Sampling Throughout The Hydrologic Cycle To Characterize Sources Of Volatile Organic Compounds In Ground Water

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ABSTRACT

Results of three studies in New Jersey demonstrate that analysis of samples collected throughout the hydrologic cycle can improve understanding of the sources of volatile organic compounds (VOCs) in ambient ground water. Results of the first study indicate that atmospheric concentrations of methyl-tert butyl ether (MTBE) are sufficiently high to cause detection in ground water, whereas atmospheric concentrations of the chlorinated VOCs trichloromethane (chloroform), 1,1,1-trichloroethane (TCA), and tetrachloroethene (PCE) are not. Results of analysis of unsaturated-zone gas and ground-water samples indicate that point sources of MTBE, such as spills or infiltration of urban runoff, are also prevalent and that these are the only possible sources of the chlorinated compounds. In the second study, VOC concentrations in three ground-water monitoring networks in a surficial aquifer were compared. Although it was anticipated that deeper ground water from the public supply wells would be associated with less frequent detections and lower concentrations of VOCs than water from the shallower observation wells, the opposite was found for many chlorinated VOCs. The integration of chlorinated VOCs from multiple point sources within the larger contributing areas of the public supply wells may explain this result. Chloroform, however, is detected frequently throughout the ground-water- monitoring network, indicating that its sources are widespread. MTBE is detected less frequently in observation wells that tap 10- to 15-year-old ground water than in shallow observation wells that tap recently recharged ground water and public supply wells. This result is not contradictory because some of the ground water in a given sample from a public supply well would have been recharged during the past 10 years, a period of increased MTBE use due to oxygenated-fuel programs. In the third study, the occurrence of MTBE in a lake, caused by the use of gasoline-powered watercraft, may explain the frequent occurrence of MTBE in samples from lakeside wells in the fractured-rock aquifer. The probable lake/well interaction complicates investigations of ground-water contamination with MTBE due to fuel spillage because of the difficulty of determining point-source plume dimensions with a nonpoint-source signature superimposed on the ground water.

INTRODUCTION

Research conducted as part of the U.S. Geological Survey (USGS) Toxic Substances Hydrology Program on the physical, chemical, and microbial processes that define the movement and attenuation of volatile organic compounds (VOCs) in ground water has improved understanding of the evolution of plumes originating from known sources. Even with advanced capability to predict the migration of plumes, however, it is impossible to assess the effects of all VOC releases on regional ground-water quality because of the existence of undiscovered point and nonpoint sources.

Results of work conducted as part of the USGS National Water Quality Assessment Program (NAWQA) indicate that VOCs such as trichloromethane (chloroform), methyl-tert butyl ether (MTBE), 1,1,1-trichloroethane (TCA), and tetrachloroethene (PCE) are detected frequently in shallow ground water in urban areas across the

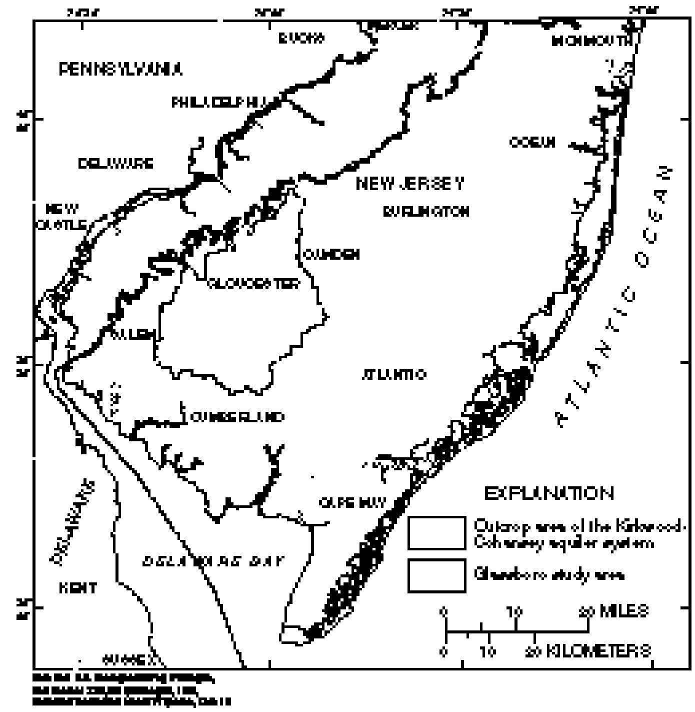


Figure 1. Location of the Glassboro study area in southern New Jersey.

Nation (Squillace and others, 1996). These findings raise many questions: What are the sources of thesecompounds, and will their concentrations increase? What is the relevance of these VOC detections to the quality of the ground-water supply? What is the ultimate fate of the contaminants? In order to begin to answer these questions, comprehensive regional-scale characterization of the distribution, movement, and attenuation of contaminants in relevant components of the hydrologic cycle is needed. This paper presents three examples of results of studies in New Jersey that demonstrate that analysis of samples collected throughout the hydrologic cycle can improve understanding of the sources and distribution of VOCs in ground water at spatial scales relevant to water supplies.

VOLATILE ORGANIC COMPOUNDS IN SHALLOW GROUND WATER, THE ATMOSPHERE, AND THE UNSATURATED ZONE

A network of 78 shallow monitoring wells was installed over a 380-square-mile study area (fig. 1), referred to as the Glassboro study area, as part of the NAWQA study of the Long Island-New Jersey Coastal Plain. This network is referred to as the land-use survey (LUS) wells because the objective of sampling these wells is to determine the quality of recently recharged ground water as a function of land use. Each well was screened over a 2-ft (foot) interval about 10 ft below the water table in the surficial Kirkwood-Cohansey aquifer system. Wells were located in agricultural, new-urban (residential and commercial development less than 25 years old), old-urban (urban development more than 25 years old), and undeveloped areas. Well locations in each land-use setting were selected randomly in an attempt to minimize bias and to ensure that data collected from the network would be representative of conditions across the study area. The locations of the LUS wells and other monitoring sites discussed in this paper are shown in figure 2.

Seventy-two of the wells were sampled from September 1 to December 31, 1996; the remaining 6 wells were sampled in November 1997. Samples from each well were analyzed for nutrients, pesticides, and VOCs (Stackelberg and others, 1997). The most frequently detected VOCs were chloroform, MTBE, TCA, and PCE. Carbon disulfide (not a VOC) also was frequently detected.

