality data, and evaluate the physical characteristics of the study area. Nineteen existing wells were inventoried (figs. 3 and 4). In addition, a wet-weather spring discharging to Little Caney Creek was identified. Nine of the wells were accessible, and the depth of each well and ground-water level were measured. Only some of the desired data could be collected from the other 10 wells. The deepest geologic formation exposed in the open well bore was determined for each well by use of a published geologic map (Englund and others, 1967) and measured or reported well depth (table 2).

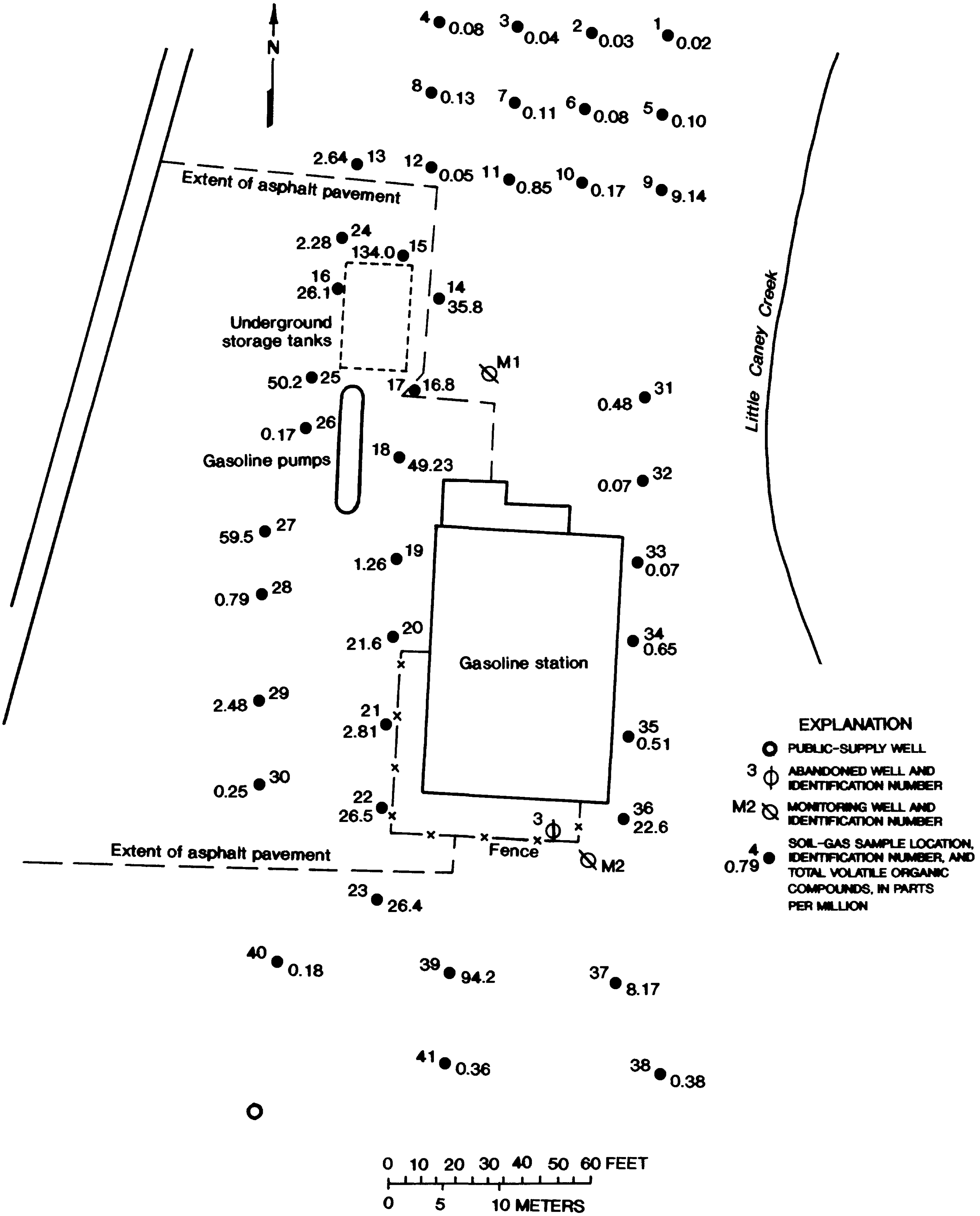


Figure 9.--Soil-gas sampling sites, existing wells, monitor wells, and concentrations of total volatile organic compounds measured near the active gasoline station, Greear, Kentucky.

