

Geohydrology and Contamination at the Michigan Department of Transportation Maintenance Garage Area, Kalamazoo County, Michigan

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

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft ² /d)	0.09290	meter squared per day
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
square foot (ft ²)	0.09290	square meter

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by use of the following equation:

$$^{\circ}\text{F} = 1.8(^{\circ}\text{C}) + 32$$

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

Abbreviated water-quality units used in this report: Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Specific conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). This unit is equivalent to micromhos per centimeter at 25 degrees Celsius (µmho/cm), formerly used by the U.S. Geological Survey.

Geohydrology and Contamination at the Michigan Department of Transportation Maintenance Garage Area, Kalamazoo County, Michigan

By Erin A. Lynch and Gary C. Huffman

Abstract

A leaking underground storage tank was removed from the Michigan Department of Transportation maintenance garage area in Kalamazoo County, Mich., in 1985. The tank had been leaking unleaded gasoline. Although a remediation system was operational at the site for several years after the tank was removed, ground-water samples collected from monitoring wells in the area consistently showed high concentrations of benzene, toluene, ethylbenzene, and xylenes—indicators of the presence of gasoline.

The U.S. Geological Survey did a study in cooperation with the Michigan Department of Transportation, to define the geology, hydrology, and occurrence of gasoline contamination in the maintenance garage area. The aquifer affected by gasoline contamination is an unconfined glacial sand and gravel aquifer. The average depth to water in the study area is about 74.7 feet. Water-level fluctuations are small; maximum fluctuation was slightly more than 1 foot during August 1993–August 1994. Hydraulic conductivities based on aquifer-test data collected for the study and estimated by use of the Cooper-Jacob method of solution ranged from 130 to 144 feet per day. Ground water is moving in an east-southeasterly direction at a rate of about 1 foot per day.

Leakage from perforated pipes leading from the underground storage tanks to the pump station was identified as a second source of gasoline contamination to saturated and unsaturated zones. The existence of this previously unknown second source is part of the reason that previous remediation efforts were ineffective. Residual

contaminants in the unsaturated zone are expected to continue to move to the water table with recharge, except in a small area covered by asphalt at the land surface.

The gasoline plume from the perforated pipe source has merged with that from the leaking underground storage tank, and the combined plume in the saturated zone is estimated to cover an area of 30,000 square feet. The combined plume is in the upper 20 feet of the saturated zone. The relative distribution of benzene, toluene, ethylbenzene, and xylenes indicate that factors such as sorption, solubility, and susceptibility to microbial degradation are affecting the movement of the combined plume. Given these factors, the plume is expected to move at a rate of less than 1 foot per day.

INTRODUCTION

In August 1993, the U.S. Geological Survey (USGS), in cooperation with the Michigan Department of Transportation (MDOT), began a study to determine the hydrogeologic framework and extent of gasoline contamination at the MDOT maintenance garage in Kalamazoo County, Mich. The USGS study was prompted by high concentrations of benzene, toluene, ethylbenzene, and xylenes (BTEX) in water samples collected quarterly, from 1986 to 1993, from a monitoring well near the former location of a leaking underground storage tank (LUST). The occurrence of BTEX in water samples is an indicator of the presence of gasoline. Concentrations of BTEX were expected to decrease after removal of the LUST and installation of a remediation system. The remediation system consisted of a purge well and filtration system for purged water. The continued presence of BTEX

indicated a need for an improved understanding of the geology, hydrology, and extent of gasoline contamination in the study area.

Purpose and Scope

This report describes (1) the hydrogeologic framework of the uppermost sand and gravel aquifer at the MDOT maintenance garage area, including hydraulic properties and direction and rate of ground-water flow, and (2) the locations of gasoline contamination in the unsaturated and saturated zones. This report contains geologic, hydrologic, and water-quality data. The study took place over a period of 19 months from August 1993 through February 1995.

Description of Study Area

The study area is southeast of the intersection of U.S. Route 131 and State Route 43 in section 13, Oshtemo Township, Kalamazoo County, Mich. (fig. 1). The study area is about 300,000 ft² and includes MDOT maintenance garage property, a Consumers Power Company right-of-way, and Elks Club Golf Course to the east.

Land-surface relief in the study area is only about 4 ft in the vicinity of the maintenance garage; however, elevation decreases by about 5 ft to the east, beyond the edge of the parking area, and by about 9 ft to the southeast, beginning just north of two old salt storage sheds (fig. 2).

Previous Studies

In 1984, MDOT completed a preliminary investigation of soil and ground-water contamination at the Kalamazoo County maintenance garage. The investigation was prompted by unexplained inventory shortages for an underground storage tank (UST). As a result of their investigation MDOT determined that (1) the UST had leaked, (2) gasoline had fully penetrated the unsaturated zone, (3) a gasoline plume had formed on the water table and had moved eastward, (4) most of the gasoline was still in the immediate vicinity of the UST, and (5) the leading edge of the plume was probably still within property boundaries.

In 1985, an investigation was done to clarify geologic and hydrologic conditions at the Kalamazoo maintenance garage and to delineate plume

dimensions. The results of the investigation indicated that two sand aquifers underlie the site and that they are separated by a clay layer interpreted to function as a confining unit. The clay layer was determined to be about 18 ft thick at the maintenance garage supply well (fig. 2). Average depth to water in the area was 73 ft. Horizontal hydraulic conductivity of the upper aquifer was estimated to range from 48 to 254 ft/d. Estimates of ground-water flow velocities ranged from 0.52 to 1.34 ft/d, and flow was toward the southeast. Gasoline from the UST was confined to the upper aquifer, and the plume was estimated to be 280 ft long and 260 ft wide (Lynch, 1985).

Monitoring wells DOT1, DOT2, and DOT3 remain from the initial investigation by MDOT. Monitoring wells KCS1, KCS2, KCS3, KCS4, KCS6, and KCS7 remain from the 1985 investigation. Since 1987, MDOT has sampled water from these monitoring wells quarterly and analyzed it for BTEX. Of these samples, those from monitoring well KCS6 have consistently contained concentrations of BTEX. The minimum concentration of benzene in these samples was 1,100 ppb, collected October 25, 1990. This value exceeds the limit in Michigan Environmental Response Act 307, Type B criteria. The State of Michigan cleanup standards have been changed as a result of recently enacted amendments to Part 201 of the Natural Resources and Environmental Protection Act, 1994, PA (formerly known as Act 307). Type B criteria are now referred to as generic residential criteria. Under this criteria the health based drinking water value for benzene is 5 ppb, toluene is 1,000 ppb, ethylbenzene is 700 ppb, and xylenes is 10,000 ppb (Alan J. Howard, Michigan Department of Natural Resources, written commun., June 6, 1995).

Methods of Data Collection and Analysis

The geohydrology of and the location and movement of gasoline contamination in the study area were investigated through installation of monitoring wells, split-spoon sampling and soil analysis for BTEX, geophysical logging, collection of water-level data, aquifer tests, water sampling and analysis for BTEX, and a soil and water survey with on-site analysis for relative concentrations of benzene, toluene, and xylenes (BTX).

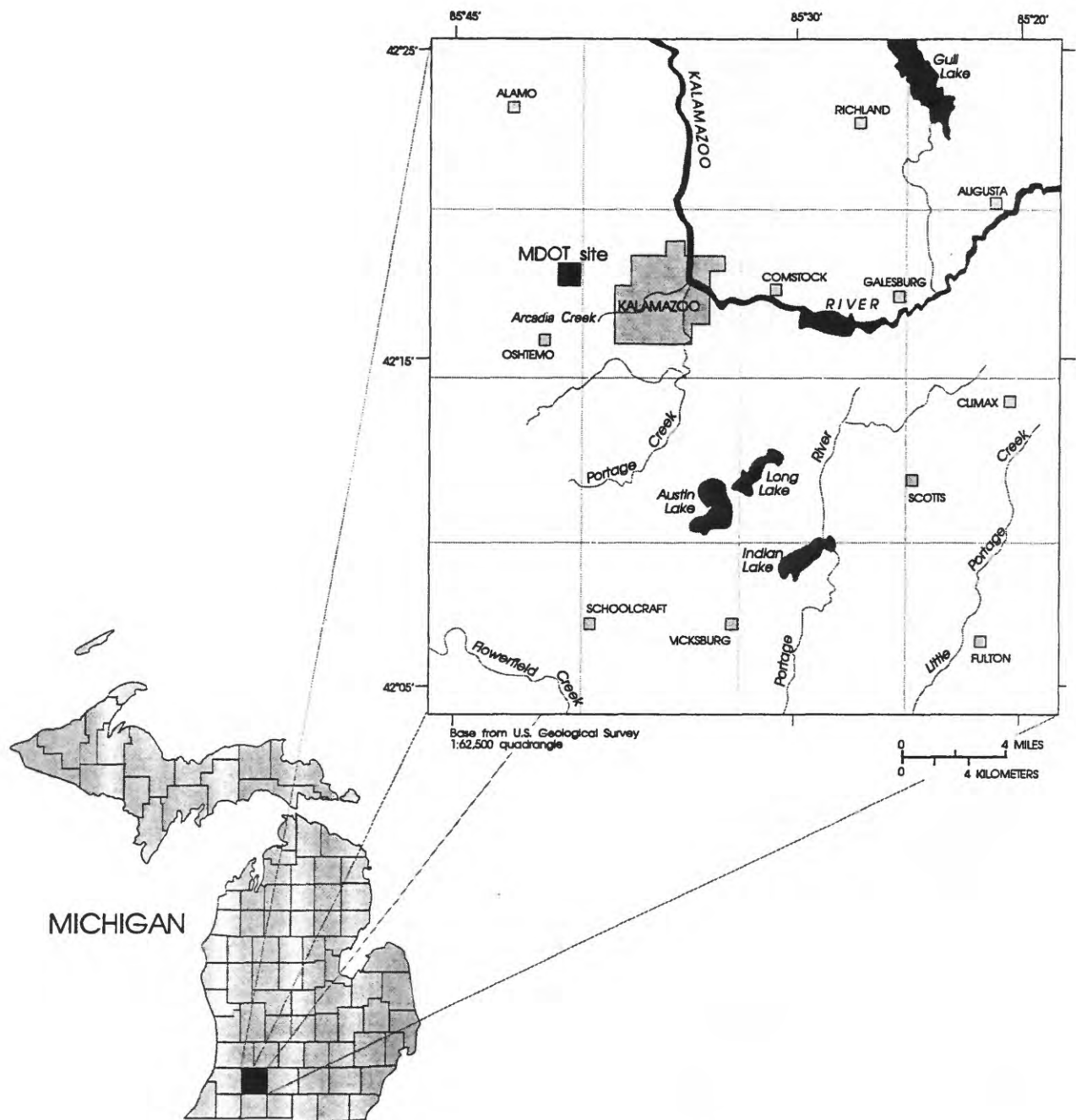


Figure 1. Location of Michigan Department of Transportation maintenance garage (MDOT site), Kalamazoo County, Michigan.

Monitoring-Well Construction

Twenty-one monitoring wells (KM1, KM2S, KM2D, KM3–KM12, KM13S, KM13D, KM14–KM16, KM18–KM20) were installed in the uppermost sand and gravel aquifer (fig. 2; table 1). Twenty boreholes were drilled, by use of hollow-stem augers, about

6 to 7 ft into the saturated zone. Two-inch inside diameter wells constructed of polyvinyl chloride (PVC) casing and stainless-steel screens were installed through the auger stem. Threaded casing and screen joints enabled well construction without the use of glues. Well screens are 10 ft in length and span the groundwater surface. If present, gasoline floating on the

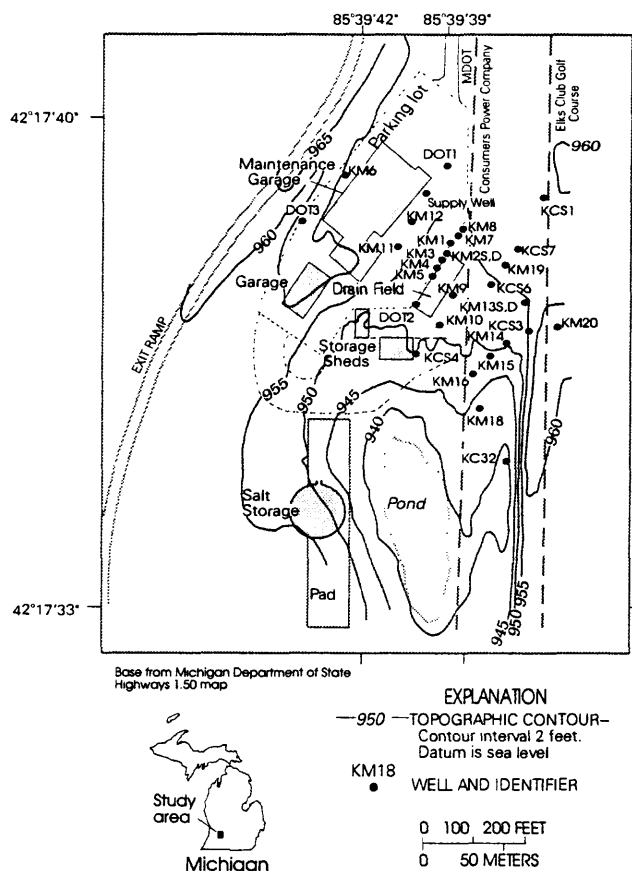


Figure 2. Monitoring-well locations and site topography in the Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan.

ground-water surface also would be within the screen and could be measured. The aquifer materials were allowed to collapse around the screen so as to create a natural gravel pack in wells KM1–KM11. After the depth of the collapsed annular space was measured to ensure that the screen was covered, the annular space was then filled with granular bentonite to 3 ft below land surface. The remaining 3 ft was filled with cement, and a protective covering was installed (fig. 3).

Wells KM12–16 and KM18–20 were installed such that the annular space was filled with a clean sand and gravel pack to about 3 ft above the well screen. Granular bentonite was then installed to 3 ft below the land surface, followed by cement and a protective covering (fig. 3).