Atmospheric samples are collected at three sites in the Glassboro study area. The sites represent conditions of heavy, intermediate, and light vehicular traffic. Atmospheric samples are collected once every 12 days at each site and have been analyzed for VOCs at the Oregon Graduate Institute (OGI) since April 1997. Samples are collected approximately 6 ft above land surface by drawing air intermittently through a sorbent cartridge with a programmable pump over a 24-hour period. The cartridges are shipped to OGI, where VOC concentrations are determined by using a method of thermal desorption and gas chromatography/mass spectroscopy (GC/MS) detection. This method (Pankow and others, 1998) was developed by OGI for the USGS to provide atmospheric and unsatur-

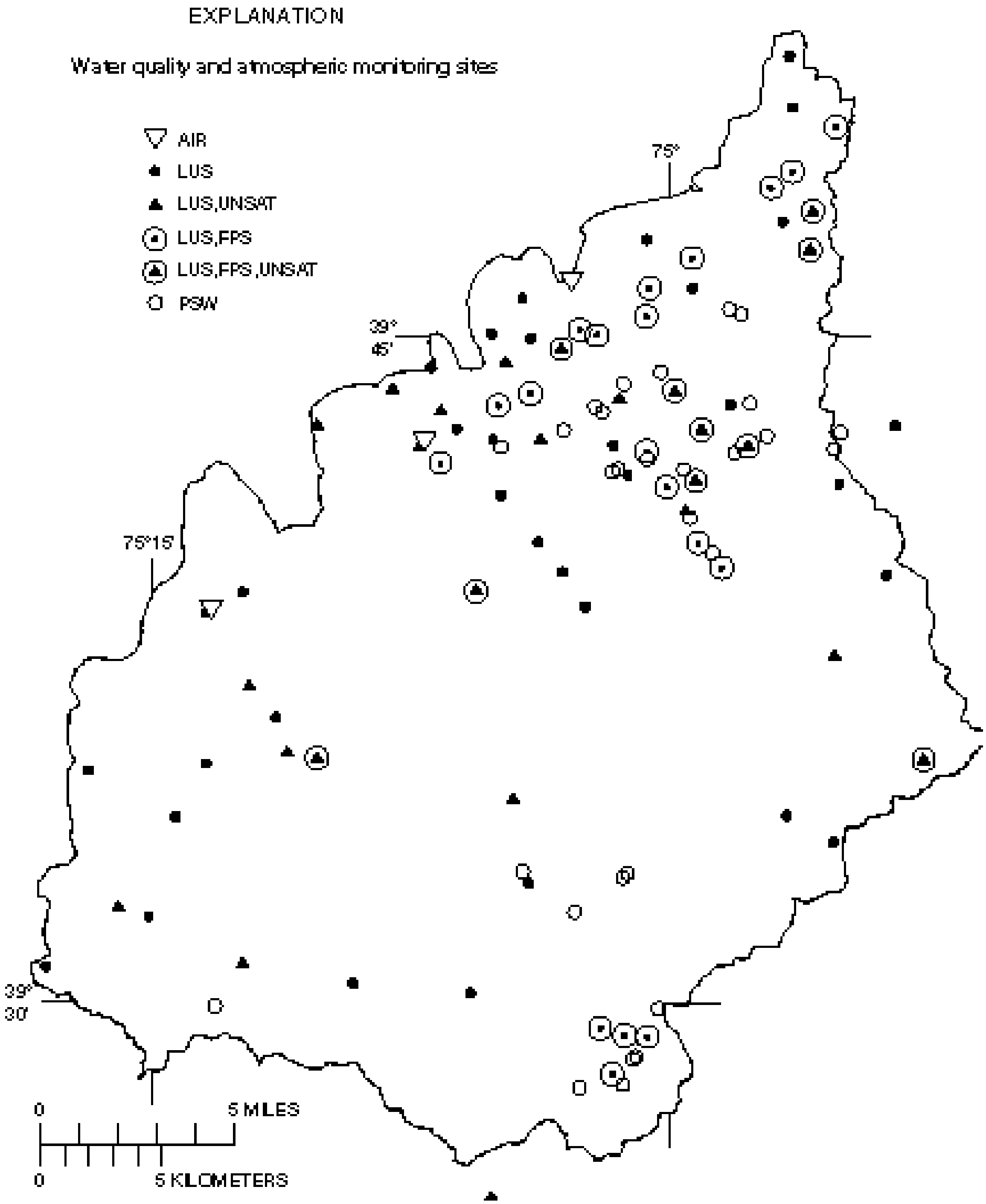


Figure 2. Location of atmospheric monitoring sites (AIR), land-use survey (LUS) and flow-path study (FPS) monitoring wells, unsaturated-zone-gas and shallow-ground-water monitoring sites (UNSAT), and public supply wells (PSW) in the Glassboro study area, New Jersey.

ated-zone-gas concentration data for a list of VOCs that approximates the VOC analyte list used in the NAWQA program.

Ground-water concentrations and detection frequencies of the most frequently detected VOCs are presented in figure 3 . Atmospheric VOC concentrations measured from April 29, 1997, through June 25, 1998, expressed as aqueous-phase equivalent concentrations at 15 °C also are shown. The values of Henry's Law coefficients used are the same as those reported by Baehr and others (1999). Atmospheric concentrations of the chlorinated VOCs (chloroform, TCA, PCE, and TCE) are not sufficiently high to cause detections in shallow ground water, as their aqueous-phase equivalents are below method detection limits. Median-level atmospheric MTBE concentrations correspond to a calculated aqueous concentration of about 0.1 µg/L (microgram per liter), and the highest atmospheric MTBE concentrations correspond to an aqueous concentration of about 1.0 µg/L; therefore, atmospheric MTBE concentrations can potentially explain all but the seven highest MTBE concentrations reported for the LUS wells, which most likely are the result of gasoline spills.

The possibility that MTBE in the atmosphere is the cause of most of the MTBE detections in shallow ground water is of fundamental importance. If