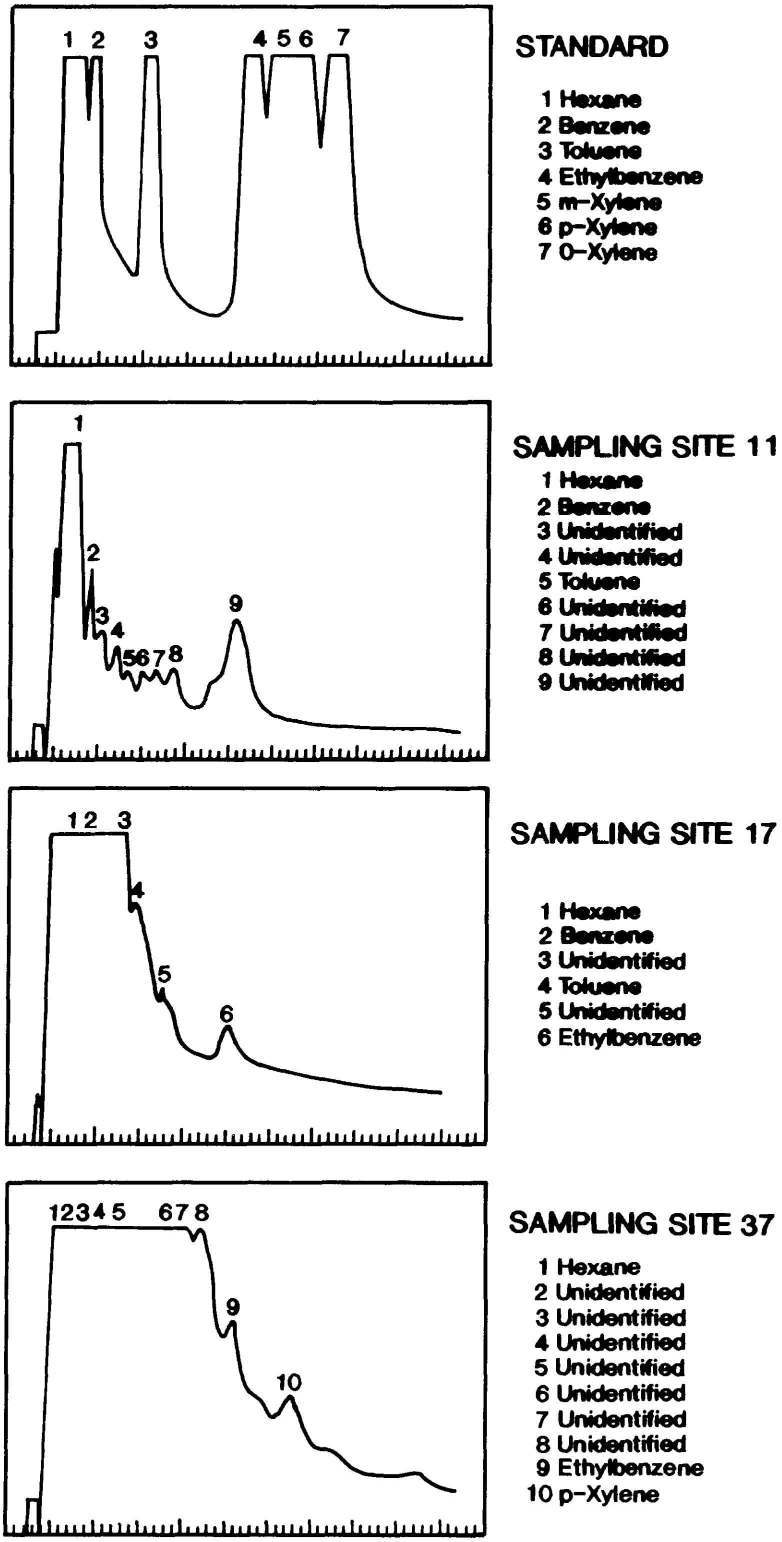


Figure 10.--Example chromatograms from analysis of soil gas near the active gasoline station by use of a portable gas chromatograph.

Alluvium

Water samples collected from two hand-dug alluvial wells (wells 9 and 16) and the wet-weather spring were initially screened in the field by use of the PGC (fig. 11). Results of the field screening indicated no BTX contamination in the two wells; the wet-weather spring tested positive for the presence of BTX compounds. Laboratory analysis of additional water samples collected from the wet-weather spring revealed that concentrations of several VOC's exceeded Maximum Contaminant Levels (MCL's) established by the USEPA (table 3).

Soil and soil-gas sampling revealed BTX contamination in the area surrounding the gasoline station. Further confirmation and information on contaminant transport was obtained by the sampling of two shallow monitor wells (M1 and M2) installed near the areas of high BTX concentrations (fig. 9). Well M1 was installed between the active UST's and Little Caney Creek and M2 was installed southeast of well 3. The wells were developed and altitudes of water levels were measured on February 12, 1990. The altitude of the water level in M1 was 792.06 feet above sea level; the altitude of the water level in M2 was 791.67 feet above sea level. The screening and laboratory analysis of ground-water samples collected from monitor wells M1 and M2 indicated the presence of BTX compounds (fig. 12 and table 4). Concentrations of benzene and ethylbenzene in the sample from well M2 exceeded MCL's established by the USEPA.

