



Methyl *tert*-Butyl Ether (MTBE) in Ground Water, Air, and Precipitation at North Windham, Maine

Water-Resources Investigations Report 00-4048

**Prepared in cooperation with the Town of Windham, Maine and the
Maine Department of Environmental Protection**

**U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY**

U.S. Department of the Interior
U.S. Geological Survey

Methyl *tert*-Butyl Ether (MTBE) in Ground Water, Air, and Precipitation at North Windham, Maine

By Martha G. Nielsen and John M. Peckenham

Water-Resources Investigations Report 00-4048

**Prepared in cooperation with the Town of Windham, Maine and the
Maine Department of Environmental Protection**

**Augusta, Maine
2000**

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Charles G. Groat, Director

The 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.

For additional information write to:

District Chief
U.S. Geological Survey
26 Ganneston Drive
Augusta, Maine 04330

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286, Federal Center
Denver, CO 80225

CONTENTS

Abstract	1
Introduction	1
Purpose and scope	2
Acknowledgments	2
Previous investigations	2
Description of study area	5
Hydrology	5
Land use	6
Data-collection methods	7
Ground-water samples	7
Air samples	14
Precipitation samples	14
Occurrence and distribution of MTBE in the North Windham area	15
MTBE in ground water	15
MTBE in air	20
MTBE in precipitation	22
Potential sources of MTBE in ground water	23
Atmospheric deposition	23
Other sources	25
Summary and conclusions	25
References cited	27

FIGURES

1. Map showing location of the Windham aquifer study area, North Windham, Maine	5
2. Map showing land-cover distribution in the North Windham, Maine area, 1992	8
3. Map showing locations of air-and precipitation-sampling sites and wells sampled for MTBE, Windham aquifer	10
4. Map showing the distribution of MTBE detections in wells in the Windham aquifer	19
5. Graph showing concentrations of MTBE detections by land-use classification for samples with detection limits of 0.2 micrograms per liter	20
6. Graph showing concentrations of MTBE in air, and air temperature at the start of each time-composited sampling period in North Windham, Maine, December 1998 to July 1999	21
7. Graph showing concentrations of MTBE in air, water concentrations of MTBE in equilibrium with measured air concentrations, and measured concentrations of MTBE in ground water	24

TABLES

1. MTBE detection by population density and use of reformulated gasoline, from State of Maine, 1998	3
2. Estimated average monthly temperatures in North Windham, Maine	6
3. Selected data for ground-water wells in the Windham aquifer	9

TABLES—Continued

4. Sampling conditions and selected physical properties for wells and precipitation station sampled in North Windham, July 1998 to May 1999	11
5. VOC data for ground water and precipitation sampled in North Windham, July 1998 to May 1999	16
6. Detections of MTBE in wells in the Windham aquifer by hydraulic conductivity	20
7. Selected data for air samples and concentrations of MTBE in air, North Windham, December 1998 to July 1999	21
8. Monthly predicted air-water equilibrium concentrations of MTBE (for precipitation) based on median measured MTBE concentration in air and average monthly temperatures	23

CONVERSION FACTORS, VERTICAL DATUM, AND OTHER ABBREVIATIONS

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
millimeter (mm)	0.03937	inch
Area		
square mile (mi ²)	2.590	square kilometer
Volume		
gallon (gal)	3.785	liter
Flow rate		
gallon per minute (gal/min)	3785	milliliters per minute
inch per year (in/yr)	25.4	millimeter per year
Pressure		
millimeter of mercury at 60 °F (in Hg)	0.001316	atmosphere
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day

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

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

Vertical datum: 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.

Altitude, as used in this report, refers to distance above or below sea level.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L). Concentrations of chemical constituents in air are given as parts per billion by volume (ppbv). Volume of air is measured in liters (L). Flow rate for air measured is given in milliliters per minute (mL/min).

Methyl *tert*-Butyl Ether (MTBE) in Ground Water, Air, and Precipitation at North Windham, Maine

by Martha G. Nielsen and John M. Peckenham

ABSTRACT

Thirty-one monitoring wells in the Windham aquifer in North Windham, Maine, were sampled for methyl *tert*-butyl ether (MTBE) from July 1998 to May 1999. MTBE was detected in 35 percent of the wells sampled in the Windham aquifer. MTBE was detected in 64 percent of wells in the high-yielding part of the aquifer; these wells account for 82 percent of all wells with detectable MTBE. Land cover also was found to be associated with MTBE in the wells in the study area, with the urban and low-density residential areas having more MTBE than undeveloped areas. The median concentration in wells with detectable MTBE was 1.13 µg/L (micrograms per liter).

Air and precipitation samples were collected in North Windham along with groundwater samples. Air samples were collected every 10 days from December 1998 to July 1999 (20 samples). MTBE was present in all 20 air samples collected, at concentrations ranging from 0.03 ppbv (parts per billion by volume) to 1.0 ppbv. Before Maine opted out of the reformulated gasoline (RFG) program in the spring of 1999, median concentrations in air at the North Windham site were 0.25 ppbv. After Maine stopped using RFG, the median concentration in air dropped to 0.09 ppbv.

No MTBE was detected in four samples of precipitation at North Windham. The lack of rainfall during the study period prevented the collection of an adequate number of samples, and technical difficulties negated the results of some of the analyses of the samples that were collected.

Based on the equilibrium partitioning of MTBE from the air into rain, the hypothetical average concentration of MTBE in rainfall during months when recharge typically occurs (March-April and October-December) would be approximately 0.3 to 0.4 µg/L during the time that RFG was being used in Maine. After the phaseout of RFG, the maximum average concentration of MTBE in rainfall during these months would be approximately 0.1 µg/L.

The distribution and concentrations of MTBE that were detected in ground water indicate that recharge from precipitation containing MTBE is not a likely explanation for the occurrence of MTBE in the Windham aquifer.

INTRODUCTION

With the 1992 implementation of the 1990 Clean Air Act, certain areas in the country that exceeded the ambient carbon monoxide standard began using oxygenated gasoline containing methyl *tert*-butyl ether (MTBE). By 1995, oxygenated gasoline also was mandated to control ground-level ozone and other airborne volatile organic compounds (VOCs). Soon after the widespread use of gasoline containing MTBE began, water-quality surveys began detecting MTBE in ground water, often without the other gasoline compounds—benzene, toluene, ethyl benzene, and xylenes (collectively known as BTEX compounds)—usually found in ground water near gasoline spills. To meet part of the Federal requirement of reducing VOC concentrations in Maine's air by 15 percent, the State of Maine elected to use

reformulated gasoline (RFG) that contained 11 percent MTBE by volume (Maine Department of Human Services, 1995). In December 1994, RFG was introduced in southern Maine, in Kennebec, Sagadahoc, Androscoggin, Cumberland, York, Lincoln, and Waldo Counties.

Although MTBE has been detected in ground water in Maine since before 1985, there was no documented evidence of widespread, low-concentration MTBE contamination in the ground water until the summer of 1998, when several widely publicized instances of contamination in drinking-water wells prompted the State of Maine to conduct a random sampling of 951 private wells and nearly all the 830 nontransient public water supplies in the state of Maine. The sampling found MTBE in ground water in all parts of Maine, including areas not required to use RFG (Maine Department of Human Services, 1998). This study and additional studies by the U.S. Geological Survey (USGS) National Water Quality Assessment Program (NAWQA) across the country documented that low concentrations of MTBE are common in ground water, especially in urban areas (Zogorski and others, 1998). The widespread occurrence of MTBE has prompted discussion about possible nonpoint sources of MTBE in ground water, especially precipitation and atmospheric deposition (Squillace, Pankow and others, 1996; Squillace, Zogorski, and others 1996; Pankow and others, 1997; Lopes and Bender, 1998; Baehr and others, 1999; Moran and others, 1999). Few studies to date, however, have co-located the collection of samples for analysis of MTBE in ground water, air, and precipitation.

In 1998, the USGS in cooperation with the Maine Department of Environmental Protection and the Town of Windham, Maine began a study of MTBE in the Windham aquifer. The study was designed to collect information on the occurrence and distribution of low concentrations (less than 2 $\mu\text{g/L}$) of MTBE in the aquifer, a shallow aquifer used for drinking water in an area in which RFG was used exclusively. The study involved collection of samples from ground water, air, and precipitation, and an evaluation of possible atmospheric sources of MTBE to the Windham aquifer.