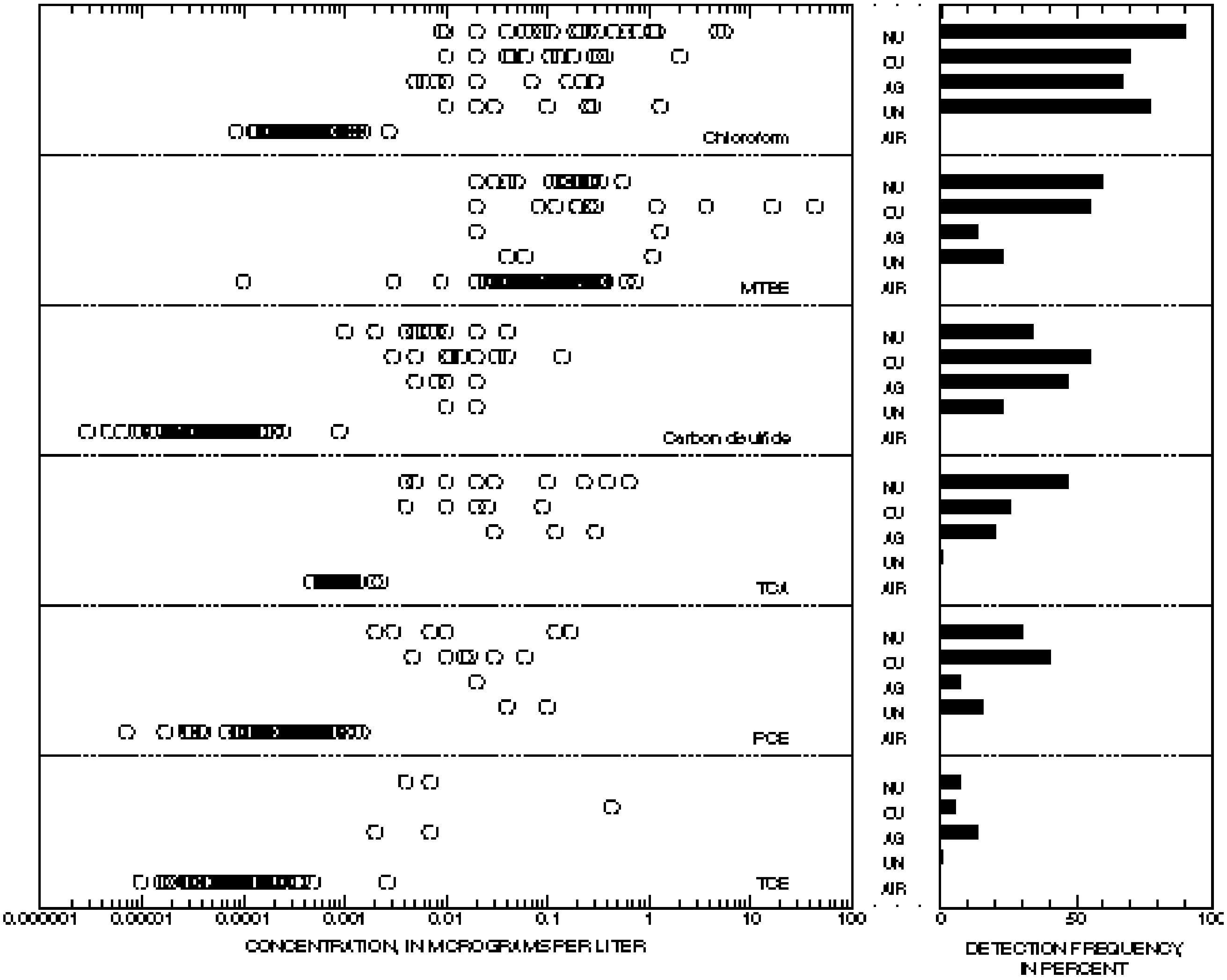


Figure 3. Volatile-organic-compound concentrations and detection frequencies in samples collected from land-use survey wells and atmospheric aqueous-phase equivalent concentrations, Glassboro study area, New Jersey. (NU, new urban; OU, old urban; AG, agricultural; UN, undeveloped; AIR, atmosphere)

low concentrations are the result of evolving plumes emanating from point sources, then MTBE concentrations theoretically could increase with time because the source concentrations from spills of oxygenated gasoline could be on the order of grams per liter. If the source is the atmosphere, however, then changes in MTBE concentrations in ground water over time would be constrained, and concentrations would remain low and proportional to atmospheric concentrations (Baehr and others, 1999).

Concentrations of VOCs in unsaturated-zone gas in the Glassboro study area provide additional information to help understand the sources and movement of these compounds. When installed, nearly all of the 78 LUS wells were instrumented with an unsaturated-zone-gas sampling probe and a shallow-ground-water sampling probe in addition to the standard 2-inch well (fig. 4). The unsaturated-zone gas probes typically are situated about 3 ft above the water table. The shallow-ground-water sampling probes typically are situated about 3 ft below the water table. Twenty-five sites were selected for simultaneous sampling of unsaturated-zone gas and shallow ground water. Some sites in each of the three land-use areas were included to ensure that the samples collected would be representative of conditions across the Glassboro study area. The minimum, median, and maximum depths to the water table at these 25 sites were 6, 12, and 23 ft, respectively. The 25 unsaturated-zone probes and corresponding shallow-ground-water probes were sampled from August to December 1997. Unsaturated-zone gas was sampled before shallow ground water so that the established unsaturated-zone gas profile would not be disturbed. Unsaturated-zone gas samples were obtained by connecting a sorbent cartridge to the vapor probe and drawing unsaturated-zone gas through the cartridge with a peristaltic pump. Cartridges were analyzed at OGI as previously described, with minor modifications for eliminating moisture accumulated in the cartridge as a result of the high relative humidity of unsaturated-zone gas. The shallow-ground-water sample was collected within 1 day of the unsaturated-zone-gas sample by filling 40-mL (milliliter) vials by using a peristaltic pump. These samples were analyzed at the USGS National Water Quality Laboratory (NWQL) in Arvada, Colo., by purge-and-trap GC/MS methods (Connor and others, 1998). This method of water analysis was the same as that used for samples from the 78 LUS wells.

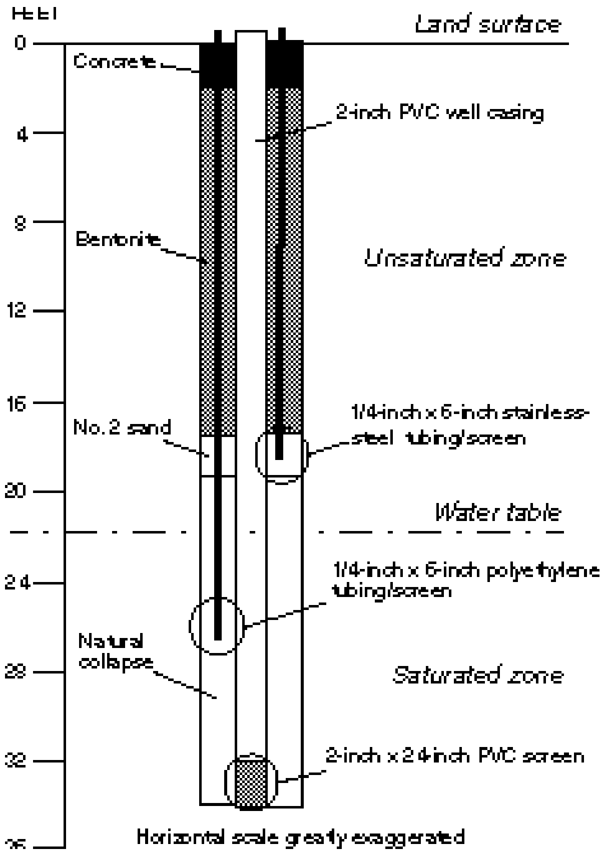


Figure 4. Typical installation of a shallow-ground-water observation well with attached probes for sampling very shallow ground water and unsaturated-zone gas.

Equivalent pore-water concentrations calculated from results of analysis of unsaturated- zone-gas samples for MTBE, PCE, chloroform, and TCA and the corresponding concentrations in shallow ground water at the 25 sites are shown in figure 5. Boxplots of atmospheric concentrations of these compounds expressed as equivalent aqueous-phase concentrations also are provided for comparison.