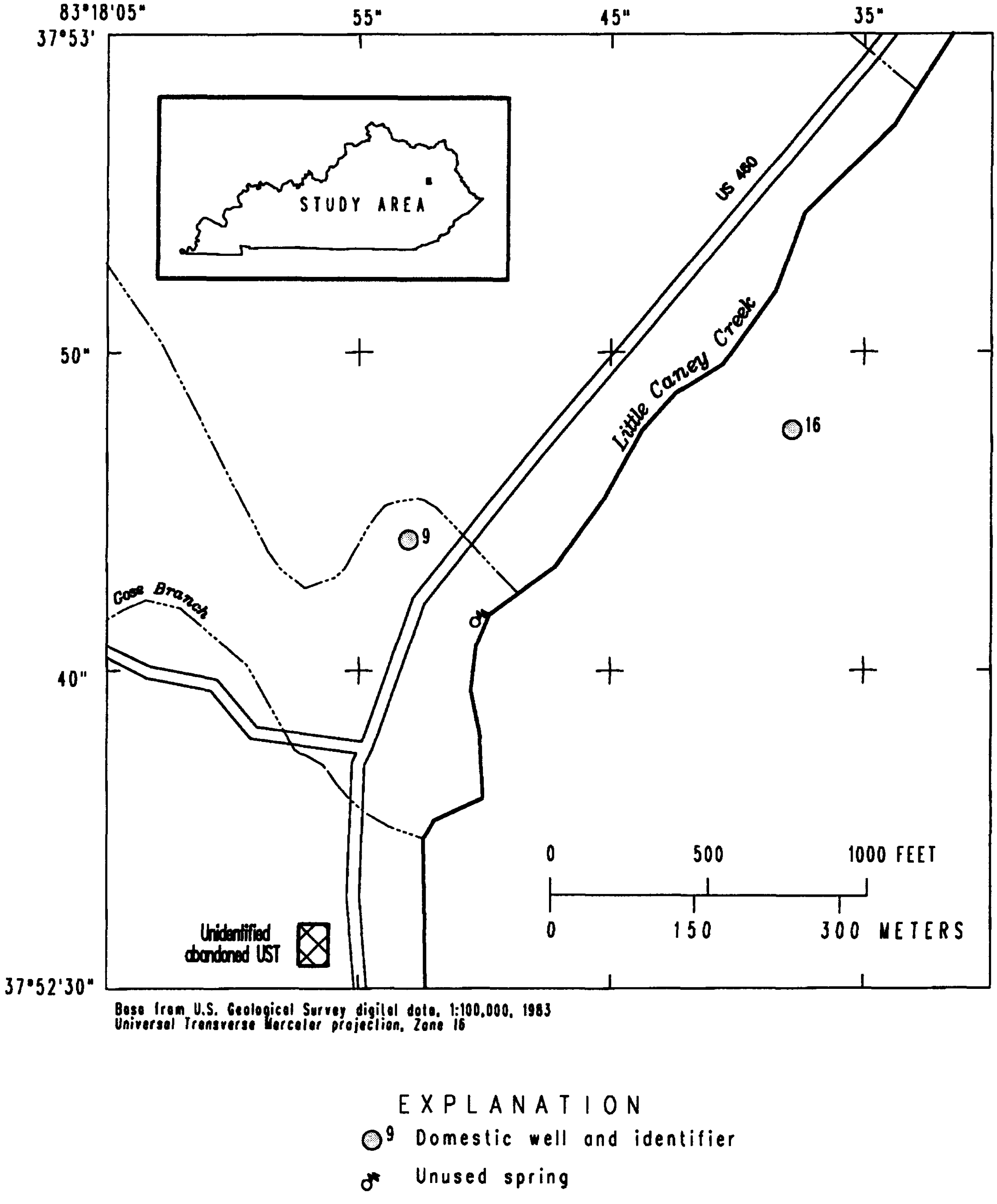
Breathitt Formation

Determination of the quality of water from the Breathitt Formation was based on the analysis of water samples from existing wells in the study area. Nine wells were inventoried that obtain water from only the Breathitt Formation; water-level data from 8 of the 9 wells (fig. 3 and table 2) indicate that the direction of ground-water flow in the formation is toward the northeast, parallel to the flow in Little Caney Creek. Deviations from this general flow direction are indicated by water-level measurements from wells 2, 4, and 5. These wells supply water to local commercial establishments and are pumped more often than the other wells in the area.

Water samples from each well were field screened for BTX compounds by use of the PGC. On the basis of the screening results, duplicate water samples from wells 1, 2, 4, 8, and 11 were sent to the laboratory for quantitative analysis. Very low concentrations of a limited number of VOC's were detected in the samples from wells 1 and 4. Concentrations of benzene in samples from well 2 exceeded MCL's established by the USEPA.

Lee Formation

Determination of the quality of water from the Lee Formation was based on the analysis of water samples from existing wells in the study area. Five wells were inventoried that obtain water from the Lee Formation (fig. 4 and table 2). The water level in well 3 was affected by a discernible layer of gasoline on top of the water column. The gasoline layer was approximately



Base from U.S. Geological Survey digital data, 1:100,000, 1983
Universal Transverse Mercator projection, Zone 16

Figure 11.--Location of hand-dug wells in alluvium and wet-weather spring, Greear, Kentucky.

Table 3.--Ground-water quality for selected wells and a spring in Greear, Kentucky

[Maximum Contaminant Levels established by U.S. Environmental Protection Agency shown in parentheses; <, less than; *, preservation previous to sampling; --, no analysis; #, light nonaqueous phase liquid sample; concentrations in micrograms per liter]