Purpose and scope

This report presents information on the occurrence and distribution of MTBE in the Windham aquifer in southern Maine. Results of analyses of samples collected in ground water, air, and precipitation are included. The report also includes information on the relation of MTBE in ground water to atmospheric deposition and to potential nonpoint sources of MTBE in ground water.

Acknowledgments

The authors appreciate the help provided by the Windham Town Council, Committee on Natural Resources, and the Town manager, Tony Plante. John Zogorski, Gregory Delzer, and David Bender of the NAWQA VOC National Synthesis Team provided invaluable consultation on sampling methods, quality assurance/quality control, and help with providing the air-sample analyses. James Caldwell and other staff of the Maine District provided excellent field support for the study.

Previous investigations

Results from the USGS NAWQA studies show that MTBE is a common contaminant in urban areas in the United States (Zogorski and others, 1998). In a National sampling of 1,171 wells (none of which were near known point sources of contamination) during 1993 and 1994, MTBE was detected in 27 percent of shallow urban wells, but in fewer than 2 percent of wells in agricultural areas (Squillace and others, 1995). The highest occurrences were in urban areas where RFG was used for at least part of the year and where depths to the water table were about 13 ft or less (Squillace, Zogorski, and others, 1996). Concentrations of MTBE in the wells sampled as part of NAWQA studies ranged from 0.2 $\mu\text{g/L}$ to 23,000 $\mu\text{g/L}$. The median MTBE concentration for urban wells was estimated to be 0.02 $\mu\text{g/L}$, through use of a logistic regression

model, and the mean concentration was 0.6 µg/L. Only 3 percent of the urban wells had concentrations of MTBE greater than 20.0 µg/L, the lower limit of the USEPA draft drinking-water health-advisory limit (Squillace, Zogorski, and others, 1996).

In southern New England, 37 percent of shallow sand and gravel aquifer wells sampled in urban areas had detectable concentrations of MTBE (Squillace and others, 1995). Furthermore, MTBE was detected in 23 percent of deep (123 to 605 ft) water supply wells in Connecticut (Grady, 1997). Concentrations of MTBE in the urban wells sampled in southern New England were all less than 5.8 µg/L. In New Jersey, MTBE was detected in 14 percent of shallow monitoring wells sampled in 1994-96 (Stackelberg and others, 1997). In a more recent study of shallow wells in urban areas in New Jersey, concentrations of MTBE ranged from 0.02 µg/L to 1 µg/L in approximately 60 percent of the wells sampled (Baehr and others, 1999).

Detections of MTBE in ground water in Maine have been documented since before 1985 (Maine Department of Human Services, 1995), when MTBE was used as an octane enhancer in premium gasoline. Most of these earlier detections were associated with gasoline spills and gasoline storage-tank leaks (Bruce Hunter, Maine Department of Environmental Protection, oral commun., 1998).

In 1998, the State of Maine conducted a comprehensive survey of MTBE in ground water, which consisted of sampling 951 randomly-selected domestic water wells and 793 of the 830 public supply wells (State of Maine, 1998). MTBE was detected at concentrations greater than 0.1 µg/L in 15.8 percent of the residential wells and in 16.0 percent of the public supply wells.

More than 90 percent of the detections of MTBE were below 1.0 µg/L. The data were interpreted with respect to well type, knowledge of a recent gasoline spill nearby, population density, and inclusion in the RFG area. No significant differences in MTBE occurrence were observed by well type (drilled bedrock wells compared to unconsolidated surficial wells) or among wells where there were known recent gasoline spills compared to those where there were no known spills (State of Maine, 1998). The State tested the risk of an MTBE occurrence associated with population density and whether or not the well was in a required RFG area. Both factors were statistically significant, when controlled for the other, in determining the risk of MTBE detections in domestic and public-supply wells (table 1). The reason for the smaller percentage of MTBE detections in higher density areas for public-supply wells where RFG was not required was not evident. Data from the Maine study were compared to those from the NAWQA studies that had been completed as of 1998. MTBE detection rates for areas with more than 1,000 people/mi² were similar to those for the NAWQA studies (State of Maine, 1998).

Known and suspected sources of MTBE in ground water include point and nonpoint sources. Point sources include pipelines, storage tanks (above- and below-ground), accidental spillage, homeowner disposal, spillage during fueling, and waste motor oil. Heating-oil spills also have been recently identified as another source of some MTBE in ground water (Robbins and others, 1999). Suspected nonpoint sources include atmospheric deposition (recharge from precipitation or direct transport to ground water through gaseous diffusion), vehicle evaporative losses, and urban runoff (Moran and others, 1999; Baehr and others, 1999).

Table 1. MTBE detection by population density and use of reformulated gasoline, from State of Maine, 1998
[mi², square mile; RFG, reformulated gasoline]

Population Density	Domestic wells - percentage of wells with detections of MTBE		Public supply wells - percentage of wells with detections of MTBE	
	RFG use required	RFG use not required	RFG use required	RFG use not required
More than 180 people/mi ²	24	19	35	9
Less than 180 people/mi ²	18	9	19	11

Point sources will cause locally elevated concentrations of MTBE and other related gasoline compounds. Point sources have the potential to generate very high concentrations of MTBE in water (up to 50,000 $\mu\text{g/L}$ (Barker and others, 1991)). The geochemical characteristics of point sources are local effects (limited area of contamination), steep concentration gradients (marked changes in concentrations away from source area), and consistent time-series changes in concentrations over time if the point source is not continuous (concentrations decrease in a consistent manner).

Nonpoint sources, most significantly direct precipitation (and subsequent recharge of contaminated rainfall), and stormwater runoff (primarily containing gasoline flushed from land surfaces), have been suggested as the source of some low levels of MTBE in ground water (Zogorski and others, 1998; Pankow and others, 1997). Concentrations of MTBE in ground water from nonpoint sources are limited to low levels, well below 20 $\mu\text{g/L}$ (Moran and others, 1999).

A number of authors have investigated how MTBE in air may move into precipitation and enter ground water through infiltration. Compared to other gasoline components, MTBE is not very volatile (Squillace and others, 1997), and, like other VOCs, its volatility from water is inversely related to temperature. As precipitation falls through urban air, it reaches equilibrium with the gaseous phase of any VOCs present. VOC concentrations in precipitation are controlled by the ambient VOC concentration in the air and ambient air temperature (Henry's Law). Air concentrations of MTBE measured as part of a study in New Jersey were higher than the detectable threshold of 0.05 ppbv more than 84 percent of the time (Baehr and others, 1999). The median atmospheric concentration in the New Jersey study of 0.25 ppbv corresponds to an equivalent aqueous phase concentration of $0.1 \pm \mu\text{g/L}$ (Baehr and others, 1999). Over the range of temperatures of 25° to 5°C, VOC concentrations can change (increase) by a factor of 3 to 7 (Lopes and Bender, 1998). It is estimated that MTBE concentrations in precipitation will exceed a laboratory reporting limit of

0.2 $\mu\text{g/L}$ primarily at cold temperatures or high air concentrations according to Henry's Law (Lopes and Bender, 1998).

Investigators in a small number of studies have attempted to use models to predict the behavior of aqueous phase MTBE once it starts to infiltrate the unsaturated zone. Pankow and others (1997) modeled various scenarios of recharge in a hypothetical aquifer to test the possibility that MTBE in precipitation could have traveled into shallow ground water during the time frame of its use as a gasoline additive for control of vehicular emissions. Assuming no attenuation, they found that it took just 14.3 in/yr of recharge to saturate ground water 6.5 feet below the water table with atmospheric levels of MTBE in 5 years. Baehr and others (1999) developed a model to predict the concentration of MTBE at the water table, taking into account diffusion, recharge flux, thickness of the unsaturated zone, and several theoretical decay functions. They found that the concentration of MTBE at the water table, relative to the incoming concentration at the land surface, is most sensitive to the thickness of the unsaturated zone if the assumption is made that MTBE is mildly degradable and recharge is more than 20 in/yr. They also found that the reason why MTBE is not universally detected in shallow ground water could be easily explained by variations in saturated thickness and recharge. Factors that may affect the degradation rate of MTBE, such as aquifer material composition, also would contribute to the heterogeneity of MTBE detection. The degradability of MTBE in the unsaturated zone, however, is not well understood (Baehr and others, 1999).