Two monitoring-well pairs (KM2S–KM2D, KM13S–KM13D) were installed in the study area. A well pair consists of a shallow well, with a 10-foot-long screen set about 6 to 7 ft into the water table and a

Table 1. Selected data for monitoring wells installed by the U.S. Geological Survey in the Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan

Well identifier	Relative altitude of measuring point, in feet above sea level	Distance of measuring point, in feet above or below (-) land surface	Well depth, in feet below land surface	Depth to bottom of casing, in feet below land surface
KM1.....	797.46	2.30	82.50	72.50
KM2S.....	797.69	2.55	80.36	70.36
KM2D.....	796.40	1.00	103.93	98.93
KM3.....	797.69	2.55	79.79	69.69
KM4.....	797.58	2.50	78.48	68.48
KM5.....	797.56	2.45	79.74	69.74
KM6.....	799.37	2.35	80.63	70.63
KM7.....	797.19	2.40	78.22	68.22
KM8.....	797.25	2.50	80.23	70.23
KM9.....	792.79	2.50	74.79	64.79
KM10.....	791.98	3.05	73.89	63.89
KM11.....	795.85	-.08	78.66	68.66
KM12.....	796.27	-.25	82.50	72.50
KM13S.....	794.11	2.60	77.20	67.20
KM13D.....	792.44	.90	102.70	97.70
KM14.....	790.25	2.80	74.75	64.75
KM15.....	787.49	2.80	71.85	61.85
KM16.....	787.28	2.80	77.40	67.40
KM18.....	781.25	2.40	68.50	58.50
KM19.....	795.47	.80	82.67	72.67
KM20.....	797.23	-.40	81.08	71.08

deep well, with a 5-foot-long screen set about 20 ft deeper. The shallow wells are designated by an S at the end of the well name and deep wells are designated by a D at the end of the well name. The clay layer described earlier in this report is estimated to be at least 10 ft below the base of the deep wells in the well pairs. Well pair KM2S–KM2D is about 90 ft downgradient from the source area. Well pair KM13S–KM13D is 275 ft downgradient from the source area, at the east edge of the Consumers Power Company right-of-way. The well pairs were used to describe the vertical distribution of contaminants in the saturated zone.

To prevent cross contamination, field personnel thoroughly cleaned the drill rig, augers, and other tools before the start of drilling, between boreholes, and after each day of drilling. The relative altitude to the top of casing was surveyed for each well by USGS personnel (table 1).

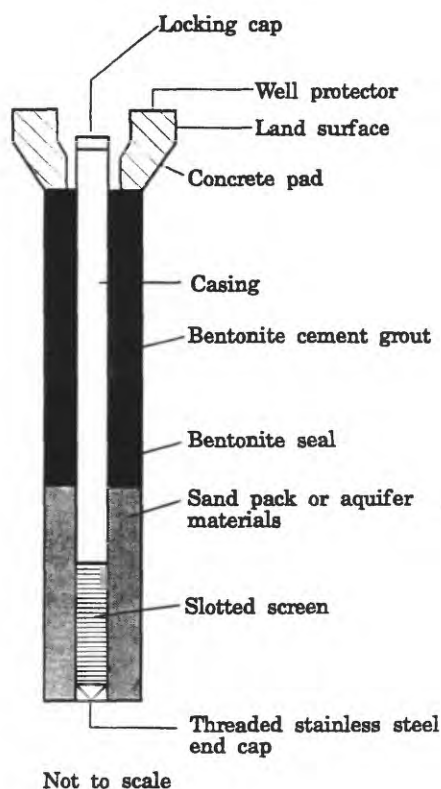


Figure 3. Monitoring-well construction for wells drilled by the U.S. Geological Survey in the Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan. (Modified from Alexander and others, 1992, fig. 13).

Split-Spoon Sampling

Twenty-six split-spoon samples were collected through a hollow-stem auger at 5-foot intervals during drilling of monitoring wells KM11 and KM12, from the base of fill to the water table. These wells were in the area of the former LUST and in the pipe-trench area, where pipes from underground tanks led to the pump station. Soil samples were removed from the split-spoon sampler and placed in 120-mL glass vials. Samples were stored on ice and shipped the same day to Quanterra Environmental Services¹ in Arvada, Colo., for analysis per laboratory schedule SW8020. Schedule SW8020 calls for a purge and trap gas chromatography/mass spectrometry method for BTEX. The reporting limit for this method is 0.2 milligram per kilogram (mg/kg) or 0.2 part per million (ppm).

¹ Use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Resulting analyses of soil samples were used to describe the vertical distribution of BTEX in the unsaturated zone near the suspected sources of contamination. Sieve analysis was done on samples from monitoring well KM11 to determine grain-size distribution.

Borehole Geophysical Logging

Natural-gamma logs were obtained from monitoring wells in the study area. The gamma tool responds to potassium, thorium, and uranium. These elements are common in clay minerals. Natural-gamma logs were used to identify lithology (specifically, clay-rich layers and the depths at which they are present).

Water-Level Monitoring

Water levels were measured monthly for 1 year. Water levels were used to determine direction of ground-water flow and to study water-level fluctuations. An interface probe was used to determine whether floating fuel was present when water levels were measured. In addition, two continuous water-level recorders were installed on monitoring wells KM8 and KM10. The continuous recorders were in operation for 6 and 3 months, respectively. Continuous water-level records (15-minute recording intervals) were used to examine high-frequency water-level fluctuations.

Aquifer Testing

Two aquifer tests were done in the study area. An aquifer test is a method for estimating hydraulic conductivity and other hydraulic properties of aquifer materials. In an aquifer test, water is pumped from a well, and water levels or drawdown in nearby wells is measured over time. From this information, an integrated hydraulic conductivity over a section of the aquifer can be computed. An aquifer test was done on September 13, 1994, in which monitoring well KM1 was the pumped well and wells KM2 and KM7 were observation wells for water levels. A second aquifer test was done on September 16, 1994, in which monitoring well KM15 was the pumped well and wells KM14 and KM16 were observation wells for water levels. Both tests were run for about 2 hours until water levels stabilized.

Ground-Water Sampling

Ground-water samples were collected to delineate the contaminant plume(s) in the saturated zone and to determine the distribution of BTEX therein. Two rounds of water sampling for BTEX were completed. Ground water was sampled by use of a centrifugal pump. Wells were purged prior to sampling by pumping until water temperature and specific-conductance readings stabilized. Purging is an effort to try to ensure that collected water is representative of aquifer water. Specific conductance, pH, and dissolved-oxygen concentrations were recorded in the field for water from most of the wells sampled. Three 40-mL vials, containing dilute hydrochloric acid as a preservative, were then filled with water so that no bubbles were present. The vials were then fitted with Teflon septum caps. Samples were immediately stored on ice and shipped the same day to the USGS National Water Quality Laboratory in Arvada, Colo. Samples were analyzed per laboratory schedule 1378, similar to USEPA method 524.2. Schedule 1378 calls for a purge and trap capillary gas chromatography/mass spectrometry method for BTEX. Reporting limits for this method are 0.2 parts per billion (ppb).

Water from monitoring wells was sampled in order from lowest to highest anticipated concentrations of BTEX. Water samples were collected over the course of 3 days. The sampling pump was decontaminated between each sample collection by flushing with

a solution of Liquinox (a cleaning agent) and tapwater, followed by flushing with tapwater. A replicate sample was collected on the second day of sampling. A rinse-water blank was collected on the second day of sampling. Three equipment blanks were collected. One equipment blank was collected after every seventh sample.

Ground-water samples also were collected for constituents and properties that could indicate microbial activity in the contaminant plume. Two rounds of sampling were completed for these constituents and properties in selected monitoring wells. Water samples collected during the first round of sampling were analyzed by a contract laboratory for MDOT. Water samples collected during the second round were analyzed by the USGS National Water Quality Laboratory. Constituents and properties determined during the second sampling round and USGS National Water Quality Laboratory schedules are listed in table 2.

Soil and Water Survey

During the soil and water survey, soil and water samples were analyzed onsite for BTX by means of a portable gas chromatograph (PGC). Five boreholes (BH1–BH5) were drilled in the study area toward the end of the study to help define the extent of gasoline contamination in the unsaturated and saturated zones (fig. 2). Soil samples were collected, by use of a

Table 2. Constituents and properties targeted as possible indicators of microbial activity, National Water Quality Laboratory schedules, and methods of analysis

[µg/L, microgram per liter; mg/L, milligram per liter]

Constituent or property name	Laboratory schedule	Phase	Method	Reporting limit
Iron, total (µg/L)	0189	Whole water, recoverable	Atomic absorption	10
Manganese, total (µg/L)	0041	Whole water, recoverable	Atomic absorption	10
pH (standard units)	0068	Laboratory	Electrometric	.1
Alkalinity, as CaCO ₃ (mg/L)	0070	Whole water, recoverable	Electrometric titration	1
Chloride (mg/L)	1571	Dissolved	Ion-exchange chromatography	.1
Sulfate (mg/L)	1572	Dissolved	Ion-exchange chromatography	.1
Sulfide (mg/L)	0089	Whole water, recoverable	Iodometric	.5
Nitrogen, ammonia, as nitrogen (mg/L)	0301	Dissolved	Colorimetric, salicylate-hypochlorite, automated-segmented flow	.01
Nitrogen, nitrite, as nitrogen (mg/L)	0160	Dissolved	Diazotization, automated-segmented flow	.01
Nitrogen, nitrite plus nitrate, as nitrogen (mg/L)	0228	Dissolved	Cadmium reduction, diazotization, automated-segmented flow	.05

split-spoon sampler, from borehole 1 (BH1) at 5-foot depth intervals beginning at a depth of 20 ft and from borehole 2 (BH2) at 50-, 60-, 70 -, and 75-foot depths. Water samples were collected when boreholes BH1 and BH2 were within the saturated zone. Soil samples were collected beginning at about 10 ft above the water table and at 5-foot depth intervals down to the saturated zone for boreholes BH3 through BH5. Borehole BH1 was filled once sampling was completed, whereas boreholes BH2 through BH5 were converted to monitoring wells KM2D, KM13D, KM19, and KM20 (fig. 2). Water samples were collected after each well was installed, developed, and purged.

Soil and water samples were collected and placed in 40-mL borosilicate glass jars fitted with a Teflon septum cap and then were put on ice. When ready for analysis, samples were brought to a temperature of about 30°C and allowed to stabilize for at least 20 minutes. A 0.07-mL sample of the gas in the headspace above the soil or water sample was withdrawn and injected into the PGC by use of a gastight glass syringe. Compounds were tentatively identified by comparison of instrument response to the retention time of a prepared BTX standard at the same temperature. The PGC is fitted with a sensitive photoionization detector that can detect benzene in a 1-mL air sample at a concentration of 0.1 parts per billion (ppb) (Alexander and others, 1992). For soil and water samples in the soil and water survey, gas in the headspace above the soil or water sample was analyzed. In contrast, for soil samples collected during the split-spoon sampling described earlier in this report, the soil sample itself was analyzed for BTEX. For water samples collected during the ground-water sampling described earlier in this report, the water sample itself was analyzed for BTEX. Therefore, the PCG analysis indicates the relative concentrations of BTX compounds in the various samples, but it cannot be used to determine the absolute concentration.

Quality assurance and quality control (QA/QC) measures included the analysis of equipment blanks and standards to ensure proper analytical technique and operation of the PGC. Standards were analyzed periodically to ensure calibration of the PGC throughout the analyses. Changes in retention times for the BTX compounds were documented (Alexander and others, 1992).

Acknowledgments

We thank personnel at the MDOT maintenance garage in Kalamazoo County, especially Charles Sage and Joe Bell, for assistance, access, and use of facilities. We also acknowledge Consumers Power Company and the Elks Club Golf Course for allowing access to their properties, including access for monitoring-well installation. We thank Martin Rose of the USGS office in Louisville, Ky., for his participation in the soil and water survey.

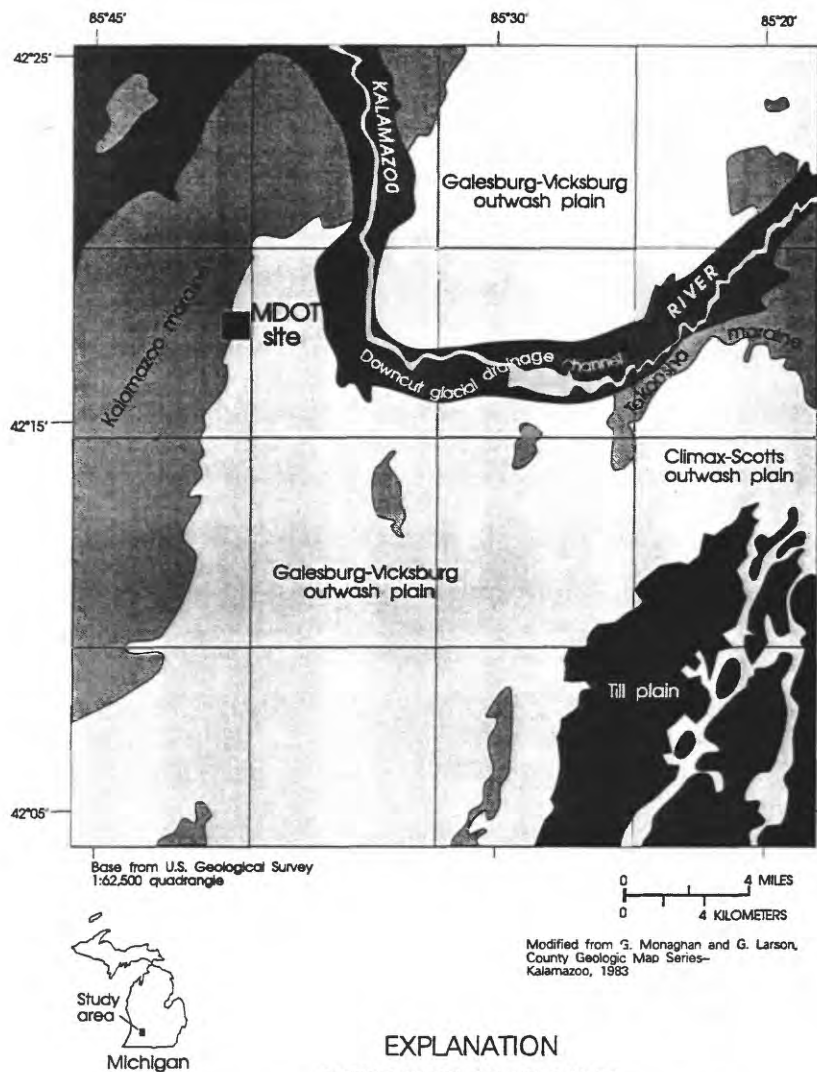
GEOHYDROLOGY

The Kalamazoo County area is characterized by glacial features formed during the Wisconsin Stage of the Pleistocene Epoch. Alluvial deposits, of Holocene age, are the result of deposition by the Kalamazoo River and its tributaries. These surficial geologic features result in a topography of rolling hills and large flat areas. The Coldwater Shale, of Mississippian age, underlies glacial deposits in the study area.