MTBE was detected in samples of shallow ground water from 7 of the 25 sites (28 percent). At the three sites where MTBE concentrations were highest, the concentration was greater than both the calculated unsaturated-zone concentration and the atmospheric concentration range. On the basis of the concentration gradient, the net movement of MTBE at these sites is upward across the water

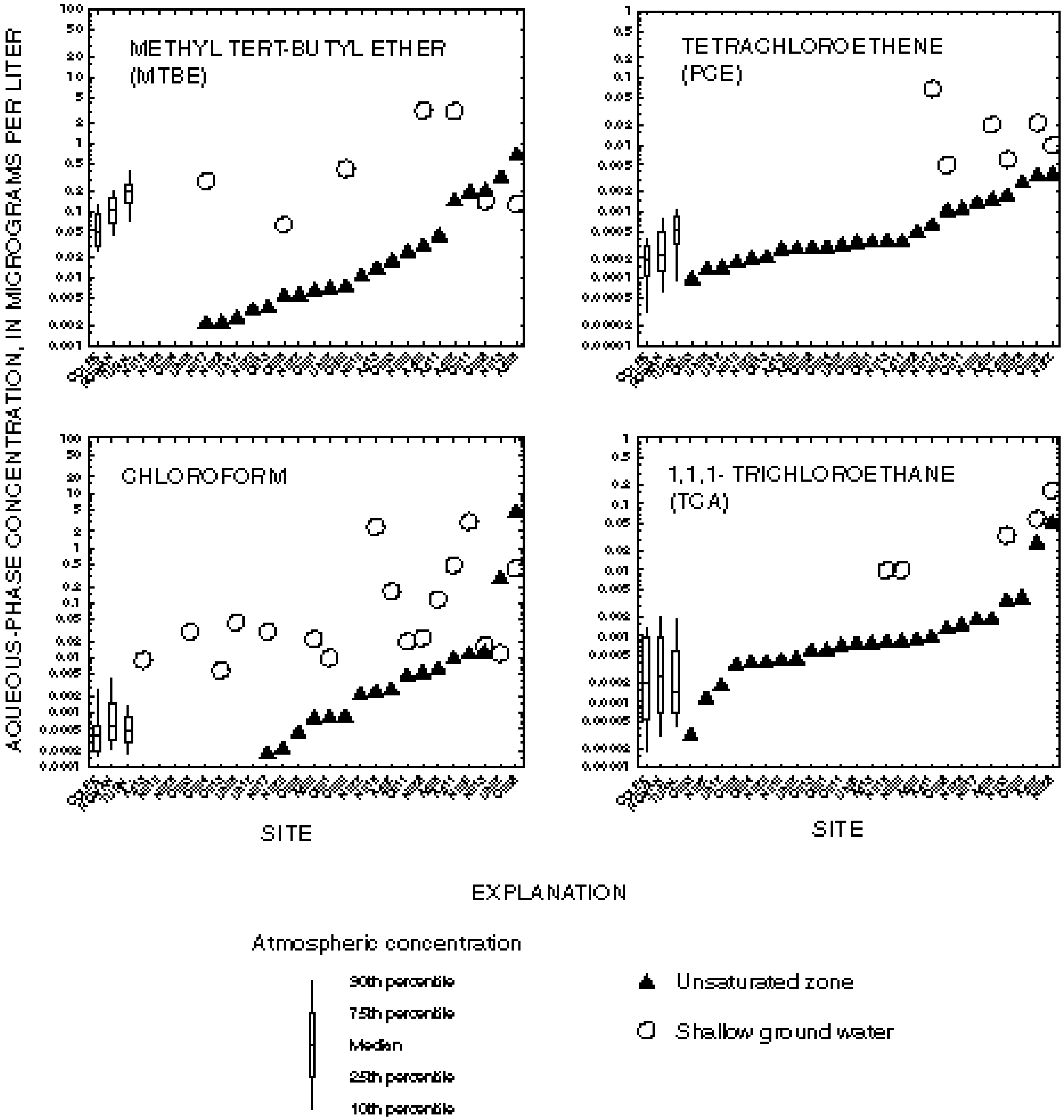


Figure 5. Distribution of MTBE, PCE, chloroform, and TCA in the atmosphere, unsaturated zone, and shallow ground water, Glassboro study area, New Jersey.

table, indicating that MTBE is outgassing or volatilizing from ground water to the unsaturated zone. The source of MTBE at these three sites is likely a gasoline spill and MTBE migrated to the site as a solute in ground water. At two sites, concentrations in ground water were lower than the calculated unsaturated-zone aqueous concentration, but within the atmospheric concentration range. The net movement of MTBE at these sites, therefore, is downward across the water table, with the atmosphere the likely source. At the remaining two sites where MTBE was detected in shallow ground water, the ground-water concentration was greater than the calculated unsaturated-zone aqueous concentration. This situation also indicates outgassing from ground water. The MTBE source could be a distant gasoline spill or runoff from paved surfaces that eventually infiltrated to ground water; however, the atmospheric source cannot be ruled out because recharge could occur upgradient.

In contrast, the distributions of PCE and TCA indicate a consistent and simpler explanation for movement across the water table. At all six sites (24 percent) where PCE was detected and all five sites (20 percent) where TCA was detected in ground water, the concentrations in ground water were greater than those that could be attributed to the atmosphere. PCE and TCA outgassing therefore is indicative of an upgradient source and migration of each of these compounds to the site as a solute in ground water.

The frequent detection of chloroform in ground water at 17 of the sites (68 percent) is attributed to a more widespread source (discussed below). At 14 of the 17 sites where chloroform was detected in ground water, the concentration gradient across the water table indicates outgassing and, therefore, the source was upgradient and chloroform migrated to the site as a solute in ground water. At three sites the direction of chloroform movement was downward, indicating that the source most likely was nearby at land surface or within the unsaturated zone.

COMPARISON OF VOLATILE ORGANIC COMPOUNDS IN THREE GROUND-WATER MONITORING NETWORKS

The outcrop of the surficial Kirkwood-Cohansey aquifer system forms the western boundary of the study area. The aquifer thickens toward the southeast to a maximum thickness of about 200 ft within the study area. The base of the surficial Kirkwood-Cohansey aquifer system is formed by a thick confining unit. Because the sediments that comprise the aquifer are highly permeable, it is vulnerable to contamination from the land surface in developed parts of the study area, which are expanding rapidly as a result of population growth.

In addition to the LUS network, designed to assess the quality of the youngest ground water, 30 monitoring wells were installed at intermediate depths in the surficial aquifer as part of the NAWQA study of water quality in the Kirkwood-Cohansey aquifer system in the Glassboro study area. These wells have 2-ft screened intervals, typically 30 to 40 ft below the water table. The well depth at each location was selected to sample ground water predicted with a regional ground-water-flow model to be 10 to 15 years old. These wells, referred to as flow-path study (FPS) wells, were colocated with a new-urban or old-urban LUS well. The FPS wells were sampled in November 1997.

The ground-water monitoring network also includes 30 public supply wells (PSWs) in the Glassboro study area that are screened in the surficial Kirkwood-Cohansey aquifer system. Most of the PSWs are in new-urban or old-urban land use areas. The minimum, median, and maximum depths from land surface to the top of the screened interval for the 30 PSWs sampled are 50, 100, and 151 ft, respectively, and the screened interval typically is about 30 ft. From February to March 1998, untreated (raw) water was collected from 20 of these PSWs; the remaining 10 PSWs were sampled in December 1998.