MTBE is also present at detectable levels in urban stormwater in areas where RFG was used (Delzer and others, 1996). MTBE was detected in more than 43 percent of stormwater samples collected for permitting requirements for urban stormwater runoff in areas with RFG use. The source of MTBE in the stormwater samples may be either gasoline washoff from paved surfaces or MTBE in the precipitation (Lopes and Bender, 1998). Modeling the behavior of MTBE and other BTEX compounds found in stormwater runoff, at concentrations of MTBE above 1.0 $\mu\text{g/L}$ (the

lower detection limit for samples in the study), showed that MTBE was most likely to have come from dissolved gasoline entrained during the storm event and not from precipitation. This was determined primarily by the co-occurrence of MTBE and other BTEX compounds in the storm-water runoff.

DESCRIPTION OF STUDY AREA

Hydrology

The Windham aquifer (fig. 1) is a shallow, glacial sand and gravel aquifer in Cumberland County, southern Maine. It is mapped as a significant sand and gravel aquifer (Neil, 1998), with expected yields to properly constructed wells from 10 to more than 50 gal/min. The aquifer consists primarily of marine deltaic sand and gravel, interbedded in places with a marine silt/clay deposit. A buried esker (a long narrow ice-contact ridge) lies in the northern part of the aquifer (Gerber, Inc., 1997). Thickness of the aquifer ranges from approximately 10 ft to more than 120 ft, and depth to water in the aquifer ranges from 5 ft to more than 50 ft. Hydraulic conductivities calculated from slug tests (Bouwer and Rice method, Bouwer and Rice, 1976) range from less than 1 ft/d to more than 400 ft/d (W.J. Nichols, U.S. Geological Survey, written commun., 1999). Average hydraulic conductivities used in a calibrated model of the aquifer (Gerber, Inc., 1997) are 250 ft/d in the buried esker; 44 ft/d in the sand and gravel; 1.5 ft/d in the till surrounding the aquifer; and less than 0.1 ft/d in the marine silt/clay. Flow paths based on observed and modeled heads indicate recharge areas in the western and southwestern areas of the aquifer and discharge areas at Outlet Brook and on the edges of the aquifer (Gerber, Inc., 1997; W.J. Nichols, written commun., 1999). Some recharge also may come from Little Sebago Lake, a heavily developed lake that borders the Windham aquifer on the northeast.

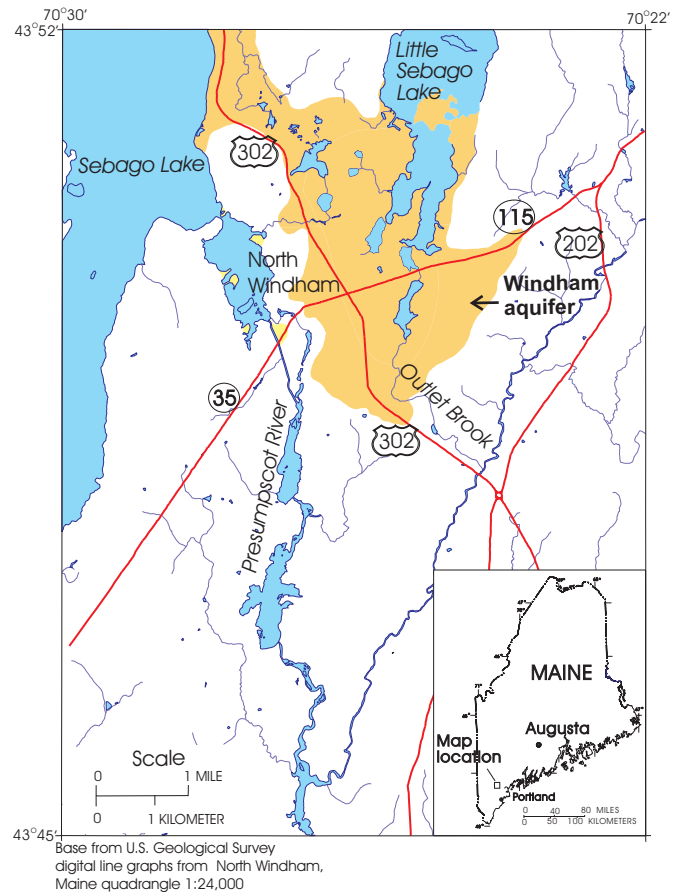


Figure 1. Location of the Windham aquifer study area, North Windham, Maine.

Average annual precipitation near Windham is 42 in. (Knox and Nordenson, 1955). Temperature data are available for East Hiram, Maine, 18.5 mi west of Windham, for 1979-97 (National Oceanic and Atmospheric Administration, 1979-97). The National Weather Service does not publish average monthly temperatures for stations with fewer than 30 consecutive years of data; therefore, the average monthly temperatures for the East Hiram station were estimated on the basis of the available period of record, (19 years) (table 2). The mean of the monthly average temperatures for 1979-97 at East Hiram was adjusted by the average departure from normal of all temperatures in the Southern Interior climatic division for the same time period to estimate the average monthly temperatures at East Hiram. The average annual temperature at East Hiram is estimated to be 43°F.

The potential for MTBE-laden precipitation to recharge the Windham aquifer depends on several meteorological factors, including the amount of precipitation, amount of ground-water recharge, and average yearly and monthly temperatures. An estimate of the maximum amount of yearly recharge available to sand and gravel aquifers can be calculated using average annual temperature (to estimate evapotranspiration) and precipitation (Lyford and Cohen, 1988). The estimated average annual temperature of 43°F translates into an estimate of annual evapotranspiration of 19.5 in. Using this value with an annual average precipitation of 42 in. for the Windham area, maximum potential recharge to the Windham aquifer is 22 in/yr. A ground-water-flow model of the Windham aquifer (Gerber Inc., 1997) used a recharge value of 50 percent of the annual precipitation (21 in/yr), which is in good agreement with the above estimate. This method, which is primarily applicable as a tool in modeling studies to determine the maximum amount of potential recharge, uses the assumption that the soils are highly permeable and that none of the direct precipitation is converted to surface runoff during precipitation events. In a nonurbanized area underlain by a sand and gravel aquifer, this is a reasonable assumption (Pluhowski and Kantrowitz, 1964). In the Windham area, rainfall from some of the urbanized area is collected in runoff detention basins, which route runoff from paved areas into ground-water recharge zones.

Land Use

The Town of North Windham, which is situated directly over the Windham aquifer, has experienced rapid development during the last 20 years, along with much of southern Maine. Once an area of pastures and woodlands with minor urban development, it is now a major bedroom community of nearby Portland. An extensive area of commercial development, including numerous strip malls and major retail outlets, now covers much of the Town center. The Town is unsewered, and this makes the productive aquifer vulnerable

to contamination from residential and commercial sewage disposal, urban runoff, and other human activities that contribute contaminants to the subsurface. The Windham aquifer was used as a major source of drinking water for the Portland

Table 2. Estimated average monthly temperatures in North Windham, Maine

[Values estimated from National Weather Service station data in East Hiram, Maine]

Month	Average monthly temperature in Windham, in degrees Fahrenheit
January	18
February	19
March	30
April	42
May	53
June	62
July	68
August	65
September	57
October	47
November	36
December	22

Water District until 1998, when one of the large supply wells was found to be contaminated with MTBE. Currently, almost all of the residents of North Windham get their water from Portland Water District's Sebago Lake intake, although a small number of residents still use the aquifer as a drinking-water source (James West, Portland Water District, oral commun., 1999).

Because point sources (small spills and leaky storage tanks) of MTBE to shallow aquifers, which have been documented in many parts of the State, are in areas of human activity, a measure of the degree of human activity on the land would be useful. A digital land-use geographic information system (GIS) coverage of the North Windham area, based on satellite images taken in 1991-92, provides a qualitative means of assessing the amount of urbanization (human activity) near each well in the study area (fig. 2). This dataset, part of the National Land Cover Data (NLCD), was produced by the U.S. Geological Survey/National

Mapping Division/ Earth Resources Observation System (EROS)/Land Cover Characterization Program (Vogelman and others, 1998). These data are currently (2000) preliminary and have not yet been assessed for accuracy. The land-cover classification can be generalized as undeveloped (includes forested [several categories], and agricultural [several categories]), low-density residential, urbanized lands (several categories), and other (such as wetlands, water, and barren lands). The Town center of North Windham is clearly visible, including development along Routes 115 and US 302 (fig. 2). Residential areas around Collins Pond and Little Sebago Lake also are visible. Undeveloped land, including agricultural and forested areas, surrounds and is intermingled with developed areas in North Windham.