Ground water is present in glacial and alluvial deposits as well as in the Coldwater Shale in Kalamazoo County. However, sand and gravel aquifers within the glacial and alluvial deposits provide most of the ground-water supplies for the county (Rheume, 1990).

Geologic Setting

The MDOT maintenance garage in Kalamazoo County is on the west edge of the Galesburg-Vicksburg outwash plain where it meets the Kalamazoo moraine (fig. 4). All wells in the study area are installed in the sand and gravel aquifer. Glacial materials in the study area are composed of medium to coarse sand, some gravel, and minor clay. Lithology of glacial deposits in which monitoring wells were installed by the USGS in the study area is given in table 3. A perched saturated zone was identified during drilling of wells KM16 and KM17. The altitude of this perched zone corresponds to the altitude of the surface of the pond in the study area (fig. 2). The perched zone is interpreted to extend south of the area of contamination as described under the "Contamination" section later in the report. Monitoring well KM17 was removed because of damage to the well when drill augers were withdrawn. Monitoring well KM18 was installed to the northeast within 5 ft of the location of KM17 (fig. 2).



- Outwash plain—Mostly medium to very coarse sand and gravel. Pebble to cobble gravel common
- Upland moraine, kame field, or highly collapsed outwash—Mostly sandy till. Boulders and cobbles common on the surface
- Downcut glacial drainage channel—Mostly medium to very coarse sand and gravel. Deposits form a deeply incised valley-train system
- Till plain—Mostly coarse sandy and cobbly till. Clay-rich in areas. Boulders common on the surface

Figure 4. Areal extent of surficial deposits in the vicinity of the Michigan Department of Transportation maintenance garage (MDOT site), Kalamazoo County, Michigan.

Table 3. Description of drill cuttings obtained during installation of monitoring wells in the Michigan Department of Transportation garage area, Kalamazoo County, Michigan

[LSD, land surface datum; in., inch; ft, foot]

Well	Lithology	Depth (feet below LSD)	Well	Lithology	Depth (feet below LSD)
KM1	Sand, medium, brown; some fine gravel	0 - 5	KM3	Sand, medium, brown; some silt	56 - 74
	Sand, medium to fine, some silt, brown; some fine gravel (wet)	5 - 9		Sand, very coarse, grayish; some coarse gravel, stones to 0.5 in.	74 - 79
	Sand and clay, clay somewhat sandy, gray	9 - 10	KM4	Sand, medium, dark brown	0 - 4
	Sand, medium to fine, brown; some clay (sandy); medium to fine gravel (wet)	10 - 15		Rock or fill, then sticky clay	4 - 5
	Sand, medium, brown; some silt (wet)	15 - 20		Sand, medium, silty, brown; some fine gravel	5 - 11
	Sand, medium to coarse, brown; little silt, drier; some stones to 0.5 in.	20 - 25		Soupy clay (silt?)	11 - 12
	Sand, medium to fine, brown, and clay; some stones 1 to 1.5 in. at 27 ft	25 - 30		Sandy clay	12 - 13
	Sand, medium, brown; silt	30 - 35		No material (clay zone?)	13 - 22
	Sand, fine, brown; silt; some fine gravel	35 - 40		Soupy clay (silt?)	23
	Sand, medium to fine, silty, brown	40 - 50		Clay (?)	23 - 32
	Sand, medium, brown; some medium to fine gravel	50 - 55		Some stones	32 - 33
	Sand, medium to coarse, brown; some medium gravel	60 - 82		Large boulder (able to drill through or around it)	36 - 38
				No material (clay zone?); cuttings adhering to auger similar to those at other holes, except perhaps more gravel, with stones to 1 in.	38 - 80
KM2	Sand, medium to fine; silt; some clay, brown	0 - 5	KM5	Fill	0 - 5
	Sand, fine, brown; clay from 9 to 12 ft	5 - 12		Medium sand, brown	5 - 7
	Sand, medium, dry, brown; some clay and silt	12 - 19		Clay; clayey sand	7 - 10
	Sand, brown, and stones to 1 in.	19 - 22		No cuttings; gravel at about 50 ft, stones on augers 0.5 to 0.75 in.	10 - 79
	Sand, medium, brown; some silt; fine gravel, a few stones to 1 in.	22 - 28	KM6	No log made; clay in upper part of hole	0 - 80
	Clay—no return of material	29			
	Soupy clay	30	KM7	Damp, coarse sand; some small pebbles	0 - 5
	Silt and sandy clay (dry)	31 - 35		Coarse sand, moist, but drier than above	5 - 18
	Sand, medium to fine, brown; silt; some clay (dry) and fine gravel	35 - 55		Damp, coarse sand with a little more clay	18 - 20
	Sand, coarse; silt, brown; some fine gravel; a few stones to 1 in.	55 - 60		Sand and gravel; cobbles up to 2 in.	20 - 77
	Sand, coarse, brown; some medium to fine gravel; sand on augers from saturated zone had an odor	60 - 80	KM8	Sand; some clay	5 - 10
				Sand	10 - 70
				Coarse sand to gravel varied composition; small pebbles	70 - 79
KM3	Topsoil; rocks, piece of concrete	0 - 2	KM9	Soil, black, organic	0 - 2
	Medium to coarse, dark brown sand; appears to be fill	2 - 6		Clay, light-brown	2 - 5
	Rock, then dark-gray silty clay	6 - 7		Clay, lighter than above; sand (medium to coarse)	5 - 10
	Silty clay with coarse gravel (dry)	7 - 9		Clay, sandier (medium to coarse)	10 - 20
	Silty clay, dark brown; some gravel	9 - 15		Sand, distinct color change at 35 ft	20 - 30
	Same, except lighter brown	15 - 20		Sand; gravel to 0.5 in.	30 - 45
	Sand and silt, brown; some fine gravel	20 - 25		Sand (medium to coarse); fine pebbles	45 - 74
	Sand, medium, brown; some silt	25 - 37		Odor of gas noted as auger from 60 ft was pulled (HNU, 10 ppm); odor persisted to bottom of hole as augers were pulled	
	Sandy silt, brown; some clay (wet)	37 - 39	KM10	Soil, then clay, very dense, medium brown (sample collected)	0 - 5
	Sand, medium, brown; some silt (dry)	39 - 55		Clay, very dense black-brown to medium brown (sample collected)	5 - 10
	Sand, coarse, grayish; some medium gravel; few stones to 0.5 in.	55 - 56			

Table 3. Description of drill cuttings obtained during installation of monitoring wells in the Michigan Department of Transportation garage area, Kalamazoo County, Michigan—*Continued*

Well	Lithology	Depth (feet below LSD)	Well	Lithology	Depth (feet below LSD)
KM10	Sand, medium with heavy clay component	10 - 15	KM12	Medium to coarse sand; gravel 10%; 2-inch clay layer at 13.5 ft	0 - 25
	Sand, medium to coarse (wet)	15 - 40		Medium to fine sand; finer gravel 5%; 1.5-inch clay later at 38 ft	25 - 40
	Distinct color change			Medium to coarse sand; gravel 10%	40 - 63
	Dominantly sand, lighter in color than above; minor gravel, pebbles up to 0.25 in.; clay, pebbles (sample collected)	40 - 74		Medium to coarse sand; gravel 10%; more finer grained materials than above	63 - 83
	Moist most of the way down				
KM11 ¹	Medium to coarse sand; minor gravel; 2.5-inch-thick clay layer at 14.5 ft depth	13 - 30	KM13	Medium sand; gravel 5%, 0.5-inch pebbles dominant	0 - 77
	Medium to coarse sand; minor gravel	33 - 35	KM14	Medium sand; gravel 5%, 0.5-inch pebbles dominant; 1.5-foot clay layer at top	0 - 75
	Medium to coarse sand; more gravel than above	38 - 40	KM15	Medium sand; gravel 5%, 0.5-inch pebbles dominant; 2-foot clay layer at top	0 - 72
	Medium to coarse sand; minor gravel	43 - 45	KM16	Medium sand; some gravel, < 5%	0 - 19
	Medium to coarse sand; minor gravel	48 - 50		Silty sand; some gravel (saturated)	19 - 27
	Medium to coarse sand; minor gravel	53 - 55		Medium sand; some gravel, < 5%	27 - 78
	Medium to coarse sand; minor gravel	58 - 60	KM17	Medium to coarse sand; some gravel, < 5%, less with depth; minor clay near top	0 - 14
	Medium to coarse sand; minor gravel	63 - 65		Silty sand with some gravel, (saturated)	14 - 23
	Sand with gravel (moist)	68 - 68.5		Medium to coarse sand; some gravel, < 5%	23 - 65
	Sand with more gravel than above (moist)	68.5 - 69			
	Fine to medium sand	69 - 70			
	Sand; some gravel	73 - 78			
	Lower augers had a green sheen on them after having been in the borehole				

¹Record for this well has gaps because log is based on split-spoon samples.

Sieve analyses of split-spoon soil samples collected during construction of monitoring well KM11 revealed relatively homogeneous grain-size distribution with depth. Four ranges of grain size and a composite of two ranges were examined (table 4). Medium sand and coarser material dominates, averaging 64.3 percent by weight of the soils sampled. An average of 91.8 percent by weight of materials are within the range of fine sand to coarser material. Samples from depths of 24, 29, 39, and 69 ft have a slightly finer grained component. Samples from depths of 49 and 59 ft have a slightly coarser grained component. This variation in grain-size distribution may affect the distribution of recharge and of gasoline in the unsaturated zone. This relation is examined in the discussion of unsaturated-zone contamination later in this report.

Natural-gamma logs from monitoring wells in the study area also indicate relatively homogeneous lithology, vertically and laterally. Natural-gamma logs for each monitoring well show little variation with depth (fig. 5). The natural-gamma log from monitoring well KM11 shows some variation in the first 12 to 15 ft (fill materials); however, below 15 ft, the log is similar to those from other wells in the study area. The natural-gamma log from monitoring well KM4 has an anomalous peak at a depth of approximately 39 ft. The driller's log describes difficulty in drilling at a depth corresponding to this peak in this particular well. The altitude of this anomalous peak corresponds to the approximate altitude of the perched saturated zone found at monitoring wells KM16 and KM17. However, this peak is not observed in natural-gamma logs from monitoring well KM5, adjacent to and only 15 ft away from KM4. Therefore, this peak is interpreted to be a local anomaly—possibly a fine-grained, clay-rich lens.

Table 4. Results of sieve analysis of soil samples collected from monitoring well KM11, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan

Depth, in feet	Range of grain size (in percent by weight)				
	Medium sand and coarser	Fine sand	Very fine sand	Coarse silt and finer	Medium sand and coarser plus fine sand
14	63.5	34.4	1.7	0.4	97.9
19	62.2	30.4	4.9	2.5	92.6
24	54.6	30.5	7.2	7.7	85.1
29	55.6	29.7	7.3	7.4	85.3
34	67.3	23.0	5.0	4.7	90.3
39	55.8	31.5	7.4	5.3	87.3
44	68.5	28.7	1.8	1.0	97.2
49	80.6	15.4	2.2	1.8	96.0
54	69.1	27.1	2.3	1.5	96.2
59	73.6	17.0	3.8	5.6	90.6
64	71.7	21.9	4.0	2.4	93.6
69	48.7	36.7	10.6	4.0	85.4
74	64.2	31.1	2.3	2.4	95.3
Average	64.3	27.5	4.7	3.6	91.8

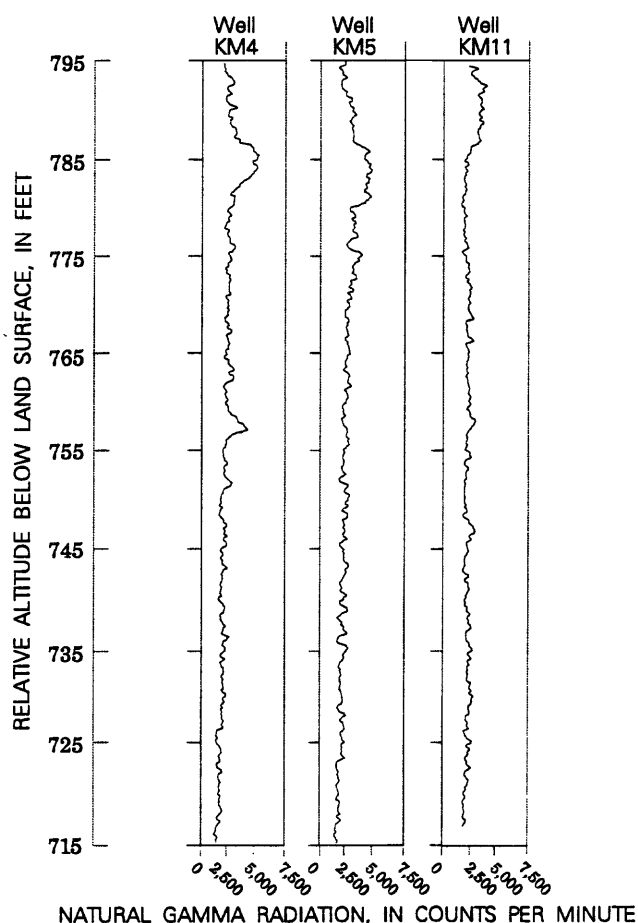


Figure 5. Natural-gamma logs for wells KM4, KM5, and KM11, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan.

Hydrology

Precipitation in Kalamazoo County averages 35 in./yr. Of this precipitation, 3 in. discharges as surface runoff and 9 in. as base flow. Evapotranspiration and ground-water flow out of the county account for the other 23 in. of precipitation (Rheaume, 1990).

An average recharge rate of 11 in./yr was estimated for outwash plains in the Kalamazoo County area by Rheaume (1990) on the basis of ground-water runoff to streams. Most of the water supply in Kalamazoo County is ground water from glacial sand and gravel deposits. Two aquifers have been identified in the glacial deposits of the area; an uppermost, unconfined aquifer and a lower, semiconfined aquifer (Rheaume, 1990).