VOC concentrations and detection frequencies in samples collected from the three classes of wells are summarized in figure 6. Only data from 50 of the 78 LUS wells that are located in new-urban or old-urban land-use areas are plotted because these land uses predominate in the vicinity of the 30 PSW and 30 FPS wells. Before sampling, it was anticipated that the PSWs would be associated with less frequent VOC detections and lower concentrations because of older water, longer flow paths, and natural attenuation of contaminants. The frequency of detection of many chlorinated VOCs (including TCA, PCE, and TCE), however, was significantly higher in the PSWs than in both LUS and FPS wells. Some chlorinated VOCs (including carbon tetrachloride, cis-1,2-dichloroethene, 1,2-dibromomethane, and trans-1,2- dichloroethene) were detected frequently in PSWs but rarely in LUS and FPS wells. This may indicate that the larger contributing area (the area at the land surface that contributes water to a well) of a PSW integrated a sufficient number of sources of these less frequently used VOCs to cause detection. Chemical transformation of parent VOCs along extended flow paths

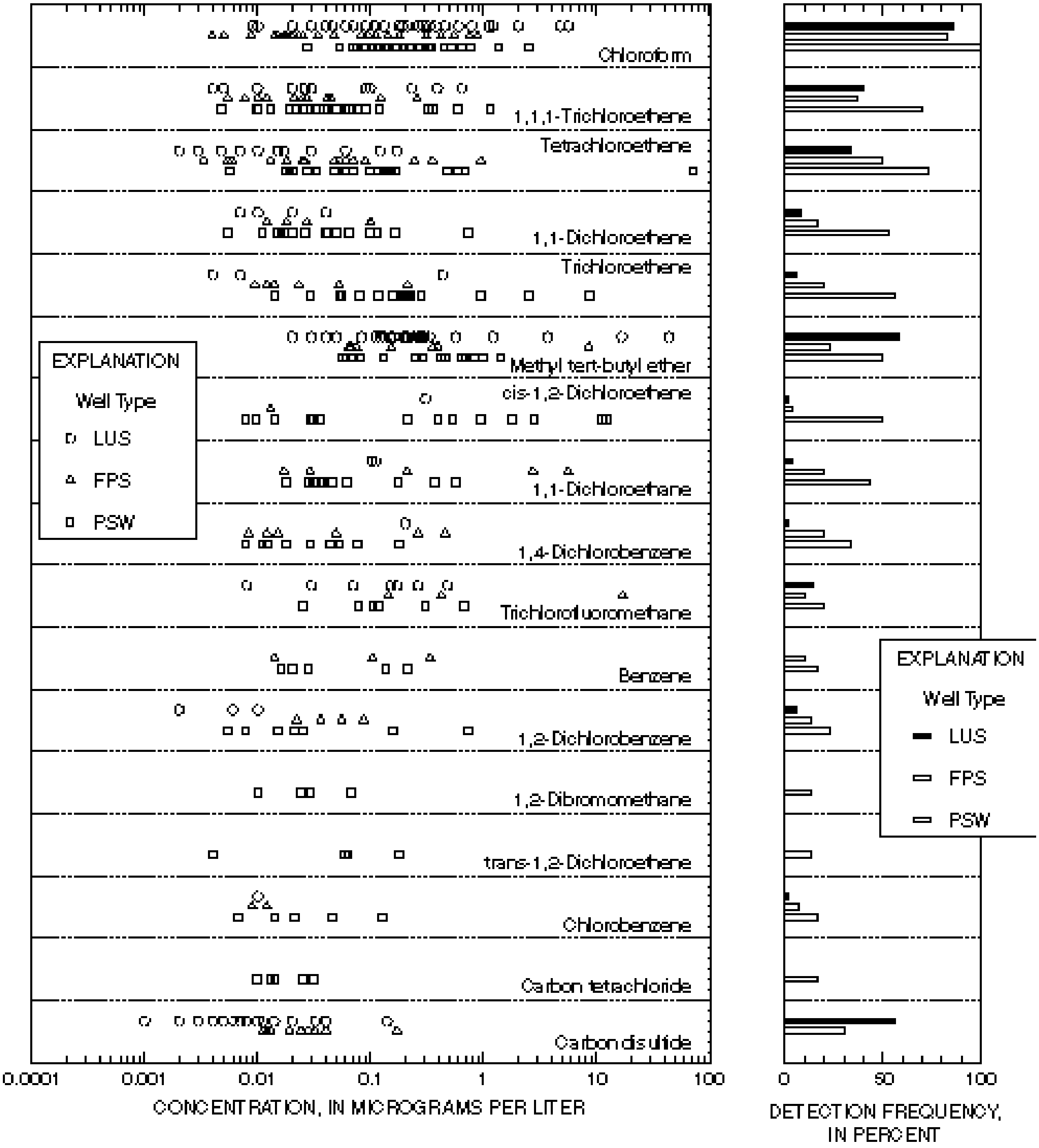
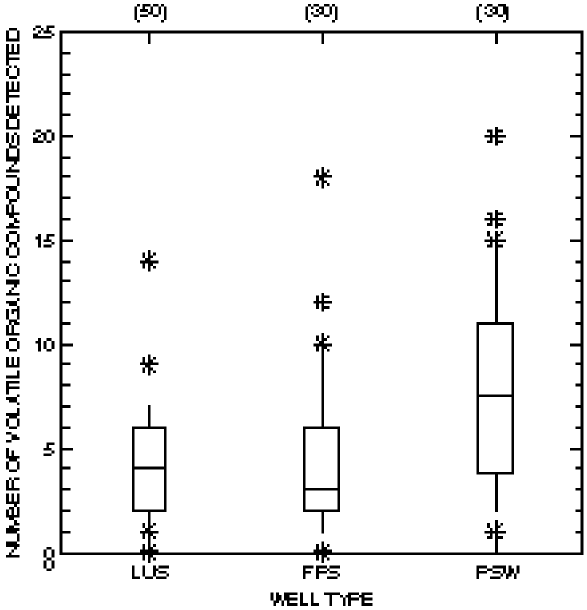
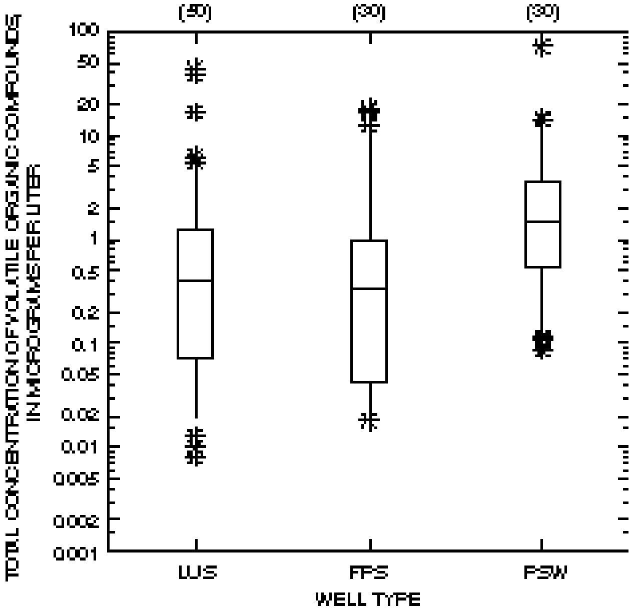


Figure 6. Distribution of volatile-organic-compound concentrations and detection frequencies in samples from land-use survey (LUS), flow-path study (FPS), and public supply wells (PSW), Glassboro study area, New Jersey.