DATA-COLLECTION METHODS

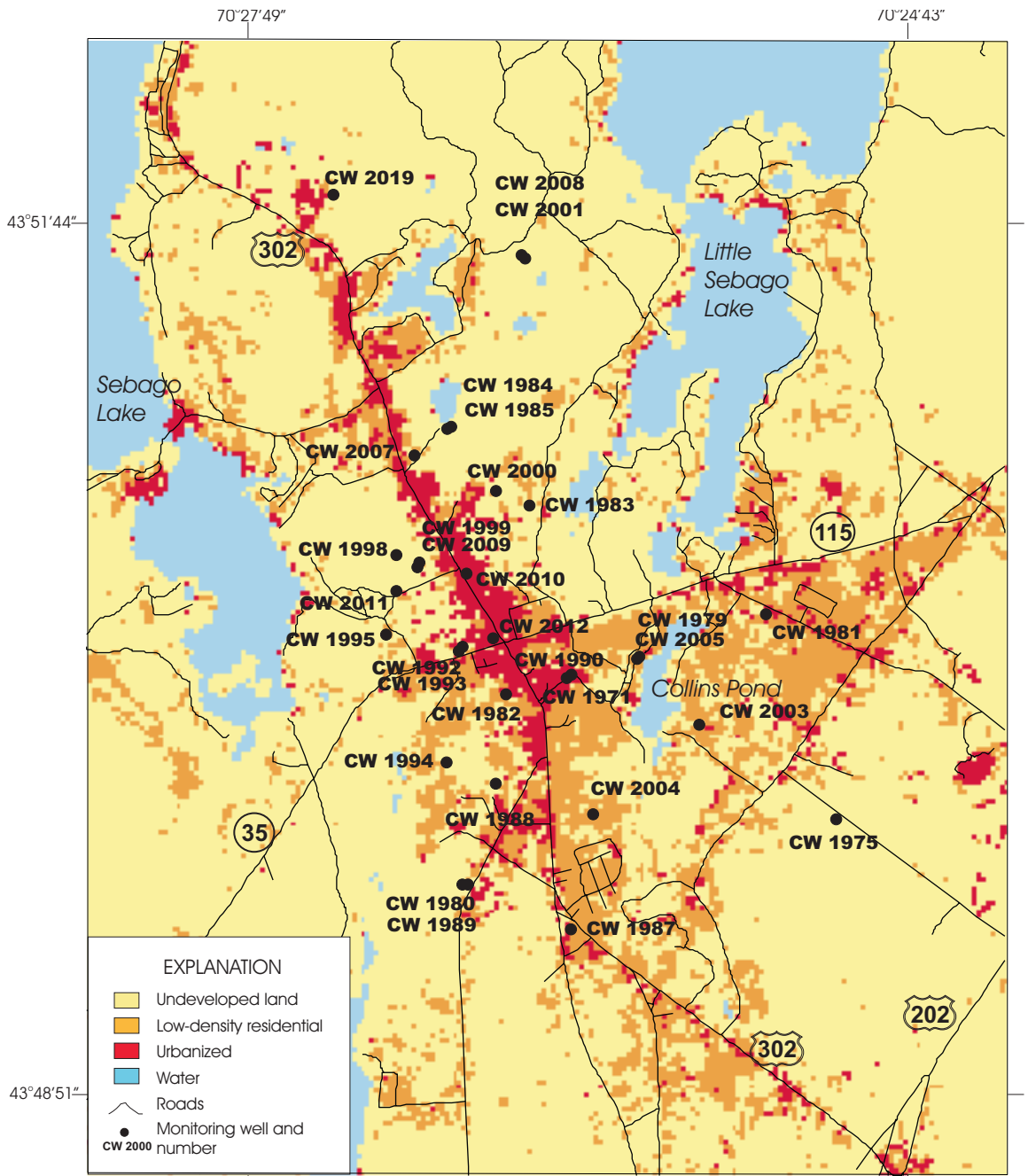
Ground-water samples

An existing network of shallow wells (fig. 3), installed by the USGS and distributed throughout the ground-water flow system in the Windham aquifer was used for this study (Nichols and Silverman, 1998). These wells are completed in different types of glacial sediments. Samples were collected in July and August, 1998 in 31 wells; subsequent sampling rounds in November and December 1998 and April and May, 1999 included a smaller number of wells (the number of times each well was sampled is shown in fig. 3). Well depths ranged from 19 to 132 ft, with screened interval depths ranging from 8 to 130 ft (table 3). Screened intervals were mostly 5 or 10 ft long, with a few wells having longer screens (up to 30 ft). Depth to water in the wells at the time of sampling ranged from 4.5 to 61.1 ft (table 4). All the wells are completed in unconfined parts of the aquifer; the sampling points range from water-table position to more than 110 ft below the water table. Seven pairs of nested wells were sampled to

evaluate vertical distributions of MTBE. The dominant land cover (table 3) near each well was determined from the NLCD land-cover classification.

USGS National Water Quality Assessment protocols for sampling ground-water wells (Koterba and others, 1995) were followed in sample handling, quality assurance/quality control (QA/QC), sampling equipment, and cleaning. The USGS protocols were modified, however, to follow the U.S. Environmental Protection Agency (USEPA) low-flow (minimal drawdown) sampling procedures (Puls and Barcelona, 1995). A small number of wells did not yield enough water to meet the minimum drawdown requirements. These wells were pumped dry and sampled the next day.

The sampling equipment setup was simplified from USGS protocols to reflect what was necessary for the small number of constituents sampled in this study. A submersible Fultz 300R pump with Teflon-lined tubing was used to collect samples. The Teflon outflow tube was connected to a Hydrolab flow-through cell for monitoring field parameters. Once field parameters stabilized (did not change more than 5 percent for three consecutive measurements) and drawdown was kept to within 20 percent of the standing head, the flow rate was measured and the sample collected. Flow rates were generally within the range of 0.026 to 0.11 gal/min (100 mL/min to 400 mL/min). Samples for analysis of VOCs (benzene, toluene, ethyl benzene, xylene, and methyl tert-butyl ether) were collected directly from the Teflon outflow tube into three 40-mL amber glass volatile organic analysis vials with septum tops and no air space. Samples were kept on ice and shipped within 24 hours to the USGS laboratory for analysis. After sampling, all the equipment was cleaned with a dilute Liquinox solution, rinsed with distilled water, rinsed with methanol, and rinsed again with distilled water. The pump and cleaned tubing were packed in plastic sheeting for transport between sites.



Roads from U.S. Geological Survey digital line graphs from North Windham, Maine quadrangle 1:24,000
 National Land Cover Data produced by the U.S. Geological Survey / National Mapping Division / Earth Resources Observation System (EROS) / Land Cover Characterization Program
 "land-cover data are preliminary and have not yet been assessed for accuracy."

Figure 2. Land-cover distribution in the North Windham, Maine area, 1992. (Vogelman and others, 1998)

Table 3. Selected data for ground-water wells in the Windham aquifer

[--, no data available; Aquifer codes: IC, ice-contact deposits; GL, glacial sediments, undifferentiated; TL, till; M, marine; D, deltaic deposits
 Water-level data from Nichols and Silverman, 1998 (data values rounded)]