Water Levels

This study focuses on the uppermost, unconfined aquifer. The water table in the study area mimics topography in the immediate vicinity of the maintenance garage (fig. 6). East of the maintenance garage and especially on Consumers Power Company property, the water table does not mimic topography. Where the water table does not mimic topography, the land surface has been modified during building construction. The highest water levels are in the westernmost part of the study area; from there, water levels gradually drop off toward the east-southeast. The average depth to water in the immediate vicinity of the

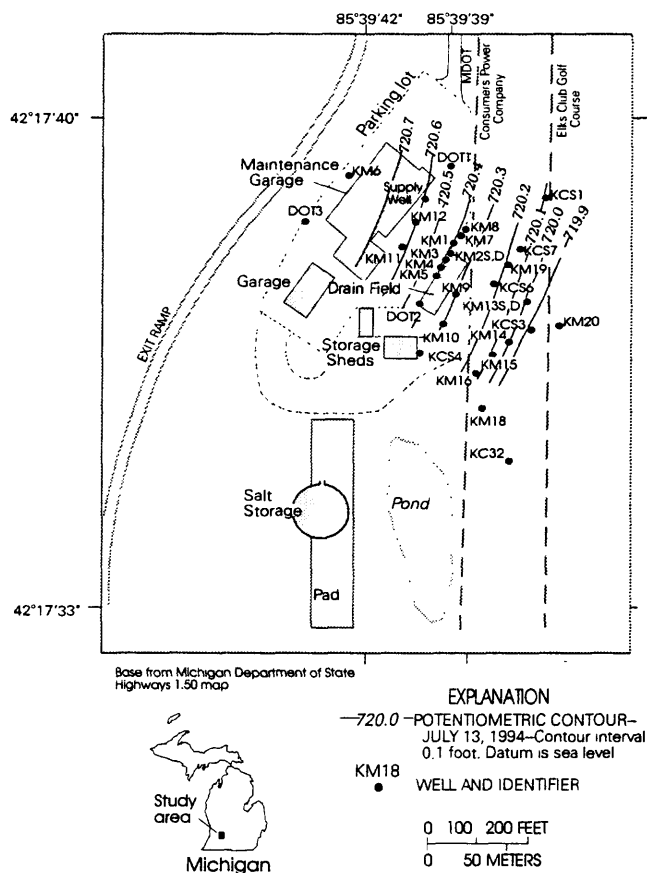


Figure 6. Water table in Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, July 13, 1994.

maintenance garage is approximately 74.7 ft. In the area east of the maintenance garage, where the land surface has been modified, the average depth to water is approximately 66.1 ft. The maximum measured difference in water level across the study area is 0.68 ft (KM6–KM18) over a distance of 462 ft.

Monthly changes in water levels were consistent between wells. Measured water levels were at a maximum on December 13, 1993 (table 9 at back of report). Measured water levels in USGS wells in the study area were at a minimum on July 13, 1994. The maximum recorded fluctuation in water level over the course of a year was just over 1 ft, with the exception of monitoring well KM10, where the maximum fluctuation was slightly greater than 2 ft.

A direct correlation between precipitation and water level is not apparent. Data from National Oceanic and Atmospheric Administration climatological stations at the Kalamazoo State Hospital and Gull Lake stations were obtained for the period of study. The

Kalamazoo State Hospital station is approximately 2 mi from the study area, however data are missing or incomplete from September through December 1993 and for February 1994. The Gull Lake station is the next closest station to the study area. It is approximately 15 mi from the study area. Data for the Gull Lake station are more complete, although some daily values are missing for January and February 1994. Both sets of data show the same trends for precipitation. Therefore, data from the Gull Lake station were used to compare monthly precipitation to water-level data in the study area. In figure 7, a hydrograph of monthly water-level data from monitoring well KM1 is plotted along with a bar graph of monthly precipitation from the Gull Lake station. A direct correlation is not observed. Several factors could affect the correlation of the water table with amount of precipitation. Because the water table is approximately 67 to 75 ft below land surface, there may be a relatively large lag between the time of precipitation and the response time of the water table as water travels through the unsaturated zone. If depth to the saturated zone were the only factor involved, precipitation should be directly reflected in levels of the water table with some delay time. The hydrograph in figure 7 is typical of the monthly data from all USGS monitoring wells at the site. Clearly, a response to local precipitation is not observed unless it is delayed by 3 to 4 months. Recharge from an upgradient source may also affect water levels in the study area. An even greater lag time is expected for water to infiltrate the unsaturated zone then travel downgradient to the study area. The final factor to consider is climate. During the winter months, precipitation in the form of snow and ice remains at the land surface and is held in storage. Once temperatures rise and snow and ice melt in the spring, water held in storage can infiltrate the unsaturated zone and reach the water table. During the summer months, evapotranspiration increases and a smaller percentage of precipitation infiltrates the unsaturated zone to reach the water table. Therefore, the water-table altitude is expected be high in the spring and early summer and low in the late summer and winter. These trends are not apparent in hydrographs from monitoring wells in the study area.

Continuous water-level recorders were installed on monitoring wells KM8 and KM10. Water-level data were recorded every 15 minutes. High-frequency fluctuations on the order of 1.8 in. were common on the

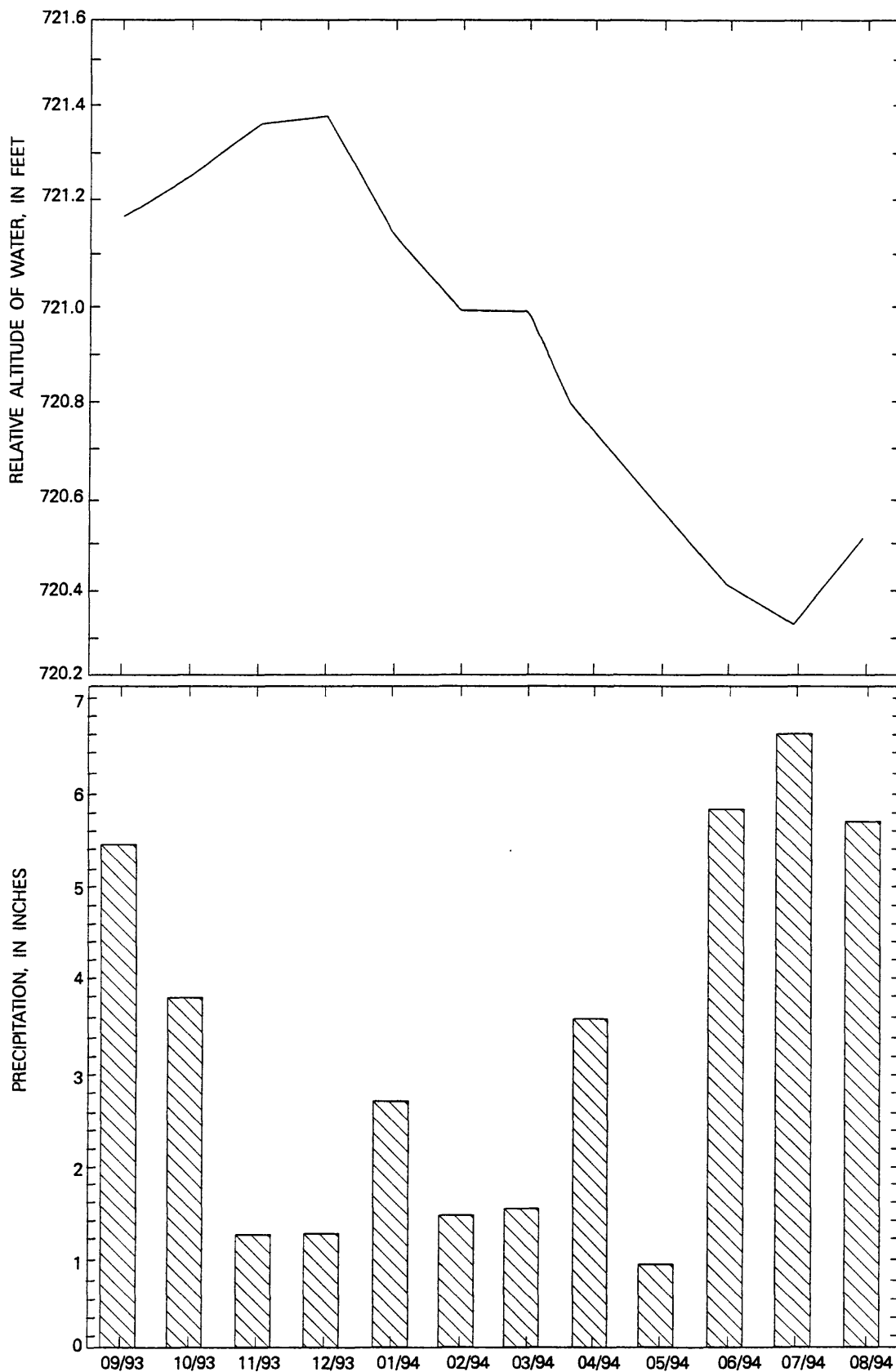


Figure 7. Monthly water-level data from monitoring well KM1 and monthly precipitation for the period of study, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan.

continuous record. These fluctuations were common on every month's record. Figure 8 shows daily water levels from monitoring well KM8 for May, 1994. They may be a function of the instrumentation or they may be due to local pumpage of the maintenance garage supply well, which is approximately 110 ft from well KM8. The supply well, however, is screened in the sand and gravel aquifer below the clay layer.

Hydraulic Properties of the Aquifer

Hydraulic conductivity was determined from transmissivity and thickness of the aquifer according to the equation

$$K = \frac{T}{b}, \quad (1)$$

where

T is transmissivity, in ft^2/d ;

K is hydraulic conductivity, in ft/d ; and

b is thickness of the aquifer, in ft (Lohman, 1979, p. 6).

Transmissivity was determined from the aquifer-test data by the Cooper-Jacob method of solution for unsteady radial flow in a confined aquifer. A close approximation of transmissivity in unconfined aquifers can be made with this method if drawdown is small in relation to saturated thickness (Stallman, 1965). Transmissivity was determined from the following equation (Todd, 1980, p. 130, equation 4.45):

$$T = \frac{2.30Q}{4\pi\Delta s}, \quad (2)$$

where

T is transmissivity, in ft^2/d ;

Q is constant well discharge, in ft^3/d ; and

s is drawdown, in ft taken where $\frac{t}{t_0} = 10$;
therefore $\log \frac{t}{t_0} = 1$.

A transmissivity of $4,100 \text{ ft}^2/\text{d}$ was estimated from the aquifer test where well KM1 was pumped and wells KM2 and KM7 were monitored for drawdown. A transmissivity of $4,600 \text{ ft}^2/\text{d}$ was estimated from the aquifer test where well KM15 was pumped and wells KM14 and KM16 were monitored for drawdown. These values are similar to calculated transmissivities of 20,000 to 60,000 (gal/d)/ft for the Alamo-Oshtemo area, defined by Allen and others (1972). Converted to the same units as those presented for this study the transmissivities defined by Allen and others (1972) are 2,700 to 8,000 ft^2/d .

Calculated horizontal hydraulic conductivity from the aquifer test where well KM1 was pumped and wells KM2 and KM7 were monitored for drawdown is 130 ft/d. Calculated horizontal hydraulic conductivity from the aquifer test where well KM15 was pumped and wells KM14 and KM16 were monitored for drawdown is 140 ft/d.

Ground-Water Flow

On a regional scale, water flows eastward from a potentiometric high west of the study area, through the study area, and eventually to Arcadia Creek or the Kalamazoo River (fig. 1) (Rheume, 1990).

In the study area, ground water flows to the east-southeast with a maximum measured gradient of 0.0015 ft/ft (fig. 6). Velocity of ground-water flow depends on the gradient of the potentiometric surface,

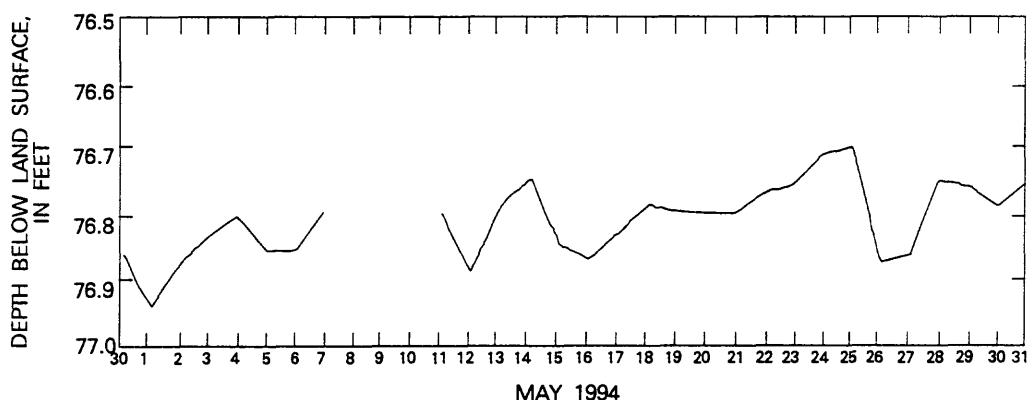


Figure 8. Daily water levels at monitoring well KM8, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, May 1994.

hydraulic conductivity, and effective porosity of the aquifer according to the following equation (Lohman, 1979, p. 10):

$$v = \frac{K \frac{dh}{dl}}{\theta}, \quad (3)$$

where

v is average velocity,

$\frac{dh}{dl}$ is gradient of the potentiometric surface,

K is hydraulic conductivity, and

θ is effective porosity.

Based on a hydraulic conductivity of 135 ft/d and an effective porosity of 20 percent (Lynch, 1985), the velocity of ground-water flow in the study area would be about 1.0 ft/d in an east-southeasterly direction.

CONTAMINATION

Two sources of gasoline contamination have been identified in the study area. These sources have affected the unsaturated zone in the source areas and the saturated zone in and downgradient from the source areas.

Sources of Contamination

The original source of unleaded gasoline to the unsaturated and saturated zones was the LUST adjacent to the MDOT maintenance garage. This LUST was estimated to have leaked 6,000 gal of unleaded fuel. The LUST was removed in 1984.

In August 1993, all other UST's, the piping, and the pump station were removed from the study area. At that time a second source of gasoline contaminants was identified. Piping leading from the UST's to the pump station was perforated and had been leaking for an undeterminable period of time, on the order of years.