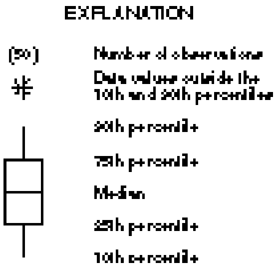


Figure 7a. Distribution of the number of volatile organic compounds detected per sample in the land-use survey (LUS), flow-path study (FPS), and public supply wells (PSW), Glassboro study area, New Jersey.

Figure 7b. Distribution of total volatile-organic-compound concentration per sample in the land-use survey (LUS), flow-path study (FPS), and public supply wells (PSW), Glassboro study area, New Jersey.

also may explain, in part, the occurrence of these VOCs in PSWs. When all VOCs are considered in aggregate, the number of VOCs per sample (fig. 7a) and the total VOC concentration per sample (fig. 7b) are significantly higher in PSWs than in LUS and FPS observation wells. (As in figure 6, only data from 50 of the 78 LUS wells are plotted in figures 7a and 7b.)

The PSW contributing areas are proportional in size to water use and vary widely among the 30 PSWs sampled. A typical contributing area, given a regional recharge rate of 17 inches per year, is about 200 acres for a well producing 100 million gallons per year (17 inches per year multiplied by 200 acres equals approximately 100 million gallons per year). An aerial photograph illustrating land uses within the contributing area of a typical PSW is shown in figure 8a. The contributing area was estimated with a ground-water flow model by applying particle tracking. The model also was used to demonstrate that water entering the well is a blend of very young water from the part of the contributing area nearest the well and older water from the outer extent of the contributing area. The ground-water flow model's particle-tracking application was used to predict the time required for ground water to travel from the point of recharge to the well throughout the contributing area (fig. 8b). The median age of ground water in this typical con-

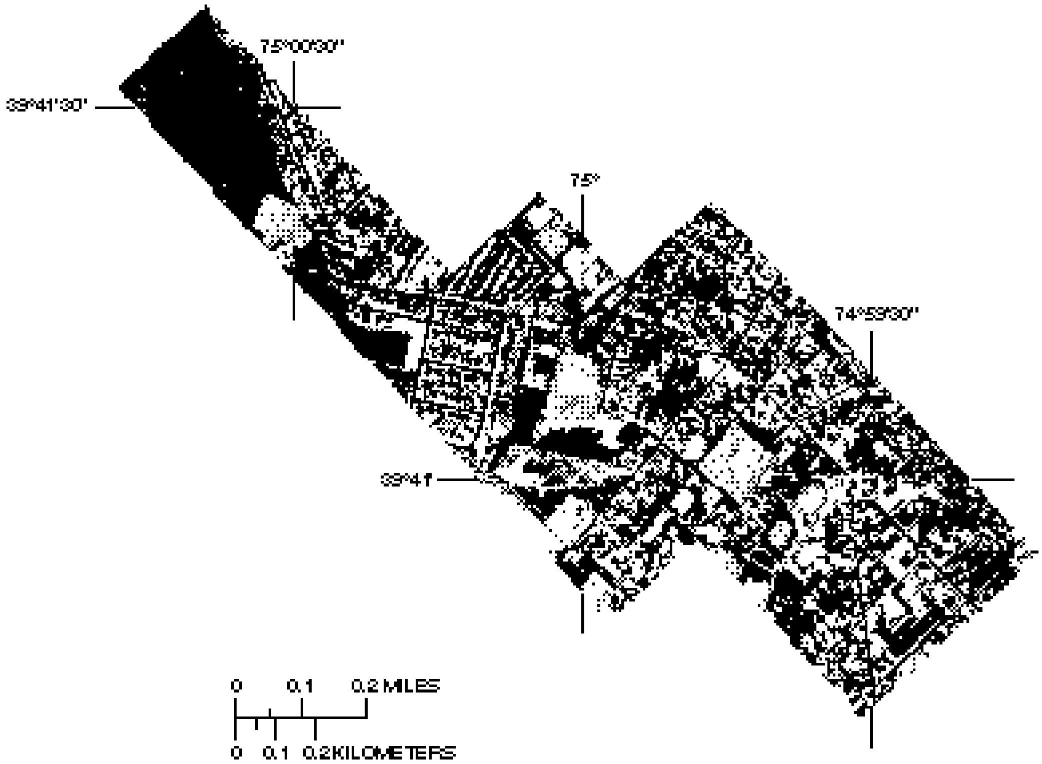


Figure 8a. Aerial photograph illustrating land-use variability within the contributing area of a typical public supply well, Glassboro study area, New Jersey.