Local well number	U.S. Geological Survey station identification number	Well depth, in feet	Land surface elevation, in feet above sea level	Aquifer code	Screened interval, in feet below land surface	Water level range, in feet below land surface	Screen length, in feet	Dominant land use
CW 1971	435002070255701	22	299.8	IC	17-22	12-16	5	urbanized
CW 1975	434934070244101	47.5	273.9	M	32.5 - 37.5	21-26	5	undeveloped
CW 1979	435008070253901	109	309.1	D	104-109	37-39	5	low-density residential
CW 1980	434919070262601	36	307.1	IC	31-36	14-18	5	undeveloped
CW 1981	435018070250201	57.7	312.9	IC	44-49	22-28	5	low-density residential
CW 1982	434958070261601	55	297.5	GL	40-45	15-18	5	low-density residential
CW 1983	435039070261101	37.6	307.8	GL	32-37	15-18	5	undeveloped
CW 1984	435056070263701	132	295.1	IC	120-130	3-7	10	undeveloped
CW 1985	435055070263601	25.7	295.1	IC	15.5 - 25.5	3-7	10	undeveloped
CW 1987	434910070255601	111	303.5	IC	101-111	58-60	10	low-density residential
CW 1988	434941070261901	55	290.6	GL	48-55	1-4	7	low-density residential
CW 1989	434919070262602	19	307	GL	14-19	11-18	5	undeveloped
CW 1990	435002070255601	80	299.9	IC	60-80	25-28	20	urbanized
CW 1992	435008070262901	54	305	GL	37-42	10-14	5	urbanized
CW 1993	435008070262902	27	305	GL	22-27	8-11	5	urbanized
CW 1994	434945070263401	20	276.7	TL	10-15	0-4	5	undeveloped
CW 1995	435012070265101	52	307.5	TL	22-32	11-15	10	undeveloped
CW 1998	435027070264801	35	312	GL	30-35	6-20	5	undeveloped
CW 1999	435026070264101	80	310.8	GL	78-80	18-23	8	urbanized ¹
CW 2000	435041070262301	70	319.7	GL	40-50	26-28	10	urbanized ¹
CW 2001	435131070261401	127	309.3	GL	97-127	13-16	30	undeveloped
CW 2003	434946070252301	67	316.2	GL	57-62	44-45	5	low-density residential
CW 2004	434927070255101	58	315	GL	38-58	49-50	20	low-density residential
CW 2005	435008070253902	48	309	GL	38-48	34-36	10	low-density residential
CW 2007	435040070264501	24	301.4	GL	14-24	8-10	10	low-density residential
CW 2008	435131070261402	27	309.5	GL	17-27	13-15	10	undeveloped
CW 2009	435026070264102	22	310.8	GL	12-22	11-14	10	urbanized ¹
CW 2010	435018070263201	32	310.7	GL	22-32	14-16	10	urbanized
CW 2011	435014070264901	27	310.7	GL	17-27	12-14	10	undeveloped
CW 2012	435004070262101	27	307.6	GL	17-27	13-16	10	urbanized
CW 2019	435136070271201	--	312.8	--	8.1 - 13.1	3-9	5	undeveloped

¹New urban development since satellite imagery was taken (fig. 2).

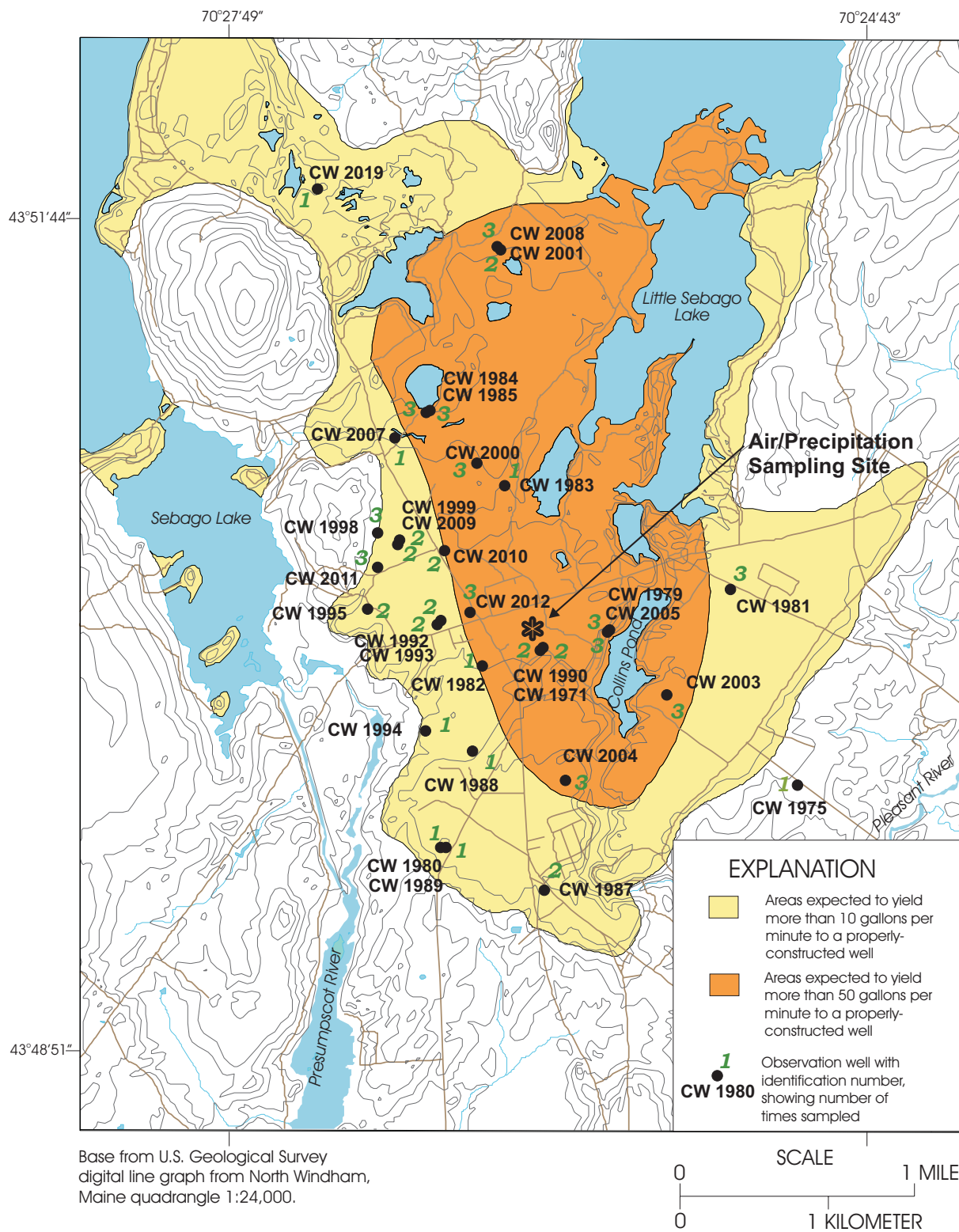


Figure 3. Locations of air- and precipitation-sampling sites and wells samples for MTBE, Windham aquifer, Windham, Maine. (Aquifer boundaries from Neil, 1998.)

Table 4. Sampling conditions and selected physical properties for wells and precipitation station sampled in North Windham, July 1998 to May 1999

[°C, degrees Celsius; diss, dissolved; gal/min, gallons per minute; mg/L, milligrams per liter; min., minutes; µS/cm, microsiemens per centimeter; --, no data]

U.S. Geological Survey station identification number	Local well number or name	Date	Time	Depth to top of sampling point, in feet	Flow rate, in gal/min	Pumping period, in minutes	Water temperature, in °C	Static water level, in feet below land surface	Alkalinity, diss, field, in mg/L as CaCO ₃	Specific conductance, in µS/cm at 25°C	Dissolved oxygen, in mg/L	pH, field, in standard units
GROUND WATER WELLS												
435002070255701	CW 1971	07/21/98	1630	19	0.079	42	18.3	14.17	3	52	9.5	5.4
435002070255701	CW 1971	04/29/99	1100	19	.058	34	12.1	14.85	--	49	7.3	5.5
434934070244101	CW 1975	07/31/98	1200	35	.042	150	19.8	26.48	43	108	8.7	8.6
435008070253901	CW 1979	08/05/98	1025	100	.048	40	15.3	40.54	39	263	3.4	6.6
435008070253901	CW 1979	05/04/99	1145	104	.21	32	9.5	41.57	--	292	6	6.6
434919070262601	CW 1980	07/30/98	1030	33	.02	40	21.3	17.97	16	152	10.5	6
435018070250201	CW 1981	08/06/98	1320	46	.1	20	15.1	26.98	12	262	4.8	5.6
435018070250201	CW 1981	11/19/98	1130	46	.02	9	8	28.8	7	257	3.9	5.5
435018070250201	CW 1981	04/30/99	0955	46	.053	12	10.8	27.42	--	234	2.6	5.3
434958070261601	CW 1982	08/06/98	1040	42	.069	20	19.2	19.06	40	169	7.8	7.8
435039070261101	CW 1983	08/04/98	1425	34	.024	40	19.6	18.67	18	90	11	6.5
435056070263701	CW 1984	09/02/98	1115	120	.058	90	19.3	7.9	46	146	5.6	6.5
435056070263701	CW 1984	10/29/98	1130	120	.185	60	11.2	7.53	43	148	5.7	6.5
435056070263701	CW 1984	04/27/99	1300	100	.13	70	8.8	7.44	--	154	5.6	6.6
435055070263601	CW 1985	07/23/98	1035	18	.1	35	25.8	7.01	10	66	.6	5.9
435055070263601	CW 1985	11/18/98	1115	19	.18	30	9.3	6.98	11	74	.6	6
435055070263601	CW 1985	04/27/99	1115	16	.16	42	7.2	6.85	--	73	1.9	6
434910070255601	CW 1987	09/03/98	1020	101	.079	50	13.4	61.11	39	225	1.1	7.5
434910070255601	CW 1987	05/03/99	1245	101	.053	51	12.5	60.37	--	221	.5	7.5
434941070261901	CW 1988	09/01/98	1345	50	.09	45	14.4	5.3	10	145	2.9	5.5
434919070262602	CW 1989	07/30/98	1255	16	.042	60	20.9	14.45	9	109	10.9	5.6
435002070255601	CW 1990	07/28/98	1405	62	.016	50	23	28.66	25	185	6.1	8.8