Well number	Date	Chloroform	Toluene (1,000)	Benzene (5)	Ethylbenzene (700)	Total xylenes (10,000)	Naphthalene	1,2,4-Trimethyl benzene	N-propyl benzene
1	10-31-89	<0.2	0.2	<0.2	<0.2	0.2	<0.2	<0.2	<0.2
	2-12-90	<.2	.8	.9	<.2	.8	<.2	.4	<.2
	* 2-12-90	<.2	.4	.4	.2	.6	<.2	.2	<.2
2	10-31-89	<10	440	170	37	220	<10	29	<10
	2-12-90	1.7	740	260	110	580	14	100	7
3	2-16-90	<20	1,500	340	470	2,300	200	1,400	170
	#11-01-89	<10,000	3,700,000	170,000	2,400,000	10,000,000	3,000,000	2,500,000	1,600,000
	# 2-16-90	<10,000	4,500,000	240,000	4,000,000	24,000,000	2,100,000	17,000,000	2,300,000
	# 4-18-90	<10,000	1,900,000	140,000	2,600,000	13,000,000	2,400,000	6,000,000	1,400,000
4	10-31-89	<.2	<.2	<.2	<.2	.2	<.2	<.2	<.2
	2-12-90	<.2	.2	<.2	<.2	.3	<.2	<.2	<.2
	* 2-12-90	<.2	.2	<.2	<.2	.2	<.2	<.2	<.2
7	10-31-89	<20	4,500	2,200	830	4,600	185	830	<20
	2-12-90	<.2	6,400	2,300	950	4,800	230	890	18
	* 2-12-90	<.2	5,700	2,300	910	4,700	230	860	15
	2-16-90	<20	5,900	2,100	850	4,300	180	800	56
8	2-12-90	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
10	11-01-89	<10	3,200	1,600	1,200	5,500	312	1,300	107
11	10-31-89	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
13	11-01-89	<10	3,200	1,800	670	4,200	160	810	37
19	2-16-90	<.2	<.2	<.2	<.2	<.2	<.2	<.2	<.2
Spring	2-12-90	<.2	2,600	3,000	400	1,300	140	420	12
	* 2-12-90	<.2	2,300	3,200	260	1,300	100	410	12

Table 3.--Ground-water quality for selected wells and a spring in Greear, Kentucky--Continued

Well number	Date	1,3,5-Trimethyl benzene	sec-Butyl benzene	p-Isopropyl toluene	Isopropyl benzene	1,2,3-Trimethyl benzene	2-Ethyl, 1,4-dimethyl benzene	2-Ethyl, 1,3-dimethyl benzene
1	10-31-89	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
	2-12-90	<.2	<.2	<.2	<.2	.2	<.2	<.2
	* 2-12-90	<.2	<.2	<.2	<.2	.2	<.2	<.2
2	10-31-89	10	<10	<10	<10	<10	<10	<10
	2-12-90	7.1	.4	.8	4	19	4.7	<10
3	2-16-90	450	24	27	46	250	230	<20
	#11-01-89	3,400,000	240,000	400,000	360,000	3,100,000	3,100,000	140,000
	# 2-16-90	6,400,000	460,000	580,000	560,000	3,500,000	4,500,000	150,000
	# 4-18-90	3,300,000	320,000	930,000	550,000	2,800,000	3,900,000	<10,000
4	10-31-89	<.2	<.2	<.2	<.2	<.2	<.2	<.2
	2-12-90	<.2	<.2	<.2	<.2	.3	<.2	<.2
	* 2-12-90	<.2	<.2	<.2	<.2	.2	<.2	<.2
7	10-31-89	250	<20	<20	30	260	38	<20
	2-12-90	170	1.6	5.9	44	300	44	2.4
	* 2-12-90	160	3.4	5.9	41	290	42	2.5
	2-16-90	220	<20	<20	29	230	41	<20
8	2-12-90	<.2	<.2	<.2	<.2	<.2	<.2	<.2
10	11-01-89	340	<10	10	43	330	72	<10
11	10-31-89	<.2	<.2	<.2	<.2	<.2	<.2	<.2
13	11-01-89	220	<10	<10	22	240	37	<10
19	2-16-90	<.2	<.2	<.2	<.2	<.2	<.2	<.2
Spring	2-12-90	70	2.3	7.7	14	110	52	4
	* 2-12-90	66	2.2	6.9	13	110	56	3.8

Table 3.--Ground-water quality for selected wells and a spring in Greear, Kentucky--Continued

Well number	Date	2-Ethyl toluene	1,2,3,4-Tetramethyl benzene	1,2,3,5-Tetramethyl benzene	N-Butyl benzene	Methyl tertiary-butyl ether
1	10-31-89	<0.2	<0.2	<0.2	<0.2	--
	2-12-90	<.2	<.2	.2	<.2	--
	* 2-12-90	<.2	<.2	.2	<.2	--
2	10-31-89	<10	<10	<10	<10	--
	2-12-90	17	<10	2.7	<10	--
3	2-16-90	320	68	160	77	--
	#11-01-89	2,800,000	1,400,000	2,200,000	--	--
	# 2-16-90	4,000,000	1,300,000	3,300,000	1,800,000	30
	# 4-18-90	2,900,000	<10,000	3,000,000	2,500,000	--
4	10-31-89	<.2	<.2	<.2	<.2	--
	2-12-90	<.2	<.2	<.2	<.2	--
	* 2-12-90	<.2	<.2	<.2	<.2	--
7	10-31-89	215	<20	33	<20	800
	2-12-90	240	13	73	<.2	800
	* 2-12-90	240	12	69	<.2	400
	2-16-90	200	<20	36	<20	530
8	2-12-90	<.2	<.2	<.2	<.2	--
10	11-01-89	305	32	56	17	600
11	10-31-89	<.2	<.2	<.2	<.2	--
13	11-01-89	210	16	36	<10	600
19	2-16-90	<.2	<.2	<.2	<.2	<.2
Spring	2-12-90	140	18	100	<.2	--
	* 2-12-90	140	19	100	<.2	--