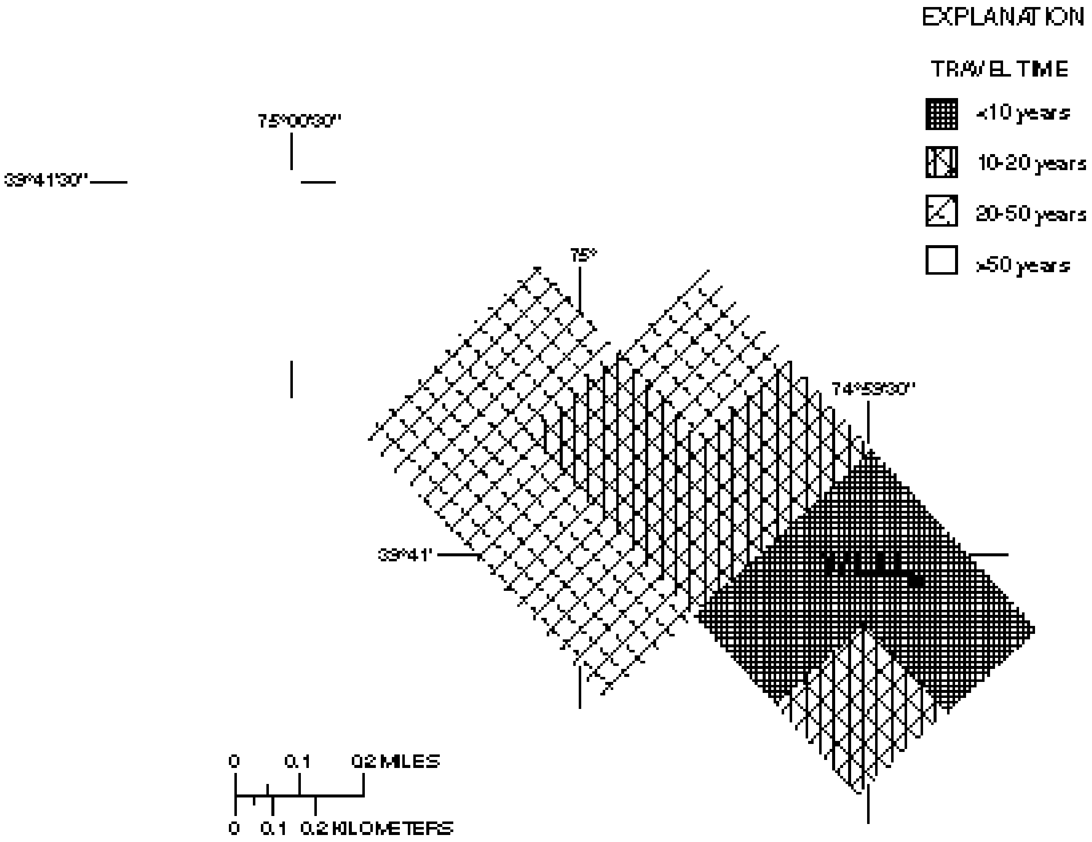


Figure 8b Map of time of travel from point of recharge to well within the contributing area of a typical public supply well , Glassboro study area, New Jersey.

tributing area is estimated to be 20 years, with 25 percent of the ground water entering the well being less than 10 years old, 25 percent between 10 and 20 years old, 30 percent between 20 and 50 years old, and 20 percent more than 50 years old. In contrast to PSWs, observation wells such as the LUS and FPS wells have very small contributing areas and, therefore, yield water that was recharged over a small area and that is essentially of a discrete age rather than a blend of water of different ages. Sampling domestic wells in the study area would provide data from another class of observation wells with contributing areas that are smaller than those of PSWs but larger than those of LUS and FPS wells.

Concentrations and detection frequencies of the two most frequently detected VOCs in the ground-water monitoring network, chloroform and MTBE, require different explanations (fig. 6). Chloroform was detected frequently throughout the monitoring network. The sources of chloroform, therefore, are thought to be widespread. For example, chloroform could be formed during the treatment of drinking water and then subsequently could enter ground water through recharge from septic tanks and irrigation of crops and lawns. Chloroform also can be produced naturally in the subsurface (Hoekstra and others, 1998), although it is uncertain whether this source can account for the detection frequencies and concentrations observed. Chloroform, like other chlorinated VOCs, is used in industry. Because of its frequent detection in water samples, a study was conducted as part of the NAWQA program to assess whether frequent chloroform detection is caused by sample preservation with hydrochloric acid (Squillace and others, in press). Results showed that such chloroform production is minor and, therefore, chloroform detections can be attributed largely to the environment .

MTBE was detected less frequently in the FPS wells than in the LUS wells and PSWs. Use of MTBE as a gasoline oxygenate did not increase until after 1992 in response to changes in the Clean Air Act and, consequently, MTBE would be expected to occur less frequently in 10- to 15-year-old ground water (FPS) than in recently recharged ground water (LUS). The higher detection frequency of MTBE in the PSW network is not contradictory, however, because a significant percentage of ground water in a given sample from a PSW would be less than 10 years old and may have intercepted both point sources and areas of high traffic density that could contribute to MTBE loading from the atmosphere. Regardless of the mechanisms, however, these results emphasize the vulnerability of the surficial aquifer to contamination, as the water pumped from PSWs includes the youngest water in the aquifer, which is in contact with developing VOC sources.

MTBE IN LAKES AND POSSIBLE EFFECTS ON GROUND-WATER SUPPLY

In the summer of 1998, MTBE concentrations in samples collected from Cranberry Lake and Lake Lackawanna in Sussex County, N.J., were as high as 29 and 14 µg/L , respectively. Although other VOCs were detected as well, concentrations of MTBE were by far the highest. These concentrations are among the highest observed in ground- and surface-water surveys conducted by USGS and are of concern, as the U.S. Environmental Protection Agency has classified MTBE as a possible human carcinogen and has issued a drinking-water advisory based on the aesthetic concerns of taste and odor of 20 to 40 µg/L (U.S. Environmental Protection Agency, 1997). The occurrence of MTBE in these lakes is attributed to the use of gasoline-powered watercraft (Baehr and Zapecza, 1998). Ground water from domestic wells and wells of small water companies is the major source of water supply for the residents of the communities of Cranberry Lake and Lake Lackawanna. These lakes have been enlarged and water levels are maintained with dams. The combination of maintained water levels in the lake and clustered well withdrawals in the densely populated lakeside communities makes lake/well interaction likely.

During November and December 1998, 14 randomly selected wells surrounding Cranberry Lake were sampled to begin assessing ground-water quality. MTBE was detected in 13 of these wells (93 percent), in concentrations ranging from 0.12 to 19.8 µg/L and a median concentration of 0.44 µg/L. Although the sample size is small, the frequency of detection of MTBE in this lakeside fractured-crystalline-rock setting appears to be significantly greater than that in random domestic-well sampling in other parts of New Jersey. Results obtained as part of the Long Island-New Jersey NAWQA study indicate a 48-percent detection frequency of MTBE above a detection limit of 0.1 µg/L in 23 samples collected from domestic wells in crystalline-rock aquifers of the New Jersey Highlands (J.A. Hopple, U.S. Geological Survey, written commun., 1999). A 7-percent detection frequency of MTBE above the 0.1- µg/L detection limit was recorded for 30 samples collected from domestic wells screened in the Kirkwood-Cohansey aquifer system across southern New Jersey (P.E. Stackelberg, U.S. Geological Survey, written commun., 1999). Concentrations and detection frequencies of MTBE in these three domestic-well surveys are shown in figure 9 (Zapecza and Baehr, these proceedings). The concentration of MTBE was equal to or greater than 0.2 µg/L in water from 13 of 34 (38-percent detection frequency) unconfined public supply wells across New Jersey sampled in 1998 as part of the USGS Drinking Water Initiative (E.F. Vowinkel, U.S. Geological Survey, written commun., 1999).

It is possible that Cranberry Lake is a source of MTBE to the community water supply and therefore may be the cause of the very high detection frequency. If such lake/well interaction occurs, then MTBE concentrations in ground water may increase during summer months when MTBE concentrations in the lake are highest (Zapecza and Baehr, these proceedings). Furthermore, lake/well interaction would greatly complicate investigations of MTBE ground-water contamination due to fuel spillage because determination of point-source plume dimensions would be difficult with a non-point-source signature superimposed on the ground water. The very high MTBE detection frequency could also result from the frequent handling of gasoline by residents because of the high rate of boat ownership. Small spills of gasoline probably are more prevalent in these communities than in the population at large and, therefore, the very high MTBE detection frequency in these in wells could be a result of the unique land use. These explanations could also work in concert.

Many lakes throughout the Highlands and the Valley and Ridge provinces of northern New Jersey are surrounded by communities similar to Cranberry Lake that depend on lakeside wells for water supplies. A regional assessment of lakes and the surrounding wells would help to determine the effect of the use of oxygenated gasoline on water quality in lakeside environments and to discern the role of lake/well interaction and land use in ground-water quality.