12 **Table 4.** Sampling conditions and selected physical properties for wells and precipitation station sampled in North Windham, July 1998 to May 1999--Continued

[°C, degrees Celsius; diss, dissolved; gal/min, gallons per minute; mg/L, milligrams per liter; min., minutes; µS/cm, microsiemens per centimeter; --, no data]

U.S. Geological Survey station identification number	Local well number or name	Date	Time	Depth to top of sampling point, in feet	Flow rate, in gal/min	Pumping period, in minutes	Water temperature, in °C	Static water level, in feet below land surface	Alkalinity, diss, field, in mg/L as CaCO ₃	Specific conductance, in µS/cm at 25°C	Dissolved oxygen, in mg/L	pH, field, in standard units
435002070255601	CW 1990	04/29/99	0940	65	.058	60	10.8	29.34	--	245	.7	7.1
435008070262901	CW 1992	07/22/98	1310	40	.048	50	17.5	13.91	10	39	7.3	5.8
435008070262901	CW 1992	04/28/99	1025	39	.053	55	10.9	14.63	--	42	9.7	5.8
435008070262902	CW 1993	07/22/98	1510	24	.048	52	22.3	11.02	9	40	9	5.8
435008070262902	CW 1993	04/28/99	1140	24	.11	40	9.9	11.61	--	38	6.5	5.8
434945070263401	CW 1994	08/31/98	1430	12	.032	30	22.5	4.5	78	252	5.8	6.3
435012070265101	CW 1995	08/31/98	1120	24	.042	86	14.7	16.65	12	204	4.8	5.7
435012070265101	CW 1995	05/03/99	1050	24	.013	45	16.1	15.84	--	271	7	5.6
435027070264801	CW 1998	07/29/98	1620	32	.055	120	22.6	16.77	6	43	9.6	5.9
435027070264801	CW 1998	11/19/98	1015	32	.03	24	7.1	23.09	19	65	12.1	5.8
435027070264801	CW 1998	04/29/99	1220	32	.069	20	12.4	15.71	--	51	11.5	6
435026070264101	CW 1999	07/21/98	1030	78	.048	25	20.7	24.14	33	136	1.6	7.9
435026070264101	CW 1999	04/30/99	1335	78	.079	19	13.6	22.44	--	116	2.4	7.6
435041070262301	CW 2000	07/22/98	0940	42	.026	40	17.6	29.62	99	562	2.1	6.1
435041070262301	CW 2000	12/01/98	1330	40	.11	54	11.8	30.47	140	557	.6	6.3
435041070262301	CW 2000	04/28/99	1420	42	.11	60	12.2	29.77	--	548	1.2	6.1
435131070261401	CW 2001	08/10/98	1155	97	.048	70	14.9	17.61	150	309	.8	8.7
435131070261401	CW 2001	12/01/98	1015	95	.12	61	9.1	17.61	157	321	.3	8.7
435131070261401	CW 2001	05/06/99	1300	97	.048	50	10.7	17.11	--	312	.4	8.8
434946070252301	CW 2003	08/10/98	1505	60	.053	28	18.1	46.86	20	146	3.6	6.4
434946070252301	CW 2003	10/30/98	1315	60	.069	35	9.2	46.88	17	146	3.7	6.4
434946070252301	CW 2003	04/29/99	1450	58	.074	39	12.8	47.42	--	139	3.2	6.4
434927070255101	CW 2004	07/29/98	1055	53	.053	40	18.4	51.48	8	103	10.1	5.7
434927070255101	CW 2004	11/19/98	1405	54	.11	21	7.8	51.93	7	125	10.1	5.6
434927070255101	CW 2004	04/30/99	1135	54	.058	33	13.9	51.61	--	154	9.1	5.5

Methyl tert-Butyl Ether (MTBE) in Ground Water, Air, and Precipitation at North Windham, Maine

Table 4. Sampling conditions and selected physical properties for wells and precipitation station sampled in North Windham, July 1998 to May 1999--Continued

[°C, degrees Celsius; diss, dissolved; gal/min, gallons per minute; mg/L, milligrams per liter; min., minutes; µS/cm, microsiemens per centimeter; --, no data]

U.S. Geological Survey station identification number	Local well number or name	Date	Time	Depth to top of sampling point, in feet	Flow rate, in gal/min	Pumping period, in minutes	Water temperature, in °C	Static water level, in feet below land surface	Alkalinity, diss, field, in mg/L as CaCO ₃	Specific conductance, in µS/cm at 25°C	Dissolved oxygen, in mg/L	pH, field, in standard units
435008070253902	CW 2005	08/05/98	1245	40	.037	40	18.1	36.7	11	164	10.3	5.7
435008070253902	CW 2005	10/30/98	1015	40	.079	30	9.2	37.05	14	197	9.7	5.6
435008070253902	CW 2005	05/04/99	1030	40	.074	43	14.8	37.52	--	190	9.6	5.6
435040070264501	CW 2007	07/30/98	1540	16	.032	40	17.5	12.14	11	328	9.6	5.4
435131070261402	CW 2008	08/10/98	0940	18	.032	33	13.6	16.04	8	36	9.8	5.6
435131070261402	CW 2008	05/06/99	1410	18	.04	25	13.8	15.83	--	60	9.6	5.5
435026070264102	CW 2009	07/20/98	1430	12	.159	25	15.4	14.49	8	52	10.8	5.9
435026070264102	CW 2009	04/30/99	1520	13	.058	40	15.1	15.75	--	203	10.3	5.4
435018070263201	CW 2010	07/28/98	1110	24	.058	55	19.5	17.22	7	87	9.8	5.7
435018070263201	CW 2010	05/06/99	1015	26	.11	37	12.7	18.18	--	157	10.1	5.5
435014070264901	CW 2011	07/21/98	1400	20	.053	30	17.2	14.34	5	38	9.8	5.6
435014070264901	CW 2011	11/24/98	1025	19	.09	35	12	15.84	6	35	10.9	5.5
435014070264901	CW 2011	05/07/99	1000	21	.026	35	13.1	15.19	--	32	11.3	5.5
435004070262101	CW 2012	09/03/98	1400	18	.056	50	18.8	17.28	42	465	8.7	6.1
435004070262101	CW 2012	11/24/98	1215	18	.06	44	13	17.71	49	493	7.5	6.2
435004070262101	CW 2012	05/07/99	1145	22	.069	46	12.9	17.17	--	431	2.9	6.3
435136070271201	CW 2019	09/01/98	1010	9	.056	45	14	9.61	17	58	6.7	6.2
PRECIPITATION STATIONS												
434958070260701	Arlington School, precip	01/25/99	0910	--	--	--	--	--	--	--	--	--
434958070260701	Arlington School, precip	05/04/99	1235	--	--	--	--	--	--	--	--	--
434958070260701	Arlington School, precip	05/04/99	1455	--	--	--	--	--	--	--	--	--
434958070260701	Arlington School, precip	05/19/99	1135	--	--	--	--	--	--	--	--	--

Quality assurance samples consisted of equipment blanks (15 percent of all samples), trip blanks, spiked samples, source-solution blanks, and ambient blanks (trip blank vials opened and exposed to the ambient air during sampling, then closed and shipped for analysis). In all, 26 percent of all the samples analyzed were QA/QC samples. During the initial round of sampling, deionized water created in the District laboratory was used for rinsing; this presented a problem, however, in that the water was later found to be contaminated with very low concentrations of VOCs. An additional round of samples was collected for all the environmental samples with VOC detections in the first round to eliminate the rinse water as a source of VOCs to the samples. Purchased distilled water was used for all additional sampling, and all sampling equipment and supplies were stored in a clean environment. Detections of MTBE in the first round of samples (11 detections) were recoded as a "less than" value larger than the observed analytical result (for example, a detection in the first round of 0.42 µg/L would have been recoded to <0.5 µg/L, to make sure that the database did not contain detections of MTBE from potentially compromised samples). MTBE was also detected in subsequent sampling rounds in 9 of the 11 wells in which it was detected in the first round.