Unsaturated Zone

Flow through the unsaturated zone differs from that in the saturated zone. Voids in the unsaturated zone are filled with water and air. Moisture is held between soil grains under surface-tension forces (capillary pressure). Moisture content and hydraulic conductivity in the unsaturated zone are both a function of capillary pressure. As moisture content of soil is increased,

hydraulic conductivity increases. Capillary pressure gradually decreases, and water eventually begins to drain from the soil. Moisture content continues to decrease until it reaches some minimum water content (Bedient and others, 1994).

Gasoline is a nonaqueous phase liquid (NAPL). Specifically, it is a light nonaqueous phase liquid (LNAPL). A downward-migrating NAPL infiltrates relatively easily into the unsaturated zone, whose pores are largely filled with air, because capillary forces do not repel the movement of NAPL. If sufficient NAPL is available, it continues to move downward from the source area by forming films between the gas and water phases and (or) blobs of NAPL that replace gas in the pores or water in the pore throats. After the original supply of NAPL is exhausted, 10 to 20 percent of the pore space in the vadose zone is occupied by residual NAPL in films and (or) blobs; the rest of the pore space is filled by an air-vapor mixture, primarily in the larger pores, and water spread on the surface of the soil grains and filling the smaller pores (Bedient and others, 1994).

Soil samples from the unsaturated zone from wells KM11 and KM12 were analyzed for BTEX as an indicator of gasoline. An average ratio of benzene:toluene:ethylbenzene:xylene in PS-6 gasoline is 1:1.7:75:3.8 (calculated from data in Poulsen and others, 1992). BTEX are attenuated upon release from the source through dilution, sorption, degradation, and volatilization. To study sorption of BTEX, one must determine the distribution coefficients (K_d) of the four BTEX compounds. The distribution coefficient is determined through an equation requiring that the fraction of organic carbon in the aquifer material and the octanol-water distribution coefficient (K_{ow}) be known. The fraction of organic carbon in the aquifer materials was not determined for this study. On the basis of published values of K_{ow} for BTEX, a relative statement can be made with respect to each compound's tendency to sorb to the solid phase (Christensen and others, 1994). Log K_{ow} values for BTEX are the following: benzene, 2.12; toluene, 2.73; ethylbenzene, 3.15; and xylenes, 3.26 (Mercer and others, 1990). These values indicate that benzene has the least tendency to sorb and is the most soluble of the BTEX compounds. Benzene therefore is the most mobile of the BTEX compounds. Xylenes have the greatest tendency to sorb and therefore are the least mobile of these compounds.

Extent

Monitoring well KM11 was drilled in the pipe trench where the perforated-pipe source was located. Monitoring well KM12 is in the area of the former LUST. Soils from both wells were split-spoon sampled during drilling, and the samples were analyzed for BTEX (table 5). The concentrations of BTEX in the soil samples tend to follow the results expected if the dominant process in the unsaturated zone is sorption to the solid phase. Benzene was not detected in any of the soil samples collected. Xylenes were consistently the highest in concentration of the four compounds in all soil samples collected. The order of concentration for toluene and ethylbenzene varied. Because benzene is the most soluble of the BTEX compounds, it would be expected to move the fastest with recharge through the

unsaturated zone. The data indicate that this process is occurring because benzene is indeed the most mobile of the BTEX compounds.

Concentrations of BTEX from analyses of soil samples vary with depth in the unsaturated zone in the area of the sources of contamination. Analyses of soil samples from KM11 show four peaks of relatively high concentrations of total BTEX (table 5, fig. 9). The shallowest sample where BTEX was detected is 19 ft. The highest concentration of total BTEX in soil samples from KM11, 99.7 ppm, was detected at a depth of 59 ft. Other depths where concentrations were high are 39 ft (91 ppm), 49 ft (59.4 ppm), and 74 ft (79.0 ppm). The variation in the distribution of BTEX may be due to several factors. Unleaded fuel probably leaked from the perforated pipes when pumps were being used, not when the pumps were idle. Therefore, input of fuel to

Table 5. Results of analyses of soil samples from monitoring wells KM11 and KM12 for benzene, toluene, ethylbenzene, and xylenes, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan

[Analysis per Quanterra Environmental Services laboratory schedule SW8020, a purge-and-trap gas chromatography/mass spectrometry method of analyzing for benzene, toluene, ethylbenzene, and xylenes. ft, foot; ppm, parts per million; ND, not detected]

Depth (ft)	Benzene (ppm)	Toluene (ppm)	Ethylbenzene (ppm)	Xylenes (ppm)	BTEX, total (ppm)	Percentage of water
KM11						
14	ND	ND	ND	ND	ND	2.8
19	ND	ND	ND	8.4	8.4	5.2
24	ND	.31	ND	1.5	1.81	7.4
29	ND	.84	.25	1.4	2.49	5.4
34	ND	18	13	60	91	5.8
39	ND	3.7	3.4	18	25.1	4.9
44	ND	ND	ND	1.1	1.1	3.0
49	ND	4.1	8.3	47	59.4	4.2
54	ND	.94	1.1	7.0	9.04	3.3
59	ND	9.7	15	75	99.7	3.2
64	ND	1.9	1.0	5.6	8.5	4.8
69	ND	8.9	6.8	32	47.7	5.1
74	ND	19	12	48	79.0	13.3
KM12						
14	ND	ND	ND	ND	ND	11
19	ND	ND	ND	ND	ND	7.5
24	ND	ND	ND	ND	ND	7.3
29	ND	ND	ND	ND	ND	6.0
34	ND	2.1	2.8	15	19.9	6.7
39	ND	77	31	140	248	10
44	ND	ND	ND	.30	.30	.90
51	ND	.26	ND	.78	1.04	.90
54	ND	ND	ND	ND	ND	2.1
59	ND	4.2	1.6	9.7	15.5	2.3
64	ND	1.0	.42	2.4	3.82	1.9
69	ND	.27	ND	.79	1.06	2.4
74	ND	ND	ND	ND	ND	5.2

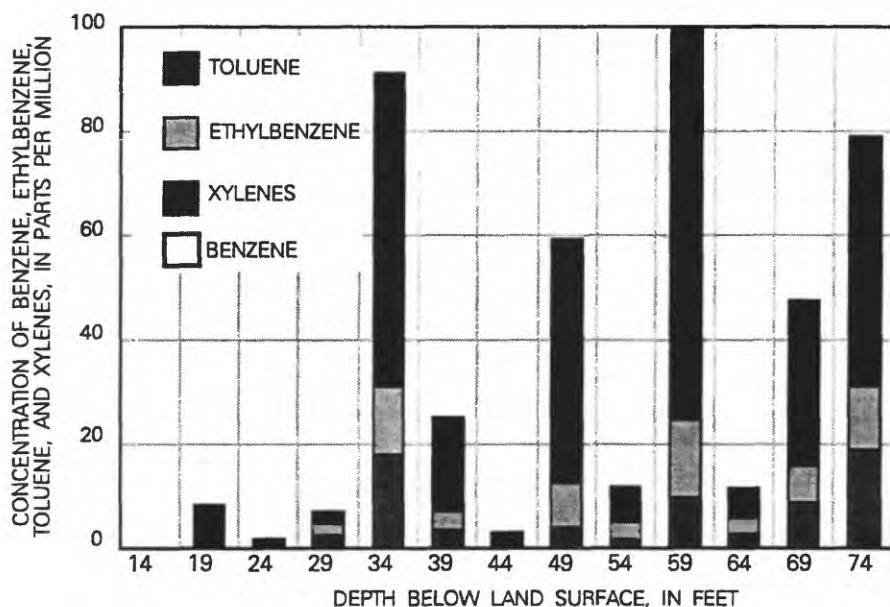


Figure 9. Concentrations of benzene, toluene, ethylbenzene, and xylenes in soil samples from the unsaturated zone, monitoring well KM11, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan.

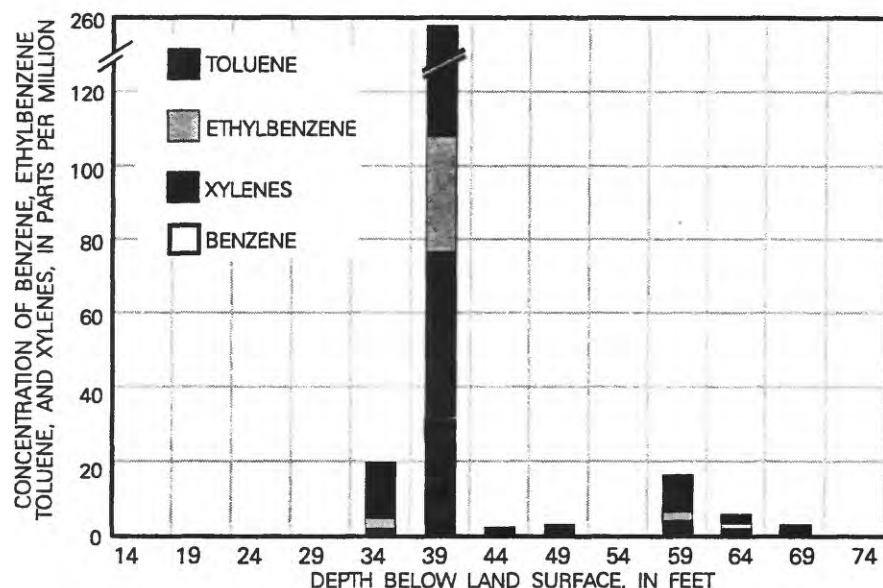


Figure 10. Concentrations of benzene, toluene, ethylbenzene, and xylenes in soil samples from the unsaturated zone, monitoring well KM12, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan.

the unsaturated zone varied with time. The variation in permeability based on grain size was also considered as a control on BTEX distribution in the unsaturated zone. The grain-size distribution for soils from KM11 was determined through sieve analyses (table 4). A correlation between distribution and concentration of BTEX with grain size was not found. The speed with which

BTEX travels through the unsaturated zone also depends on recharge, which varies over the course of a year.

Analysis of soil samples from KM12 also show variation in distribution of BTEX with depth (table 5, fig. 10). This variation is also attributed to the factors described above: variation in fuel leakage, grain-size distribution, and recharge.

The northernmost boundary of contamination in the unsaturated zone in the source area is between monitoring well KM12 and BH1 (fig. 2). BH1 was approximately 40 ft north of KM12. As part of the soil and water survey, gas from the headspace above soil samples collected from BH1 was analyzed on a PGC for BTX. Trace levels of BTX were detected in headspace-gas samples from BH1 at depths of 65 and 70 ft. Headspace-gas concentrations of 323.1 ppb benzene and 401.0 ppb xylenes were associated with soils from 75-foot depth in BH1, just above the water table. The presence of BTX in these soil samples is interpreted to be the result of volatilization from the contaminant plume in the saturated zone.

Further from the source, in borehole 2 (well KM2D, fig. 2), BTX was found in the unsaturated zone just above the saturated-zone contaminant plume. The BTX in the unsaturated zone in this area is also attributed to volatilization from the contaminant plume(s) in the saturated zone.

As described previously, benzene was not detected in soil samples collected during drilling of monitoring wells KM11 and KM12. This difference may be due to the reporting limit for BTEX analyzed in the laboratory (ppm) compared to that for BTX analyzed with the PGC (ppb).

Movement

Gasoline is expected to continue to move through the unsaturated zone to the saturated zone with recharge. Because BTEX compounds are soluble in water, residual in the unsaturated zone is expected to continue to function as an intermittent source that leaches during recharge events and seasonal changes in the water table. In some areas, where the land surface is now covered by asphalt, the contaminant may remain in the unsaturated zone indefinitely because recharge water reaching the unsaturated zone is greatly reduced.

Saturated Zone

Gasoline and other petroleum-based fuels collect in the saturated zone as pools or floating lenses on the surface of the water table that slowly solubilize into ground water. Once dissolved in water, solutes are transported by diffusion and advection. Diffusion is a process whereby solutes move in the direction of a concentration gradient; that is, from areas of higher to lower concentration. Advection is a process whereby solutes are carried along with the flowing ground water (Fetter, 1993). Monitoring wells were placed upgradient from, within, and downgradient from the source area. Most of the wells downgradient from the source were drilled in lines positioned, as closely as possible, perpendicular to the direction of ground-water flow. A cross section of the plume could then be defined, and a flux rate could be estimated.

Floating fuel was not detected in any of the monitoring wells during the study. Water samples from KM11 contained the highest concentrations of BTEX of all the wells sampled (tables 6 and 7). This well is in the pipe-trench area and is considered to be the location of the main source of contamination. Water samples from KM12, near the former location of the LUST, contained lower concentrations of BTEX. Contaminants in the unsaturated zone in both of these areas could still serve as a source of BTEX to the saturated zone through various mechanisms that would allow them to move through the unsaturated zone. As stated previously, the dominant process for this movement would probably be recharge. The area surrounding well KM11 is covered by asphalt, whereas well KM12 is in a grassy area. Movement of contaminants with recharge is not expected to occur near well KM11 but recharge is a possible mechanism near well KM12.

Extent

The first round of sampling was done before the installation of monitoring wells KM12–KM20, KM2D, and KM13D, and results of the first round were used to locate those wells. Water from well KM6 contained no detectable concentrations of BTEX (table 6), an indication that an upgradient source is not present. Water from well KM11, in the pipe-trench area, contained 48,500 ppb of total BTEX; this high concentration confirms that KM11 is in the source area.

A reasonable approximation of the width of the plume could be made from the results of analyses of water sampled in the first round (fig. 11). Well KM8 is interpreted to be near the north edge of the plume on the basis of a lower concentration of total BTEX in water sampled from it. The south boundary of the plume is defined to be south of KM5. The boundary is further defined as between wells KM9 and KM10 on the basis of high concentrations of BTEX in water from well KM9 and no detectable concentrations of BTEX in water from well KM10. Given this information, the plume is estimated to be approximately 150 ft wide at the line of wells 90 ft from the source area.

The second round of ground-water sampling was done after monitoring wells KM12–KM18 were installed. The second included samples from all monitoring wells onsite and four QA/QC samples (table 7). Wells were sampled in order of lowest to highest anticipated concentrations of BTEX. The low concentrations of BTEX in water from wells KM6, DOT1, and KM10 are interpreted to be the result of incomplete cleaning of sampling equipment on the basis of low concentrations of BTEX in equipment blank 1 collected after these wells were sampled. Concentrations of total BTEX at these wells are plotted as zero in figure 12.