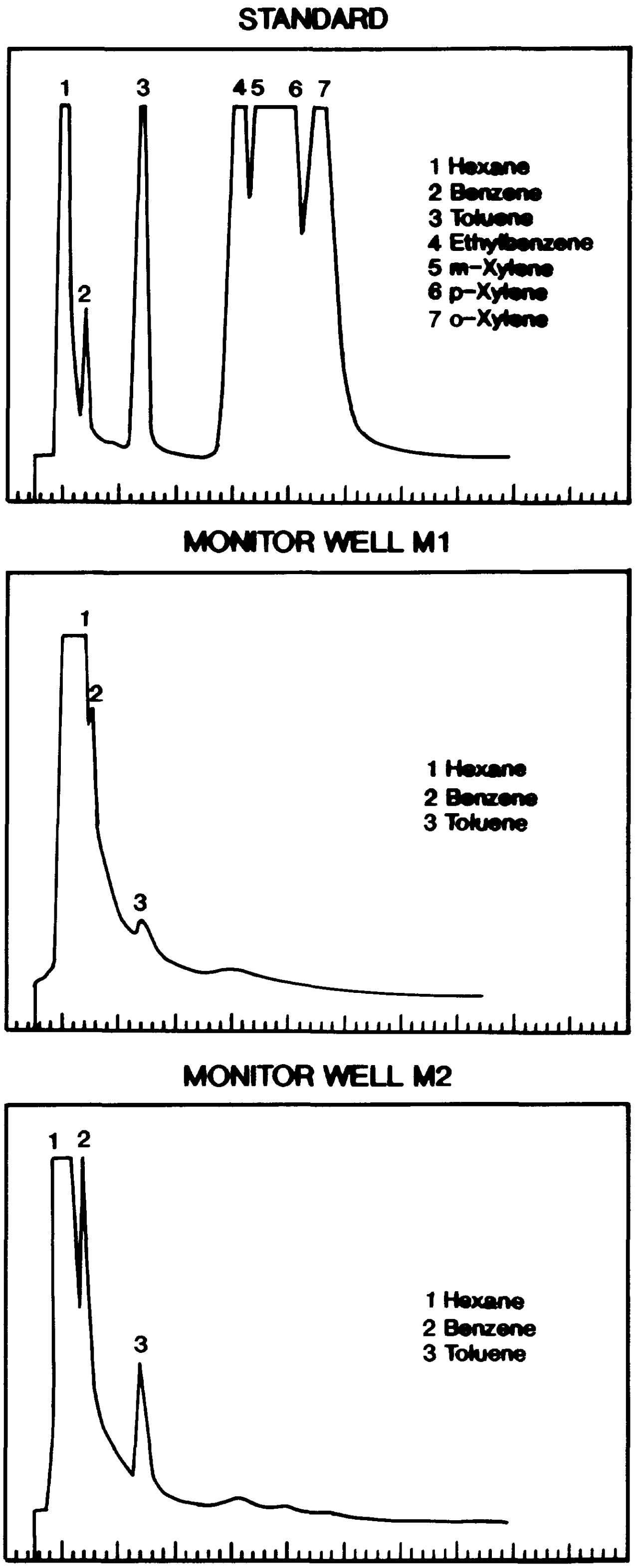


Figure 12.--Example chromatograms from analysis of water from monitor wells by use of a portable gas chromatograph.

Table 4.--Water-quality data from monitor wells

[Maximum Contaminant Levels established by U.S. Environmental Protection Agency shown in parentheses; <, less than; concentrations in micrograms per liter]

Well number	Date	Chloroform	Toluene (1,000)	Benzene (5)	Ethylbenzene (700)	Total xylenes (10,000)	Naphthalene	1,2,4-Trimethyl benzene	N-propyl benzene	1,3,5-Trimethyl benzene	sec-Butyl benzene
M1	2-16-90	<0.2	11	56	2.3	4.9	0.4	0.9	0.6	1	<0.2
M2	2-16-90	<10	650	5,800	810	1,700	85	350	68	61	<10

Well number	Date	p-Isopropyl toluene	Isopropyl benzene	1,2,3-Trimethyl benzene	2-Ethyl, 1,4-dimethyl benzene	2-Ethyl, 1,3-dimethyl benzene	2-Ethyl toluene	1,2,3,4-Tetramethyl benzene	1,2,3,5-Tetramethyl benzene
M1	2-16-90	<0.2	0.6	0.5	<0.2	<0.2	1.2	<0.2	<0.2
M2	2-16-90	<10	29	61	41	<10	170	20	31

Well number	Date	N-Butyl benzene	Methyl tertiary-butyl ether
M1	2-16-90	<0.2	<0.2
M2	2-16-90	<10	8,400

21 ft thick on November 1, 1989. This well had previously supplied the gasoline station with potable water but was no longer used because of taste and odor problems.

Water samples from wells 3, 7, and 10 screened positive for BTX compounds, and laboratory results confirmed the presence of VOC's in the samples. Concentrations of benzene, toluene, ethylbenzene, and total xylenes in the water sample from well 3 exceeded MCL's established by USEPA. Concentrations of benzene and toluene in samples from wells 7 and 10 exceeded MCL's established by the USEPA. Water samples from wells 12 and 19 did not screen positive for BTX compounds; a duplicate sample from well 19 was sent to the laboratory for background information.