Air samples

Air samples were collected following protocols developed by the NAWQA VOC National Synthesis Team in conjunction with the Oregon Graduate Institute (OGI) in Beaverton, Oregon (D.A. Bender, U.S. Geological Survey, written commun., 1998). A representative air sample is collected from an area that has unobstructed air flow, is not unduly influenced by nearby sources or activities, and is not affected by micrometeorological influences. Air samples were collected at a site on the grounds of the Arlington School, located in the center of North Windham but removed from any direct exhaust from local sources (fig. 3). The air sampler was co-located on

a platform with the precipitation-sampling equipment.

Each sampling event consisted of two simultaneously collected, time-composited samples, one of 1.5 L of air, the other of 5 L of air. Composite samples were collected by drawing a known volume of air through a multisorbent air sampling cartridge with an SKC, Inc. model 224-PCXR8 universal sampling pump. Each pump was programmed to collect a 24-hour time-composited sample, during which time the pump cycled on and off intermittently to achieve total sampling volumes of 1.5 L or 5 L. The flow rate for all samples was 30 mL/min. Two pumps were mounted inside a 17.5-in. by 7.5-in. by 14-in. weatherproof metal box with ports for two sampling cartridges, which was in turn mounted on a platform about 6.5 ft above the ground.

Samples were collected every 10 days, to sample representatively all days of the week, for 29 weeks, from Dec. 20, 1998 to July 21, 1999 (20 samples). Pre-prepared cartridges were shipped on ice overnight from OGI within 3 days of the beginning of the sampling period and kept on ice until the sampling began. For each 24-hour period, 1.5-L and 5-L samples were collected, and blank QA/QC cartridges were included for every sample analysis. At the end of the 24-hour sampling period, the cartridges were retrieved and placed on ice; the air temperature, relative humidity, and barometric pressure for the sampling period were recorded. The samples were shipped overnight to OGI for analysis. Details of the analytical methods, sample handling procedures, and QA/QC for the laboratory are explained in Pankow and others (1998).

Precipitation samples

The study was designed to collect six precipitation samples from December 1998 to July 1999; however, the study coincided with a long-term regional drought, and precipitation events to sample were limited. In addition, foaming of the samples in the laboratory did not allow for the low detection limits achieved for the ground-water

samples. (In the laboratory, the analyst must dilute a sample that foams to prevent the foam from interfering with the analytical equipment.) In all, four precipitation samples were collected, with detection limits of 0.2 µg/L to 1.0 µg/L. All samples were rainfall samples, collected during precipitation events of 0.15 in. or more.

The precipitation VOC sampler, designed by the NAWQA VOC National Synthesis team (G.C. Delzer, U.S. Geological Survey, written commun., 1999) consisted of a 10-in. diameter galvanized funnel with a narrow (0.5-in.) bottom opening and a screen to eliminate debris from entering the bottom. A Teflon tube was attached to the bottom of the funnel, which in turn was attached with a swagelock union to a Teflon gas-sampling bag. The sampler was deployed just prior to an expected rainfall event or just after the commencement of one. After the event, the Teflon bag was retrieved and the precipitation sample analyzed. Between events, the sampler was cleaned with a Liquinox solution, rinsed with distilled water and methanol, and stored in a plastic bag in a clean area.

OCCURRENCE AND DISTRIBUTION OF MTBE IN THE NORTH WINDHAM AREA

Analyses of the ground-water samples conclusively demonstrate that MTBE is widely distributed at low concentrations in the Windham aquifer. MTBE also is present in air, as analyses of those samples showed. The precipitation-sampling program was inconclusive, however, although it is possible to calculate air-water equilibrium concentrations of MTBE using air-water partitioning principles.

MTBE in ground water

MTBE was detected in many water samples from the Windham aquifer. This result is based on analyses of 64 individual samples collected from 31 wells (table 4, table 5, fig. 3). From one to three water samples were collected from each of the wells on different sampling dates in 1998 and

1999. Eleven of the 31 wells sampled (35 percent) had at least one detection of MTBE (fig. 4). MTBE was detected in 18 samples (28 percent of all samples), and the median concentration of MTBE was 1.13 µg/L (not including the samples that were recoded as “less thans” from the first sampling round). MTBE was below the detection limit in 46 samples (72 percent); however, 13 of these samples had elevated detection limits (greater than 0.200 µg/L). Two of the three highest concentrations detected (14 µg/L and 3.96 µg/L) were collected from the same well, CW 2012. This well is located in a densely developed part of the study area, close to a gasoline station.

The detection of MTBE was not accompanied by the detection of the other less water-soluble BTEX compounds (benzene, toluene, ethyl benzene, and xylene). This observation is consistent with other findings of MTBE in trace concentrations in Maine (State of Maine, 1998).

To determine if there were any spatial patterns to the MTBE detections, the data were analyzed with respect to: depth of the sample within the aquifer; location of sample in either the high- or moderate-yielding parts of the aquifer as mapped by the Maine Geological Survey (Neil, 1998); and land cover. Another variable, hydraulic conductivity (K) (independent of aquifer yield zone) also was analyzed.

Fourteen of the wells sampled were paired wells screened in both the shallow and deep parts of the aquifer. Using the distribution of detections in the paired wells, a Chi-square test (Ott, 1993) failed to detect a significant difference between the concentrations of MTBE in shallow and deep parts of the aquifer. The probability of detecting MTBE is nearly equal in each well of a pair. An analysis of the entire sample population with respect to depth of sampling point shows a higher number of detections in the shallow parts of the aquifer (wells less than 50 ft deep) than in the deeper parts of the aquifer (wells more than 50 ft deep), but there are still enough detections at depth to make the difference not statistically significant.

Table 5. VOC data for ground water and precipitation sampled in North Windham, July 1998 to May 1999--Continued

[VOC, volatile organic compound; µg/L, micrograms per liter; <, concentration known to be less than value shown; E, estimated concentration below regular reporting limit (0.2 µg/L); --, no data]

U.S. Geological Survey station identification number	Local well number or name	Date	Time	Benzene, total, in µg/L (34030)	Toluene, total, in µg/L (34010)	Ethylbenzene, total, in µg/L (34371)	M- and p-xylenes, in µg/L (85795)	Total o-xylenes, in µg/L (77135)	Methyl tert-butyl ether, in µg/L (78032)
435002070255601	CW 1990	04/29/99	0940	<200	--	<200	<200	<200	0.226
435008070262901	CW 1992	07/22/98	1310	<200	<200	<200	<200	<200	<200
435008070262901	CW 1992	04/28/99	1025	<200	--	<200	<200	<200	<200
435008070262902	CW 1993	07/22/98	1510	<200	<200	<200	<200	<200	<200
435008070262902	CW 1993	04/28/99	1140	<200	--	<200	<200	<200	<200
434945070263401	CW 1994	08/31/98	1430	<200	<200	<200	<200	<200	<200
435012070265101	CW 1995	08/31/98	1120	<200	<200	<200	<200	<200	<200
435012070265101	CW 1995	05/03/99	1050	<200	--	<200	<200	<200	<200
435027070264801	CW 1998	07/29/98	1620	<200	<200	<200	<200	<200	<700
435027070264801	CW 1998	11/19/98	1015	<200	<200	<200	<200	<200	<200
435027070264801	CW 1998	04/29/99	1220	<200	--	<200	<200	<200	<200
435026070264101	CW 1999	07/21/98	1030	<200	<200	<200	<200	<200	<200
435026070264101	CW 1999	04/30/99	1335	<200	<200	<200	<200	<200	<200
435041070262301	CW 2000	07/22/98	0940	<400	<400	<400	<400	<400	<400
435041070262301	CW 2000	12/01/98	1330	<200	<200	<200	<200	<200	0.459
435041070262301	CW 2000	04/28/99	1420	0.189	--	<200	<200	<200	0.346
435131070261401	CW 2001	08/10/98	1155	<800	<800	<800	<800	<800	<800
435131070261401	CW 2001	12/01/98	1015	<200	<200	<200	<200	<200	<200
435131070261401	CW 2001	05/06/99	1300	<200	<200	<200	<200	<200	<200
434946070252301	CW 2003	08/10/98	1505	<200	<200	<200	<200	<200	<1.00
434946070252301	CW 2003	10/30/98	1315	<200	<200	<200	<200	<200	0.723
434946070252301	CW 2003	04/29/99	1450	<200	--	<200	<200	<200	0.467
434927070255101	CW 2004	07/29/98	1055	<200	<200	<200	<200	<200	<700
434927070255101	CW 2004	11/19/98	1405	<200	<200	<200	<200	<200	3.14
434927070255101	CW 2004	04/30/99	1135	<200	--	<200	<200	<200	0.596
435008070253902	CW 2005	08/05/98	1245	<200	<200	<200	<200	<200	<1.80