Concentrations of BTEX in water from wells in the line 90 ft from the source area indicate that the width of the plume is approximately the same as it was during the first round of sampling; however, the highest concentration of total BTEX has shifted from well KM4 to KM2. The concentration of total BTEX in water from well KM11 is high, but it is lower than that in water from well KM2. This finding indicates that the main part of the plume has moved from the source area.

Table 6. Results of analyses of ground-water samples from monitoring wells, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, September 23, 1993

[Analysis per U.S. Geological Survey National Water Quality Laboratory schedule 1378, a purge and trap capillary gas chromatograph/mass spectrometry method of analyzing for benzene, toluene, ethylbenzene, and xylenes. ppb, parts per billion; R, replicate sample]

Well identifier	Benzene (ppb)	Toluene (ppb)	Ethylbenzene (ppb)	Xylenes (ppb)	Total BTEX (ppb)
KM1	260	100	160	240	760
KM2	610	1,500	430	690	3,230
KM2R	580	1,500	450	720	3,250
KM3	2,300	3,800	540	1,100	7,740
KM4	4,100	7,700	630	1,300	13,730
KM5	120	320	110	200	750
KM6	<.2	<.2	<.2	<.2	<.2
KM7	110	59	45	88	302
KM8	17	78	18	37	150
KM9	1,000	1,900	900	1,600	5,400
KM10	<.2	.3	<.2	.3	.6
KM11	3,900	32,000	2,700	9,900	48,500
Trip blank	<.2	<.2	<.2	<.2	<.2

Table 7. Results of analyses of ground-water samples from monitoring wells, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, August 9-10, 1994

[Analysis per U.S. Geological Survey National Water Quality Laboratory schedule 1378, a purge and trap capillary gas chromatograph/mass spectrometry method of analyzing for benzene, toluene, ethylbenzene, and xylenes. ppb, parts per billion; R, replicate sample]

Well identifier	Benzene (ppb)	Toluene (ppb)	Ethylbenzene (ppb)	Xylenes (ppb)	Total BTEX (ppb)
KM1	400	110	300	180	990
KM2	3,800	7,200	1,400	2,700	15,100
KM2R	4,200	7,400	1,400	2,500	15,500
KM3	1,900	5,200	480	1,000	8,580
KM4	1,700	4,200	380	770	7,050
KM5	62	600	200	340	1,202
KM6	.5	2.0	.6	1.2	4.3
KM7	26	3.0	47	20	96
KM8	.6	1.1	1.0	1.0	3.7
KM9	34	62	150	110	356
KM10	.2	2.1	.4	1.4	4.1
KM11	1,100	6,700	930	3,500	12,230
KM12	180	210	68	110	568
KM13	1,400	69	260	69	1,798
KM14	.8	1.0	1.2	1.2	4.2
KM15	2.2	1.8	2.4	1.5	7.9
KM16	14	2.1	5.9	2.3	24.3
DOT1	.4	2.8	.7	1.9	5.8
DOT2	<.2	.4	<.2	.3	<.9
KCS1	<.2	<.2	<.2	<.2	<.2
KCS3	4.2	1.5	1.0	1.2	7.9
KCS6	450	57	200	150	857
Rinse Water	<.2	<.2	<.2	<.2	<.2
Equipment 1	.5	7.6	1.1	3.2	12.4
Equipment 2	32	140	32	57	261
Equipment 3	<.2	<.2	<.2	<.2	<.2

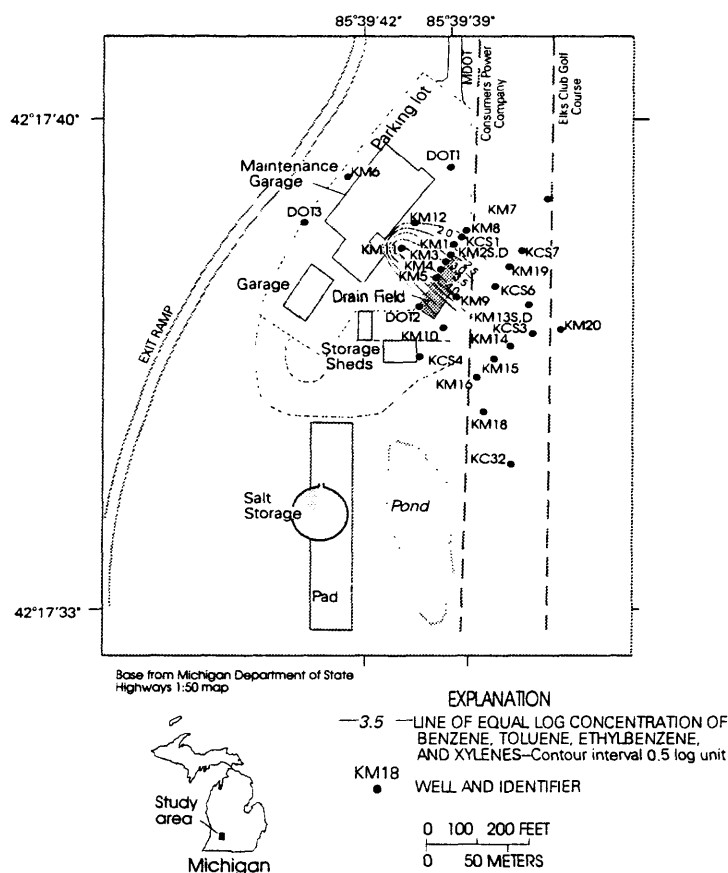


Figure 11. Log₁₀ concentrations of total benzene, toluene, ethylbenzene, and xylenes in the saturated zone, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, September 23, 1993.

The contaminant plume is interpreted to be moving through the area north of well KCS3 on the basis of concentrations of BTEX in water from well KM13 (table 7, fig. 13). Detectable concentrations of BTEX were not anticipated in water from monitoring well KM13, given its location just north of well KCS3. Water from well KCS3 historically has not contained detectable concentrations of BTEX. Relatively high concentrations of BTEX were found in water samples from well KM13. Monitoring wells KM16, KM15, KM14, and KM8, respectively, followed KM13 in the sampling sequence. Water samples from these wells contained progressively lower concentrations of BTEX. The progressive decrease in BTEX concentrations is interpreted to be a result of a progressively more thorough cleaning of the sampling pump as clean water (from the decontamination procedure and from pumpage during sampling) flowed through the pump. Water from monitoring wells KM8, KM14, KM15, and KM16 probably does not contain BTEX from the contaminant plume. Concentrations of

BTEX in water from wells KM8, KM14, KM15, and KM16 are interpreted to be the result of incomplete cleaning of the sampling pump.

Monitoring well KM19 is near the north boundary of the contaminant plume, as evidenced by results of the soil and water survey (fig. 13). Unquantifiable peaks were identified on the chromatogram from analysis of water from well KM19 during the soil and water survey. These unquantifiable peaks may indicate very low concentrations of BTX. Low concentrations of BTX are anticipated at the contaminant-plume edge.

As part of the QA/QC for this sampling, equipment blank 2 was collected after water samples with high concentrations of BTEX were collected. A relatively high concentration of BTEX was found in this equipment blank. This value is considered to be a result of incomplete cleaning of the sampling pump.

The plume is estimated to cover approximately 30,000 ft² on the basis of relatively high concentrations of BTEX in water from wells KM9, KCS6, and KM13. Data collected during the soil and water survey further constrain the estimated dimensions of the plume.

As described in the section "Unsaturated Zone," benzene is considered to be the least sorbed of the BTEX compounds because of its K_{ow} . Benzene is also the most soluble of the BTEX compounds in water. A comparison of BTEX concentrations between monitoring wells KM11 and KM13 demonstrates this relation. The concentration of benzene in water samples from well KM11, in the source area, is significantly lower than that of the xylenes, the most sorbed and least soluble of the BTEX compounds. The opposite is demonstrated in water from well KM13: the concentration of benzene is significantly higher than that of the xylenes. This finding supports the concept that benzene moves through the system more efficiently than xylenes do due to the higher solubility of benzene. The relative distribution of the BTEX compounds may also have been influenced by microbial activity as described in "Evidence of Biodegradation of Fuel Components."

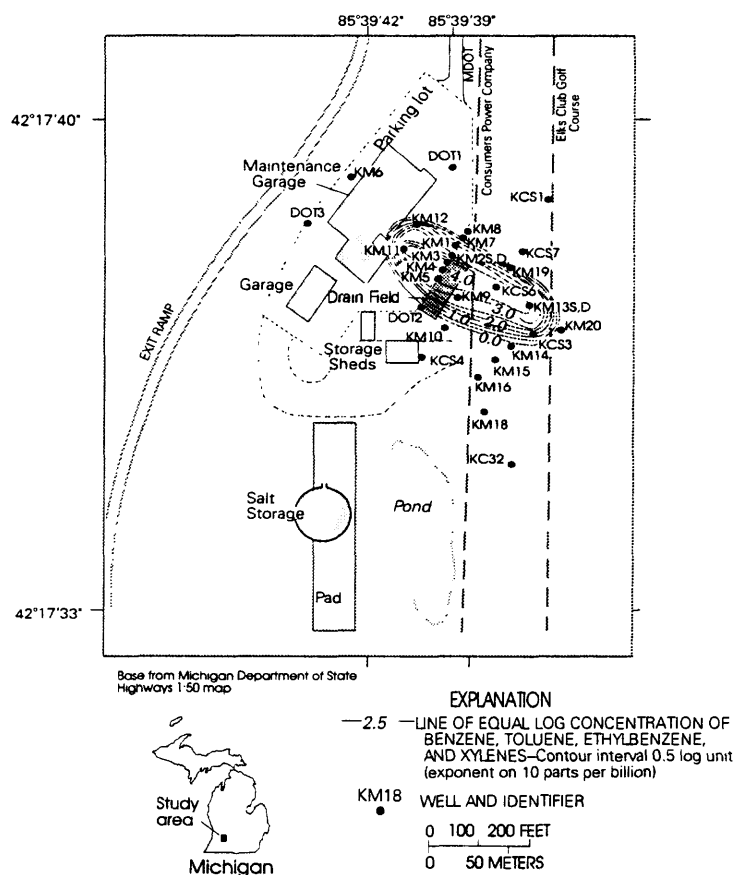


Figure 12. Log₁₀ concentrations of total benzene, toluene, ethylbenzene, and xylenes in the saturated zone, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, August 9-10, 1994.

Data from monitoring well pairs KM2S–KM2D and KM13S–KM13D (tables 6 and 7) indicate that although contaminants have mixed with ground water at the water table, they have not mixed with ground water at a depth of 20 ft or more below the water table. Samples from wells KM2S and KM13S both contain relatively high concentrations of BTEX, whereas samples from wells KM2D and KM13D contain no detectable concentrations of BTEX.

Movement

Ground water is moving at a rate of approximately 1.0 ft/d in an east-southeasterly direction. Contaminants are expected to move at a rate less than 1.0 ft/d because of sorption, differences in solubility, and susceptibility to microbial degradation, as discussed in the next section. On Consumers Power Company property adjacent and to the east of the MDOT maintenance garage property, the contaminant plume continues to move in the same

east-southeasterly direction. The plume appears to continue onto the Elks Club Golf course to the east of the Consumers Power Company right of way.

Evidence of Biodegradation of Fuel Components

The study area was evaluated for evidence of biotransformation of fuel components. Two lines of evidence indicate that the site conditions support microbial degradation of fuel components. First, dramatic changes in water chemistry are evident in the vicinity of the contamination source. Second, the ratios of fuel components change with distance along the flowpath.

Microorganisms may leave evidence of their degradation activities in the water chemistry at a contamination site. The hydrocarbons commonly dissolved in water after release from gasoline spills (BTEX) are known to be readily degraded by microorganisms where oxygen is present (Norris and others, 1994). Where oxygen is present, resulting in aerobic aquifer conditions, microorganisms use the oxygen along with the hydrocarbon for growth. Oxygen supply to ground water may be limited by the rate of diffusion of air through the overlying aquifer material, and the growth of microorganisms may use up the available oxygen and cause anaerobic aquifer conditions. When oxygen is no longer available, some microorganisms may use compounds other than oxygen during their metabolism of hydrocarbons. Oxidized compounds that can be used for microbial metabolism of hydrocarbons include nitrate, ferric iron, sulfate and carbon dioxide (Norris and others, 1994; Chapelle, 1993). During metabolism of the hydrocarbon, microorganisms convert these oxidized compounds to less oxidized forms, such as nitrogen gas or ammonia, ferrous iron, sulfide, or methane. The presence of these less oxidized compounds in the vicinity of hydrocarbon contamination is considered an indication that microorganisms have been active at the site. This is especially

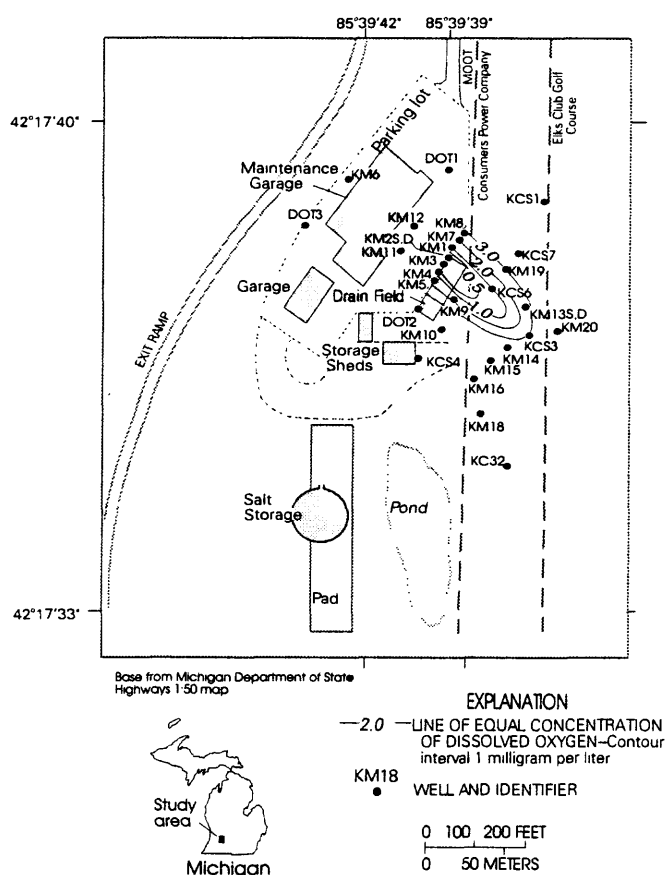


Figure 13. Dissolved oxygen concentrations in the saturated zone, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, December 9, 1994.