The water sample from well 13 screened positive for BTX compounds, and laboratory results confirmed the presence of VOC's in a duplicate sample. Concentrations of benzene and toluene in the sample exceeded MCL's established by the USEPA. The depth of well 13 could not be determined; however, well 13 is in bedrock and is thought to be in the Lee Formation because the magnitude of VOC concentrations was comparable to that detected in other contaminated wells in the Lee Formation.

Methyl-tertiary-butyl-ether (MTBE) was detected in water samples from wells 3, 7, 10, and 13. MTBE, produced commercially since 1979, is an extremely water-soluble, octane-enhancing additive commonly used in unleaded gasolines (U.S. Environmental Protection Agency, 1988). The presence of MTBE in the Lee Formation wells indicates that the source of the hydrocarbon compound contamination is associated, in part, with facilities that have stored, used, or spilled unleaded gasoline refined since 1979.

POTENTIAL PATHWAYS OF HYDROCARBON-COMPOUND MOVEMENT

On the basis of the hydrogeologic setting of the study area and the results of this investigation, a conceptual model of contaminant transport was developed. This model considers the spatial distribution and occurrence of contaminated ground-water sources, the fracture-flow nature of the primary aquifers, and the location of the most probable contaminant source in relation to contaminated wells.

The route of contaminant transport in this conceptual model is based largely on a previous hydrologic study by the USGS (Hopkins, 1970). In the report from that study, the contamination of the Breathitt and Lee Formations by the disposal of brine from oil separators into surface streams is described. The following excerpt describes the process:

> ...[B]rine...move[s] downward by natural infiltration, primarily along joint systems, from the streams to the shallow aquifer in the Breathitt Formation, and by induced infiltration from pumping wells near the stream throughout the year. The downward route from the shallow aquifers in the Breathitt Formation to the deeper confined aquifers in the Lee Formation is through wells that are drilled to the

> Lee Formation but are open to the Breathitt Formation because shallow surface casing is used. If the static water level in the Lee Formation is lower than the static water level in the shallow aquifers, as frequently true, contaminated water with high chloride concentration will flow by gravity from the shallow aquifer into the deeper well finished in the Lee Formation. This flow contaminates the water in the well. With time the contamination will spread to that part of the Lee Formation adjacent to the well. If the static water level in the Lee Formation is higher than that in the shallow aquifer, water with high chloride content is brought into the deeper well when the water level is lowered during successive periods of pumping. During repeated periods of pumping, the rising and falling of the water level mixes the fresh water from the Lee Formation with the high chloride water from the shallower aquifer in the well, eventually contaminating the aquifer.

A similar description of hydrocarbon contamination of the Lee and Breathitt Formations can be postulated for the study area. Gasolines leaking from area UST's contact the top of the Breathitt Formation and move downward by natural infiltration and by induced infiltration from the pumping of well 3. According to the owner of the gasoline station, taste and odor became unacceptable several months before pumping ceased and the well was abandoned. Drawdown of the water level in the well during pumping (22.9 ft, measured January 1990), allowed gasoline to enter the well in a greater volume than would have occurred under equilibrium conditions. The lowered water level made well 3 a virtual sump for the contaminant.

After the initial yield of water and gasoline and associated products to the well during pumping, the head generated by the column of gasoline in the well bore could be sufficiently great to cause migration of the contamination into the aquifer. Thus, contamination of deeper aquifer units probably occurred by way of bedding planes that intersect well 3. It is possible, given the volume of gasoline present in well 3 at one time, that pure gasoline was introduced to these lower units during pumping of this well. Traveltime of the contaminant in the aquifer could be accelerated by the pumping of deeper wells that intercept, directly or indirectly, the same bedding planes as does well 3. Shallower wells and wells with lower yields would be expected to have little or no connection with the system of fractures contributing water to these other wells.

SUMMARY AND CONCLUSIONS

Wells that are the sole source of drinking water for many of the residents of Greear, Ky. tap three aquifers: the alluvium, the Breathitt Formation, and the Lee Formation. In response to complaints filed by some of the residents of Greear, the Kentucky Division of Waste Management collected and analyzed ground-water samples. Test results indicated ground-water contamination by hydrocarbons associated with petroleum products.

An investigation by the U.S. Geological Survey identified several sites as possible sources of the hydrocarbon contamination. Further analysis of ground-water samples from the study area, however, showed the presence of methyl-tertiary-butyl-ether--an octane-enhancing additive used in unleaded gasolines since 1979--thus, seemingly eliminating most possible contaminant sources except the active gasoline station.

A multiphased investigation included sampling of ground water, soil, and soil-gas to delineate the areal extent of the hydrocarbon contamination, quantify the degree of contamination, and define the migration path of the contaminants in the study area. Four wells in the Lee Formation and one well in the Breathitt Formation produced water containing hydrocarbons. Well 3 yielded the most contaminated ground water and was the only well in which a discernible hydrocarbon layer was noted in the well bore; as much as 21 ft on November 1, 1989. Laboratory analysis and semiquantitative screening of soil samples indicated hydrocarbon contamination only in the area of the active gasoline station. Soil-gas analyses at several sites in the study area also detected hydrocarbon contamination, but these sites were limited to the immediate vicinity of the active gasoline station. Near the gasoline station, two areas of high concentrations of various VOC's were determined; one in the area of the gasoline station's UST's and the other near well 3. A shallow monitor well was installed in each of the areas of high VOC concentrations. Analysis of water samples collected from the two wells confirmed the presence of hydrocarbon compounds, including methyl-tertiary-butyl-ether, in the ground water from the alluvium.