SUMMARY

Even with advanced capability to predict the migration of contaminant plumes it is impossible to assess the effects of all VOC releases on ground-water quality because of the existence of undiscovered sources. Results of studies in New Jersey demonstrate that analysis of samples collected throughout the hydrologic cycle can improve understanding of the sources and distribution of VOCs in ground water at spatial scales relevant to water supplies.

Atmospheric concentrations of the fuel oxygenate MTBE in southern New Jersey are sufficiently high to explain the frequent detection of this compound in ground water at concentrations below 1 µg/L. For other frequently detected VOCs (chloroform, TCA, and PCE), the atmospheric-source hypothesis is infeasible because atmospheric concentrations are low. Point sources of MTBE, such as upgradient gasoline spills, can also explain the detections even if the atmosphere can account for the ground-water concentrations, because outgassing of MTBE across the water table has been observed at some sites. Outgassing is always observed for TCA and PCE, indicating upgradient point sources of these compounds.

Less frequent VOC detection and lower VOC concentrations were anticipated in samples from public supply wells in the Kirkwood-Cohansey aquifer system than in samples from shallow- and intermediate-depth observation wells as a result of longer flow paths and natural attenuation. The frequency of detection of many chlorinated VOCs (including TCA and PCE), however, was significantly higher in the public supply wells, as was the median total VOC concentration. This result is attributed to the fact that the public supply wells have large contributing areas that can integrate

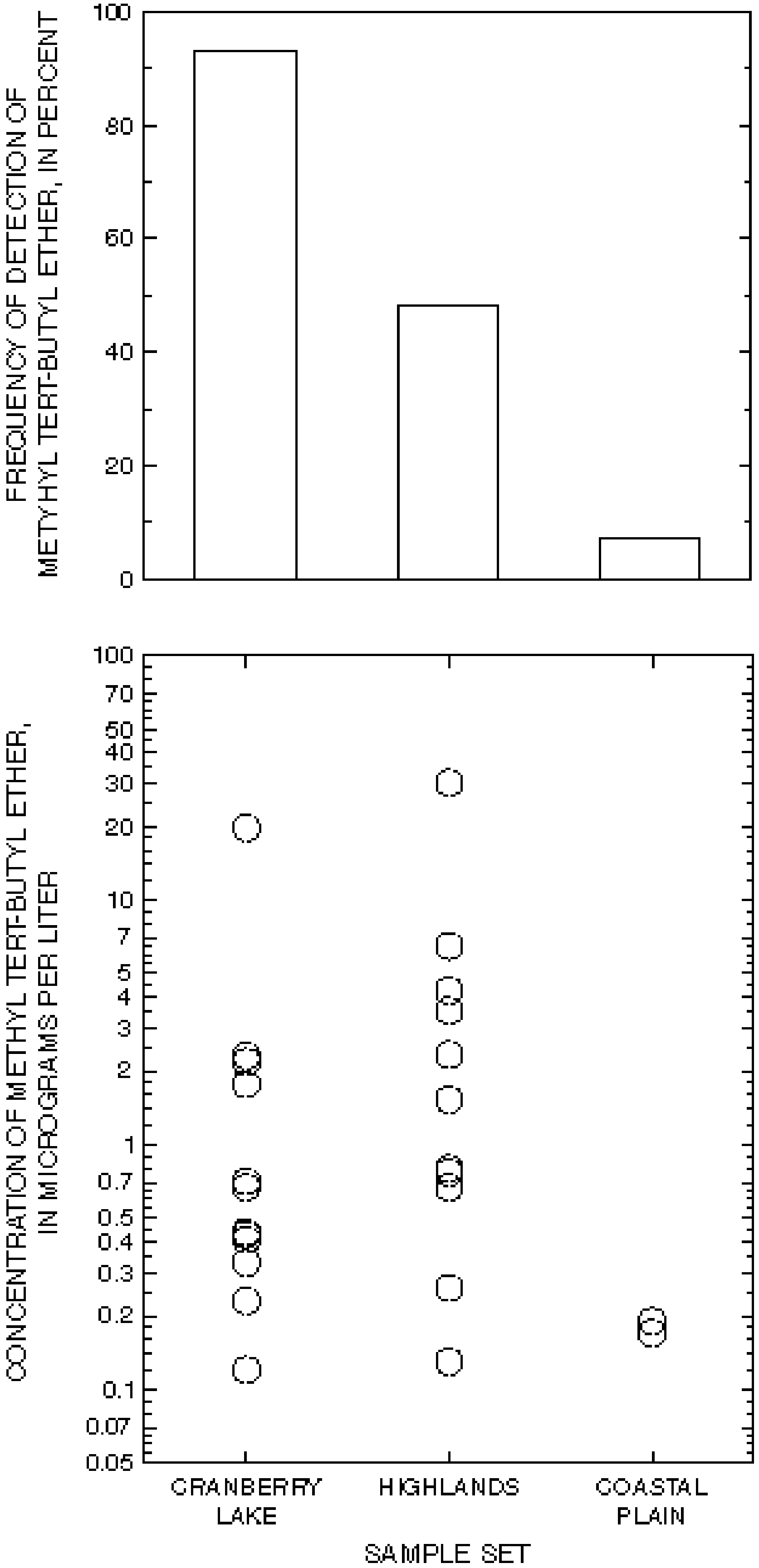


Figure 9. Distribution of concentrations and detection frequencies of MTBE in samples collected during three surveys of domestic wells, New Jersey. (from Zapecza and Baehr, these proceedings)

point sources located throughout their contributing areas.

Chloroform was detected at high frequencies in all types of wells, indicating that its source is widespread. Natural production of chloroform in the subsurface and its production in water treatment may contribute to its widespread occurrence throughout the aquifer.

MTBE was detected at similar frequencies in samples from shallow monitoring wells and public supply wells, but was found less frequently in samples from intermediate-depth observation wells. Use of MTBE as a gasoline oxygenate did not increase until after 1992 in response to changes in the Clean Air Act; consequently, MTBE would be expected to occur less frequently in the 10- to 15-year old ground water collected from intermediate-depth wells. Although the screened intervals of the public supply wells generally are deeper than those of the intermediate-depth observation wells, the MTBE detection frequency in public supply wells may be higher because some of the water in the well would be less than 10 years old, and the likelihood that some of this water would have intercepted point sources of MTBE or an area of higher atmospheric loading due to traffic density in the larger contributing area is greater. These results emphasize the vulnerability of the regional water supply to contamination, as the water withdrawn from public supply wells includes the youngest water in the aquifer, which is in contact with developing VOC sources.

MTBE concentrations in two northern New Jersey lakes are among the highest observed in ground and surface water nationwide. MTBE also was detected in 13 of 14 samples from wells surrounding one of the lakes, possibly as a result of lake/well interaction caused by the combination of maintained water levels in the lake and clustered well withdrawal in the densely populated lakeside community. Because many lakes are present throughout the Highlands and the Valley and Ridge provinces of northern New Jersey and in adjacent states, such lake/well interaction may define a regional phenomenon.

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