Table 8. Physical and chemical characteristics of ground water from selected wells, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, December 9, 1994

[USGS, U.S. Geological Survey; MDOT, Michigan Department of Transportation; mg/L, milligram per liter; µg/L, microgram per liter; µS/cm microsiemen per centimeter at 25 degrees Celsius; ND, not determined]

Constituent or property	Analyzed by USGS			Analyzed by MDOT	
	Well KM19	Well KM13	Well KM4	Well KM4	Well KM6
Alkalinity (mg/L as CaCO ₃)	398	352	435	360	340
Chloride (mg/L)	430	350	320	350	150
Dissolved oxygen (mg/L)	2.30	ND	ND	.35	8.59
Iron (µg/L)	2,300	3,400	7,900	12,000	<100
Manganese (µg/L)	710	390	320	360	<20
pH (units) ¹	7.1	7.2	7.0	7.2	7.39
Specific conductance (µS/cm)	2,054	1,750	1,810	1,210	790
Sulfate, dissolved (mg/L)	25	4.8	5.6	13	31
Sulfide, total (mg/L)	<.5	<.5	<.5	<1	<1
Temperature (degrees Celsius)	11.5	10.8	10.6	12.7	11.8

¹ pH, temperature, dissolved oxygen, and specific conductance were measured in the field by USGS.

true if the zone of less oxidized compounds is found in an otherwise aerobic aquifer (Norris and others, 1994; Chapelle, 1993).

Microbial degradation of BTEX may result in changes in the ratios of these compounds along the plume flowpath. Changes in compound ratios may occur because microorganisms prefer to use toluene and xylenes as growth substrates, particularly where oxygen is not present (Edwards and Grbic-Galic, 1992). In laboratory and field experiments, and under aerobic and anaerobic conditions, benzene is usually degraded most slowly (Norris and others, 1994). Under anaerobic conditions, if other compounds are available for microbial growth, benzene may not be degraded at all (Edwards and Grbic-Galic, 1992).

In table 8, water-chemistry data are listed for water samples collected from three wells sampled by the USGS on December 9, 1994, and analyzed by the USGS National Water Quality Laboratory. For comparison, data are also included from two samples collected by the USGS on August 19, 1994, but analyzed by an independent laboratory contracted by MDOT. Water from well KM4, approximately 80 ft immediately downgradient from the location of the leaking pipe (fig. 2), was analyzed by the two laboratories. The results from both samplings are comparable; the slight differences in the concentrations of constituents might result from dif-

ferences in analytical methods or from seasonal differences in water quality, as well as from random sampling error. Water from well KM6 (table 8) was analyzed only by the MDOT contract laboratory. These data are included to indicate water-quality conditions in an uncontaminated well. Water chemistry changed dramatically over short lateral distances, and changes in water chemistry correlated with the presence of contamination. For example, although dissolved oxygen was present in high concentration in the uncontaminated well (KM6, table 8), dissolved oxygen was present in very low concentration in highly contaminated wells such as KM4 (table 8). Dissolved oxygen was found at intermediate concentration in moderately contaminated wells such as KM19 (table 8). Sulfate, another oxidized chemical compound, was distributed similarly to oxygen, and was also found at lowest concentration in the most contaminated wells. In contrast, iron and manganese were found at highest concentrations in the contaminated wells but were generally below detectable concentrations in the uncontaminated well. The oxidized forms of iron and manganese are virtually insoluble in water, but the less oxidized forms of both elements are highly soluble in water. Detectable concentrations of iron and manganese in water commonly indicate anaerobic conditions. Finally, chloride and specific conductance were generally high in most wells within the contaminated area. The high levels of chloride and specific conductance in wells within the contaminated area most likely indicate the history of road-salt storage and contamination at MDOT site (Carrie Geyer, Michigan Department of Transportation, oral commun., 1994). No trend or pattern is evident in concentrations of other constituents.

The concentrations of dissolved oxygen, sulfate, iron and manganese indicate that microorganisms have been sufficiently active in the contaminated area to consume oxygen and other oxidized compounds such as sulfate. Dissolved oxygen concentrations in various wells were determined at several times during 1994. Trends in dissolved oxygen concentrations within the contaminated area are shown in figure 13, which indicates that the central, most highly contaminated part of the plume is virtually anaerobic. Well KM2D was completed at a depth of 98.93 ft on December 7, 1994. Field measurements of temperature, dissolved oxygen, specific conductance and pH were made on ground water from this well on December 8, 1994. Dissolved oxygen concentration in this well was relatively high (8.51 mg/L), an indication that the zone of anaerobic

ground water is not very deep. The trend in dissolved oxygen in comparison to the area of contamination holds true whether the sample was collected from a well within the septic field area or not. Wells KM2S and KM4 are within the contaminant plume and the septic field area. Water sampled from these wells on August 9, 1994 showed high concentrations of total BTEX (15,100 ppb, KM2S and 7,050 ppb, KM4). Dissolved oxygen concentrations were measured on August 19, 1994 in these wells and they are virtually anaerobic (0.4 mg/L, KM2S and 0.35 mg/L, KM4). Wells KM9 and KCS6 are located within the contaminant plume but are outside of the septic field area. High concentrations of BTEX were present in water collected on August 9, 1994 from wells KM9 (356 ppb) and KCS6 (857 ppb). Water from these wells is also virtually anaerobic (0.8 mg/L, KM9 and 0.5 mg/L, KCS6).

The trends in iron concentration within the contaminated area are shown in figure 14. These data also indicate anaerobic conditions within the central part of the plume, because the iron concentrations increase toward the plume center and only the less oxidized form of iron is soluble in water. The dramatic gradients in water chemistry and their close association with zones of increasing contamination indicate that the BTEX compounds support microbial growth in the study area.

Microbial growth on BTEX compounds probably also occurs at the leading edge and lateral and vertical margins of the plume, where oxygen supply from the surrounding aquifer would not be limiting. In these locations, no changes in water chemistry would be expected; however, the relatively narrow dimensions of some contaminant plumes have been attributed to microbial degradation of the contaminants at the plume margins (Norris and others, 1994).

In addition to changes in water chemistry within the plume, microbial activity in the study area is also indicated by changes in the ratio of BTEX components along a longitudinal plume transect. In figure 12, the ratio of benzene to the sum of toluene, ethylbenzene, and xylenes is toward increasing abundance of benzene relative to the other three constituents within the most anaerobic parts of the plume, as well as along the plume flowpath. The trend of increasing B:T:E ratio is consistent with the observation that benzene is recalcitrant to bacterial degradation, particularly under anaerobic conditions and when other, preferred compounds are present. At the plume margins where

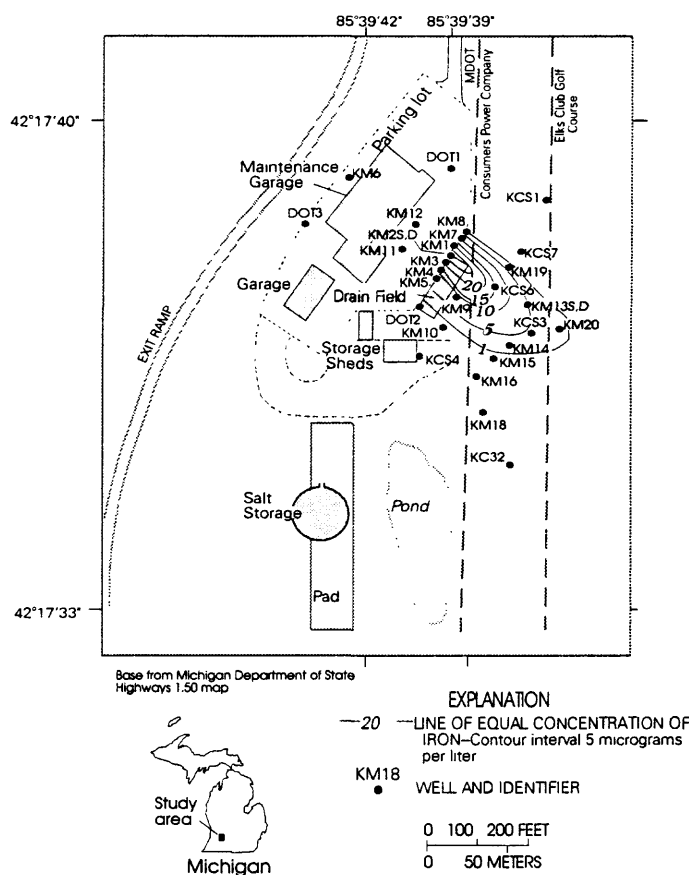


Figure 14. Iron concentrations in the saturated zone, Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, December 9, 1994.

oxygen is not limiting, benzene may be degraded relatively rapidly, especially if the other contaminants are present in low concentration.

Although water-chemistry data from the study area indicate that microorganisms have been active within the plume margins, estimation of the rate of microbial degradation of BTEX contaminants in the study area is not possible on the basis of data collected in this study. BTEX contaminants sorb variably to aquifer solids and differ as to solubility in water. To assess the bioremediation potential of the study area properly, one would need to determine the relative effect of sorption and microbial degradation on BTEX component transport by means of field and laboratory experiments. The different ratios of BTEX contaminants at various locations in the flowpath are probably a result of not only differential sorption and solubility but also differential susceptibility to microbial degradation.

SUMMARY

The aquifer examined in this study is an unconfined sand and gravel aquifer in the Galesburg-Vicksburg outwash plain. A perched zone was identified during drilling of monitoring wells KM16 and KM17. This perched zone is interpreted to extend to the south of the study area, and it does not directly underlie the gasoline-contaminant plume.

The average depth to water in the study area is approximately 74.7 ft. Water-level fluctuations are small; maximum fluctuation was slightly more than 1 ft during August 1993 - August 1994. Hydraulic conductivities based on aquifer test data collected for the study and estimated by use of the Cooper-Jacob method of solution ranged from 130 to 144 ft/d. Ground water is moving in an east-southeasterly direction at a rate of approximately 1 ft/d.

A LUST and perforated piping leading from UST's to a pump station were identified as sources of gasoline contaminants to the study area. All UST's and piping and the pump station have been removed from the area. The unsaturated zone in the area remains a source of gasoline contaminants. Residual contaminants are expected to move with recharge through the unsaturated zone in areas not covered by asphalt.

The gasoline contaminant plume covers an area of approximately 30,000 ft² in the saturated zone. The plume is not present at or below a depth 20 ft below the water table. The distributions of individual components of BTEX within the contaminant plume indicate that differential sorption, differential solubility, and differential susceptibility to microbial degradation exert some control over the movement of the contaminant plume. Given these factors, the plume is expected to move at a rate of less than 1 ft/d.

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Table 9. Monthly water levels in monitoring wells in the Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, September 18, 1993, through August 24, 1994

Date	Relative altitude of measuring point, in feet	Distance of measuring point above land surface, in feet	Depth to water from measuring point, in feet	Relative altitude of water, in feet	Well depth below land surface, in feet
KM1					
9/18/93	798.37	3.21	77.19	721.18	81.53
10/14/93	797.46	2.30	76.19	721.27	81.53
11/16/93	797.46	2.30	76.08	721.38	81.53
12/13/93	797.46	2.30	76.06	721.40	81.53
1/25/94	797.46	2.30	76.31	721.15	81.53
2/22/94	797.46	2.30	76.47	720.99	81.53
3/03/94	797.46	2.30	76.47	720.99	81.53
4/11/94	797.46	2.30	76.77	720.69	81.53
5/17/94	797.46	2.30	76.91	720.55	81.53
6/17/94	797.46	2.30	77.05	720.41	81.53
7/13/94	797.46	2.30	77.13	720.33	81.53
8/24/94	797.46	2.30	76.94	720.52	81.53
KM2S					
9/18/93	798.83	3.69	77.60	721.23	79.41
10/14/93	797.69	2.55	76.35	721.34	79.41
11/16/93	797.69	2.55	76.24	721.45	79.41
12/13/93	797.69	2.55	76.21	721.48	79.41
1/25/94	797.69	2.55	76.47	721.22	79.41
2/22/94	797.69	2.55	76.63	721.06	79.41
3/03/94	797.69	2.55	76.63	721.06	79.41
4/11/94	797.69	2.55	76.93	720.76	79.41
5/17/94	797.69	2.55	77.08	720.61	79.41
6/17/94	797.69	2.55	77.22	720.47	79.41
7/13/94	797.69	2.55	77.30	720.39	79.41
8/24/94	797.69	2.55	77.11	720.58	79.41
KM3					
9/18/93	798.81	3.67	77.56	721.25	78.85
10/14/93	797.69	2.55	76.38	721.31	78.85
11/16/93	797.69	2.55	76.23	721.46	78.85
12/13/93	797.69	2.55	76.21	721.48	78.85
1/25/94	797.69	2.55	76.46	721.23	78.85
2/22/94	797.69	2.55	76.61	721.08	78.85
3/03/94	797.69	2.55	76.62	721.07	78.85
4/11/94	797.69	2.55	76.92	720.77	78.85
5/17/94	797.69	2.55	77.07	720.62	78.85
6/17/94	797.69	2.55	77.21	720.48	78.85
7/13/94	797.69	2.55	77.29	720.40	78.85
8/24/94	797.69	2.55	77.10	720.59	78.85
KM4					
9/18/93	799.43	4.35	78.59	720.84	77.60
10/14/93	797.58	2.50	76.67	720.91	77.60
11/16/93	797.58	2.50	76.55	721.03	77.60
12/13/93	797.58	2.50	76.52	721.06	77.60
1/25/94	797.58	2.50	76.77	720.81	77.60
2/22/94	797.58	2.50	76.90	720.68	77.60
3/03/94	797.58	2.50	76.92	720.66	77.60

Table 9. Monthly water levels in monitoring wells in the Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, September 18, 1993, through August 24, 1994—*Continued*