Migration of the hydrocarbon compounds to the deeper aquifers is explained by a conceptual model based largely on a previous USGS study describing brine contamination of the Breathitt and Lee Formations from surface deposits. The development of secondary porosity through an interconnected system of vertical and horizontal fractures may explain the occurrence and distribution of contamination throughout the study area. Naturally occurring downward infiltration, induced infiltration caused by pumping of area ground-water wells, and mixing of petroleum products with ground water in well bores during pumping accelerates the spread of the contamination.

REFERENCES CITED

Baehr, A.L., 1987, Selective transport of hydrocarbons in the unsaturated zone due to aqueous and vapor phase partitioning: Water Resources Research, v. 23, no. 10, p. 1926-1938.

Devitt, D.A., and others, 1987, Soil gas sensing for detection and mapping of volatile organics: National Water Well Association, 270 p.

Englund, K.J., Huddle, J.W., and DeLaney, A.O., 1967, Geologic map of the West Liberty quadrangle, Morgan County, Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-589, scale 1:24,000.

Hopkins, H.T., 1970, Occurrence of fresh water in the Lee Formation in parts of Elliott, Johnson, Lawrence, Magoffin, and Morgan Counties, Eastern Coal Field Region, Kentucky: U.S. Geological Survey Water-Supply Paper 1867, 44 p.

Marks, B.J., and Singh, Mohindar, 1990, Comparison of soil-gas, soil, and groundwater contaminant levels of benzene and toluene: Hazardous Materials Control, v. 3, no. 6, p. 40-46.

Price, W.E., Jr., 1956, Geology and ground-water resources of the Prestonburg Quadrangle, Kentucky: U.S. Geological Survey Water-Supply Paper 1359, 140 p.

Price, W.E., Jr.; Kilburn, Chabot; and Mull, D.S., 1962, Availability of ground water in Boyd, Carter, Elliott, Greenup, Johnson, Lawrence, Lee, Menifee, Morgan, and Wolfe Counties, Kentucky: U.S. Geological Survey Hydrologic Investigations Atlas HA-37, scale 1:250,000, 3 sheets.

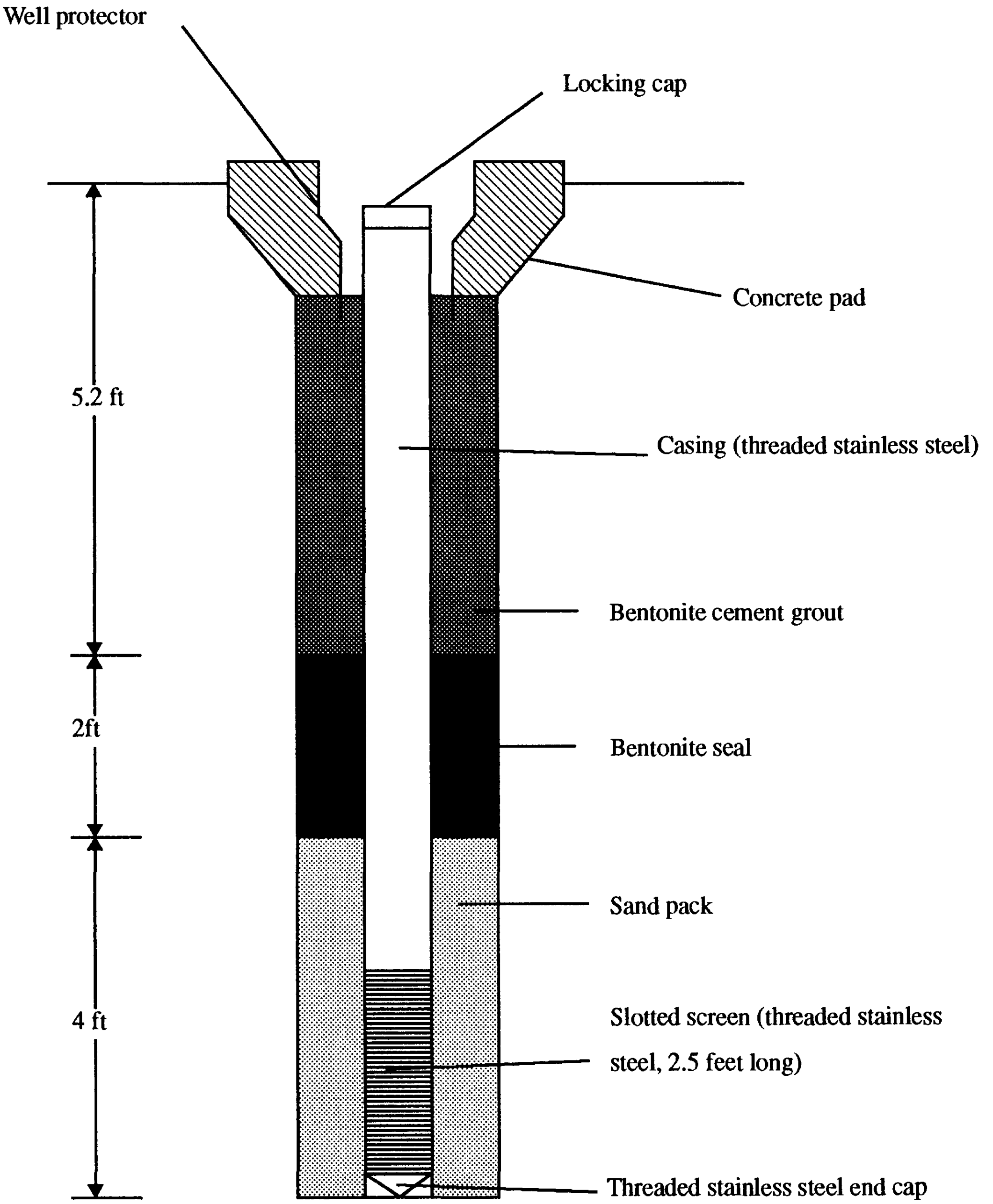
Quinones, Ferdinand; Mull, D.S.; York, Karen; and Kendall, Victoria; 1981, Hydrology of area 14, Eastern Coal Province, Kentucky: U.S. Geological Survey Water-Resources Investigations/Open-File Report 81-137, 82 p.