Date	Relative altitude of measuring point, in feet	Distance of measuring point above land surface, in feet	Depth to water from measuring point, in feet	Relative altitude of water, in feet	Well depth below land surface, in feet
KM4—Continued					
4/11/94	797.58	2.50	77.22	720.36	77.60
5/17/94	797.58	2.50	77.38	720.20	77.60
6/17/94	797.58	2.50	77.54	720.04	77.60
7/13/94	797.58	2.50	77.60	719.98	77.60
8/24/94	797.58	2.50	77.43	720.15	77.60
KM5					
9/18/93	798.40	3.29	77.17	721.23	78.79
10/14/93	797.56	2.45	76.24	721.32	78.79
11/16/93	797.56	2.45	76.14	721.42	78.79
12/13/93	797.56	2.45	76.01	721.55	78.79
1/25/94	797.56	2.45	76.35	721.21	78.79
2/22/94	797.56	2.45	76.47	721.09	78.79
3/03/94	797.56	2.45	76.50	721.06	78.79
4/11/94	797.56	2.45	76.80	720.76	78.79
5/17/94	797.56	2.45	76.96	720.60	78.79
6/17/94	797.56	2.45	77.08	720.48	78.79
7/13/94	797.56	2.45	77.17	720.39	78.79
8/24/94	797.56	2.45	76.98	720.58	78.79
KM6					
9/18/93	800.43	3.41	78.82	721.61	79.66
10/14/93	799.37	2.35	77.67	721.70	79.66
11/16/93	799.37	2.35	77.59	721.78	79.66
12/13/93	799.37	2.35	77.52	721.85	79.66
1/25/94	799.37	2.35	77.76	721.61	79.66
2/22/94	799.37	2.35	77.94	721.43	79.66
3/03/94	799.37	2.35	77.88	721.49	79.66
4/11/94	799.37	2.35	78.22	721.15	79.66
5/17/94	799.37	2.35	78.34	721.03	79.66
6/17/94	799.37	2.35	78.49	720.88	79.66
7/13/94	799.37	2.35	78.57	720.80	79.66
8/24/94	799.37	2.35	78.40	720.97	79.66
KM7					
9/18/93	797.73	2.94	76.55	721.18	77.25
10/14/93	797.19	2.40	75.94	721.25	77.25
11/16/93	797.19	2.40	75.83	721.36	77.25
12/13/93	797.19	2.40	75.80	721.39	77.25
1/25/94	797.19	2.40	76.05	721.14	77.25
2/22/94	797.19	2.40	76.22	720.97	77.25
3/03/94	797.19	2.40	76.22	720.97	77.25
4/11/94	797.19	2.40	76.52	720.67	77.25
5/17/94	797.19	2.40	76.66	720.53	77.25
6/17/94	797.19	2.40	76.81	720.38	77.25
7/13/94	797.19	2.40	76.88	720.31	77.25
8/24/94	797.19	2.40	76.79	720.40	77.25

Table 9. Monthly water levels in monitoring wells in the Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, September 18, 1993, through August 24, 1994—*Continued*

Date	Relative altitude of measuring point, in feet	Distance of measuring point above land surface, in feet	Depth to water from measuring point, in feet	Relative altitude of water, in feet	Well depth below land surface, in feet
KM8					
9/18/93	797.70	2.95	76.49	721.21	79.22
10/14/93	797.25	2.50	75.96	721.29	79.22
11/16/93	797.25	2.50	75.86	721.39	79.22
12/13/93	797.25	2.50	75.83	721.42	79.22
1/25/94	797.25	2.50	76.07	721.18	79.22
2/22/94	797.25	2.50	76.25	721.00	79.22
3/03/94	797.25	2.50	76.24	721.01	79.22
4/11/94	797.25	2.50	76.55	720.70	79.22
5/17/94	797.25	2.50	76.71	720.54	79.22
6/17/94	797.25	2.50	76.85	720.40	79.22
7/13/94	797.25	2.50	76.91	720.34	79.22
8/24/94	797.25	2.50	--	--	79.22
KM9					
9/18/93	793.23	2.94	72.05	721.18	73.90
10/14/93	792.79	2.50	71.55	721.24	73.90
11/16/93	792.79	2.50	71.44	721.35	73.90
12/13/93	792.79	2.50	71.42	721.37	73.90
1/25/94	792.79	2.50	71.67	721.12	73.90
2/22/94	792.79	2.50	71.80	720.99	73.90
3/03/94	792.79	2.50	71.83	720.96	73.90
4/11/94	792.79	2.50	71.13	721.66	73.90
5/17/94	792.79	2.50	72.28	720.51	73.90
6/17/94	792.79	2.50	72.42	720.37	73.90
7/13/94	792.79	2.50	72.50	720.29	73.90
8/24/94	792.79	2.50	72.31	720.48	73.90
KM10					
9/18/93	792.64	3.71	71.60	721.04	73.89
10/14/93	791.98	3.05	70.77	721.21	73.89
11/16/93	791.98	3.05	70.67	721.31	73.89
12/13/93	791.98	3.05	70.63	721.35	73.89
1/25/94	791.98	3.05	70.88	721.10	73.89
2/22/94	791.98	3.05	71.09	720.89	73.89
3/03/94	791.98	3.05	71.03	720.95	73.89
4/11/94	791.98	3.05	71.36	720.62	73.89
5/17/94	791.98	3.05	71.49	720.49	73.89
6/17/94	791.98	3.05	--	--	73.89
7/13/94	791.98	3.05	72.67	719.31	73.89
8/24/94	791.98	3.05	72.55?	719.43?	73.89
KM11					
09/18/93	797.23	1.30	75.82	721.41	77.67
10/14/93	797.23	1.30	75.72	721.51	77.67
11/16/93	795.85	-.08	74.22	721.63	77.67
12/13/93	795.85	-.08	74.20	721.65	77.67
1/25/94	795.85	-.08	74.44	721.41	77.67
2/22/94	795.85	-.08	74.58	721.27	77.67
3/03/94	795.85	-.08	74.60	721.25	77.67

Table 9. Monthly water levels in monitoring wells in the Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, September 18, 1993, through August 24, 1994—*Continued*

Date	Relative altitude of measuring point, in feet	Distance of measuring point above land surface, in feet	Depth to water from measuring point, in feet	Relative altitude of water, in feet	Well depth below land surface, in feet
KM11—Continued					
4/11/94	795.85	-0.08	74.87	720.98	77.67
5/17/94	795.85	-0.08	75.16	720.69	77.67
6/17/94	795.85	-0.08	75.17	720.68	77.67
7/13/94	795.85	-0.08	75.24	720.61	77.67
8/24/94	795.85	-0.08	75.08	720.77	77.67
KM12					
7/13/94	799.12	2.60	78.52	720.60	82.50
8/24/94	796.27	-.25	75.49	720.78	82.50
KM13S					
7/13/94	794.11	2.60	74.19	719.92	77.20
8/24/94	794.11	2.60	74.02	720.09	77.20
KM14					
7/13/94	790.25	2.80	70.28	719.97	74.75
8/24/94	790.25	2.80	70.10	720.15	74.75
KM15					
7/13/94	787.49	2.80	67.42	720.07	71.85
8/24/94	787.49	2.80	67.23	720.26	71.85
KM16					
7/13/94	787.28	2.80	67.13	720.15	77.40
8/24/94	787.28	2.80	66.95	720.33	77.40
MDOT1					
9/18/93	797.79	1.35	76.48	721.31	80.53
10/14/93	797.79	1.35	76.39	721.40	80.53
11/16/93	797.79	1.35	76.30	721.49	80.53
12/13/93	797.79	1.35	76.25	721.54	80.53
1/25/94	797.79	1.35	76.50	721.29	80.53
2/22/94	797.79	1.35	76.69	721.10	80.53
3/03/94	797.79	1.35	76.62	721.17	80.53
4/11/94	797.79	1.35	76.98	720.81	80.53
5/17/94	797.79	1.35	77.11	720.68	80.53
6/17/94	797.79	1.35	77.26	720.53	80.53
7/13/94	797.79	1.35	77.31	720.48	80.53
8/24/94	797.79	1.35	77.15	720.64	80.53
MDOT2					
9/18/93	797.14	1.80	75.82	721.32	78.57
10/14/93	797.14	1.80	75.74	721.40	78.57
11/16/93	797.14	1.80	75.63	721.51	78.57
12/13/93	797.14	1.80	75.59	721.55	78.57
1/25/94	797.14	1.80	75.84	721.30	78.57
2/22/94	797.14	1.80	76.00	721.14	78.57
3/03/94	797.14	1.80	75.98	721.16	78.57
4/11/94	797.14	1.80	76.32	720.82	78.57
5/17/94	797.14	1.80	76.45	720.69	78.57
6/17/94	797.14	1.80	76.60	720.54	78.57

Table 9. Monthly water levels in monitoring wells in the Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, September 18, 1993, through August 24, 1994—*Continued*

Date	Relative altitude of measuring point, in feet	Distance of measuring point above land surface, in feet	Depth to water from measuring point, in feet	Relative altitude of water, in feet	Well depth below land surface, in feet
MDOT2—Continued					
7/13/94	797.14	1.80	76.66	720.48	78.57
8/24/94	797.14	1.80	76.49	720.65	78.57
MDOT3					
9/18/93	798.81	1.35	77.16	721.65	80.27
10/14/93	798.81	1.35	77.09	721.72	80.27
11/16/93	798.81	1.35	76.94	721.87	80.27
12/13/93	798.81	1.35	76.87	721.94	80.27
1/25/94	798.81	1.35	77.10	721.71	80.27
KCS1					
9/18/93	799.68	3.35	78.66	721.02	78.26
10/14/93	799.68	3.35	78.57	721.11	78.26
11/16/93	799.68	3.35	78.46	721.22	78.26
12/13/93	799.68	3.35	78.45	721.23	78.26
1/25/94	799.68	3.35	78.67	721.01	78.26
2/22/94	799.68	3.35	78.90	720.78	78.26
3/03/94	799.68	3.35	78.87	720.81	78.26
4/11/94	799.68	3.35	79.20	720.48	78.26
5/17/94	799.68	3.35	79.35	720.33	78.26
6/17/94	799.68	3.35	79.48	720.20	78.26
7/13/94	799.68	3.35	79.52	720.16	78.26
8/24/94	799.68	3.35	79.32	720.36	78.26
KCS2					
9/18/93	780.39	.92	59.55	720.91	61.49
10/14/93	780.39	.92	59.48	720.98	61.49
11/16/93	780.39	.92	59.38	721.08	61.49
12/13/93	780.39	.92	59.36	721.10	61.49
1/25/94	780.39	.92	59.59	720.87	61.49
2/22/94	780.39	.92	59.81	720.65	61.49
3/03/94	780.39	.92	59.81	720.65	61.49
4/11/94	780.39	.92	60.11	720.35	61.49
5/17/94	780.39	.92	60.26	720.20	61.49
6/17/94	780.39	.92	60.40	720.06	61.49
7/13/94	780.39	.92	60.44	720.02	61.49
8/24/94	780.39	.92	60.25	720.21	61.49
KCS3					
9/18/93	793.94	3.15	73.28	720.66	84.69
10/14/93	793.94	3.15	73.18	720.76	84.69
11/16/93	793.94	3.15	73.06	720.88	84.69
12/13/93	793.94	3.15	73.05	720.89	84.69
1/25/94	793.94	3.15	73.30	720.64	84.69
2/22/94	793.94	3.15	73.50	720.44	84.69
3/03/94	793.94	3.15	73.49	720.45	84.69
4/11/94	793.94	3.15	73.79	720.15	84.69
5/17/94	793.94	3.15	73.94	720.00	84.69
6/17/94	793.94	3.15	74.11	719.83	84.69

Table 9. Monthly water levels in monitoring wells in the Michigan Department of Transportation maintenance garage area, Kalamazoo County, Michigan, September 18, 1993, through August 24, 1994—*Continued*

Date	Relative altitude of measuring point, in feet	Distance of measuring point above land surface, in feet	Depth to water from measuring point, in feet	Relative altitude of water, in feet	Well depth below land surface, in feet
KCS3—Continued					
7/13/94	793.94	3.15	74.10	719.84	84.69
8/24/94	793.94	3.15	73.93	720.01	84.69
KCS4					
9/18/93	791.95	4.89	71.92	720.03	77.01
10/14/93	791.95	4.89	71.96	719.99	77.01
11/16/93	789.77	2.71	69.22	720.55	77.01
12/13/93	789.77	2.71	69.21	720.56	77.01
1/25/94	789.77	2.71	69.20	720.57	77.01
2/22/94	789.77	2.71	69.20	720.57	77.01
3/03/94	789.77	2.71	69.19	720.58	77.01
4/11/94	789.77	2.71	70.28	719.49	77.01
5/17/94	789.77	2.71	70.26	719.51	77.01
6/17/94	789.77	2.71	--	--	77.01
7/13/94	789.77	2.71	70.25	719.52	77.01
8/24/94	789.77	2.71	70.28	719.49	77.01
KCS6					
9/18/93	790.50	-0.82	69.46	721.04	77.45
10/14/93	790.50	-0.82	69.37	721.13	76.45
11/16/93	793.59	2.27	72.34	721.25	76.45
12/13/93	793.59	2.27	72.31	721.28	77.45
1/25/94	793.59	2.27	72.54	721.05	77.45
2/22/94	793.59	2.27	72.76	720.83	77.45
3/03/94	793.59	2.27	72.74	720.85	77.45
4/11/94	793.59	2.27	73.00	720.59	77.45
5/17/94	793.59	2.27	73.21	720.38	77.45
6/17/94	793.59	2.27	73.35	720.24	77.45
7/14/94	793.59	2.27	73.39	720.20	77.45
8/24/94	793.59	2.27	73.21	720.38	77.45
KCS7					
9/18/93	796.50	1.46	75.51	720.99	79.08
10/14/93	796.50	1.46	75.41	721.09	79.08
11/16/93	796.50	1.46	75.31	721.19	79.08
12/13/93	796.50	1.46	75.30	721.20	79.08
1/25/94	796.50	1.46	75.51	720.99	79.08
2/22/94	796.50	1.46	75.74	720.76	79.08
3/03/94	796.50	1.46	75.72	720.78	79.08
4/11/94	796.50	1.46	76.05	720.45	79.08
5/17/94	796.50	1.46	76.20	720.30	79.08
6/17/94	796.50	1.46	76.34	720.16	79.08
7/13/94	796.50	1.46	76.36	720.14	79.08
8/24/94	796.50	1.46	76.17	720.33	79.08