U.S. Environmental Protection Agency, 1975, A study of vapor control methods for gasoline marketing operations, Volume II: EPA 350/3/75-046-b.

_____ 1983, Test methods for evaluating solid waste, physical/chemical methods: SW-846.

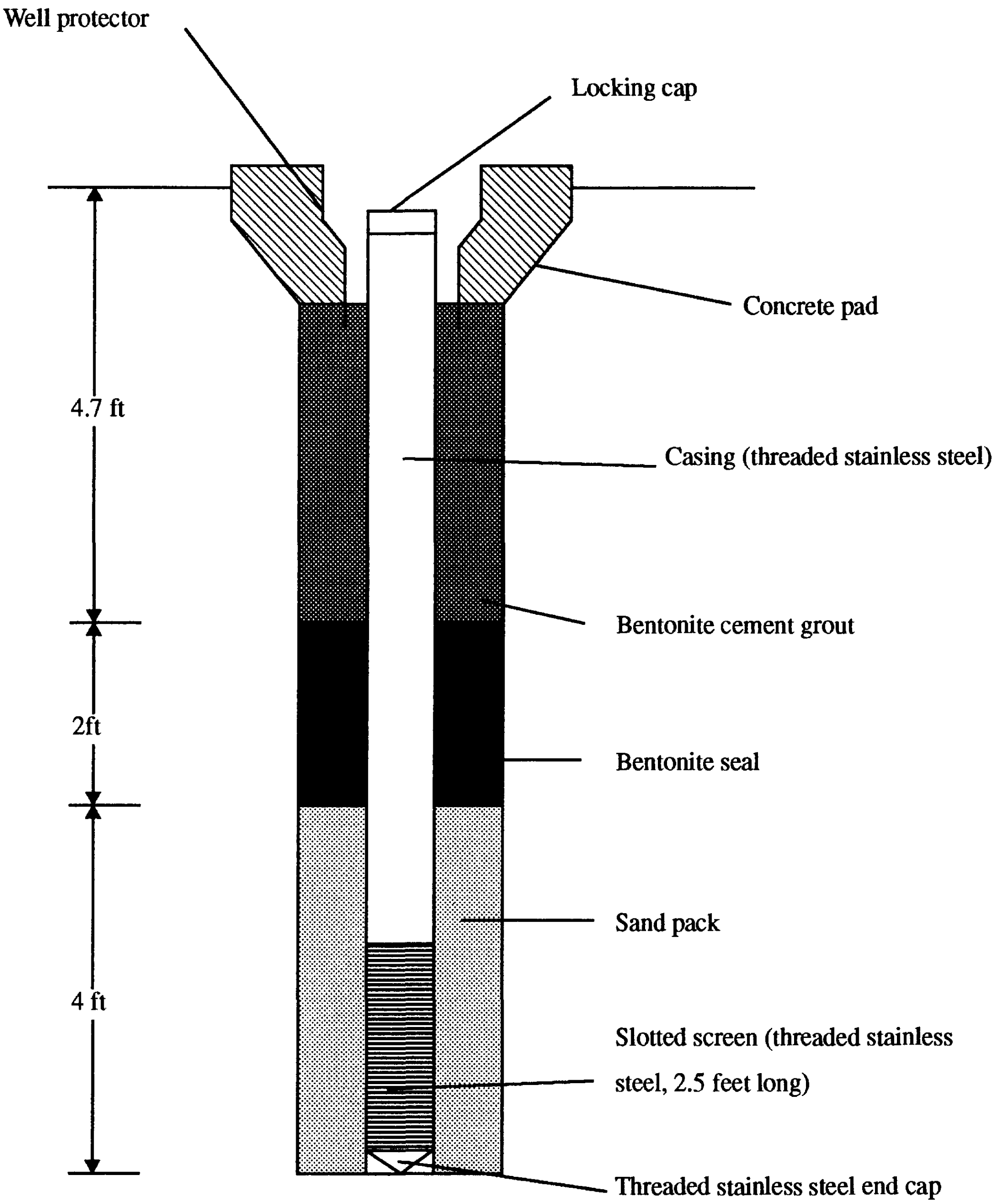
_____ 1988, Cleanup of releases from petroleum USTs--selected technologies: EPA/530/UST-88/001, 110 p.

SUPPLEMENTAL DATA



Vertical scale: 0.5 inch = 1 foot
Horizontal dimension not drawn to scale.

Figure 13.--Well construction of monitor well M1.



Vertical scale: 0.5 inch = 1 foot
Horizontal dimension not drawn to scale.

Figure 14.--Well construction of monitor well M2.