OCCURRENCE AND DISTRIBUTION OF MTBE 17

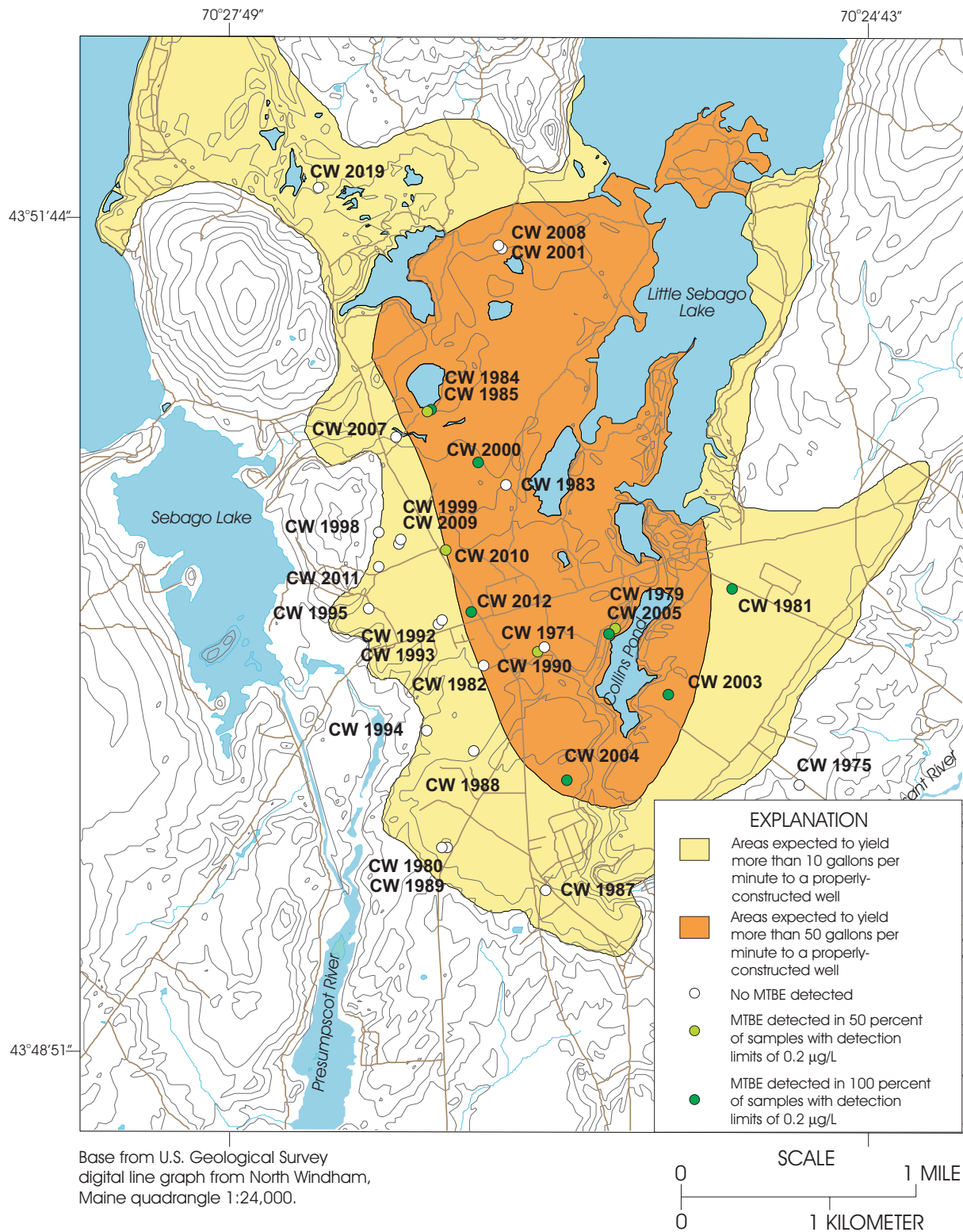


Figure 4. Distribution of MTBE detections in wells in the Windham aquifer, Windham, Maine. (Aquifer boundaries from Neil, 1998.)

To test the effect of aquifer transmissivity, the spatial distribution of MTBE detections was grouped according to location in the aquifer as either high-yield zone (wells are expected to produce more than 50 gal/min) or moderate-yield zone (wells are expected to produce between 10 and 50 gal/min), as mapped by the Maine Geological Survey (Neil, 1998) (fig. 4). The high-yield zone had many more wells with detections (64 percent) compared to the moderate-yield zone (12 percent). These two subgroups are significantly different ($p = 0.05$). (For an explanation of p values, see Ott (1993) or any general statistics textbook. In this report, p -values less than 0.05 indicate that the null hypothesis of the test was rejected.)

The wells in which MTBE were detected were grouped according to the land-cover classification described earlier: undeveloped, urban, and low-density residential (fig. 5). Although the concentration of detected MTBE was not noticeably different among the groups, the frequency of MTBE detection was quite different. MTBE was detected in 64 percent of the samples collected from wells in the low-density residential area, in 33 percent of samples from the urban area, and in 16 percent of samples from the undeveloped areas. A Kruskal-Wallis test (Helsel and Hirsch, 1992) on the MTBE concentrations by land-cover classification showed that at least one group is significantly different from the others ($p = 0.013$).

MTBE detections are more frequent in the areas of the aquifer with higher K values than in areas with lower K values. Hydraulic conductivity for each well, as determined by slug tests (W.J. Nichols, written commun., 1999,) was compared to MTBE detections (at least one per well). For

this test, the wells were divided into two equal groups of K ranges, one less than 5 ft/d, the other more than 5 ft/d. A 2x2 contingency table test (Chi-square test) shows a statistically significant difference ($p=0.013$) in the distribution of wells with detections in the two groups (table 6).

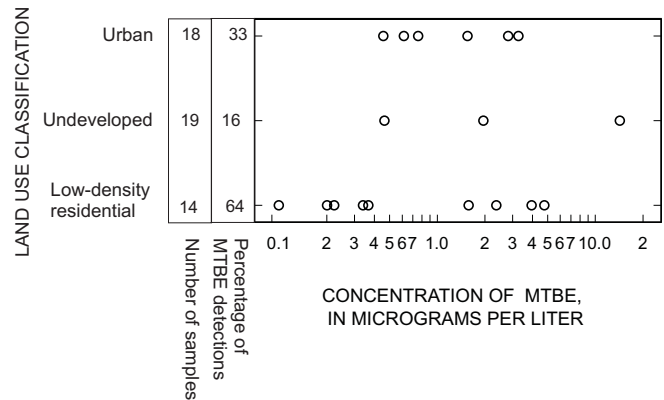


Figure 5. Concentrations of MTBE detections by land-use classification for samples with detection limits of 0.2 micrograms per liter.

MTBE in air

MTBE was detected in all of the 20 air samples collected (table 7, fig. 6). Measured concentrations of MTBE in air near the center of North Windham during this study range from 1.0 ppbv to 0.03 ppbv (fig. 6). The highest concentrations (1.0 and 0.9 ppbv) were measured in January and February 1999, before Maine opted out of the RFG program. The lowest concentrations (0.04 and 0.03 ppbv) were in late April-early May, soon after RFG use was discontinued in Maine.

Table 6. Detections of MTBE in wells in the Windham aquifer by hydraulic conductivity

MTBE detections	Numbers of wells in each hydraulic conductivity (K) group (determined by slug test)	
	$K =$ more than 5 feet/day	$K =$ less than 5 feet/day
No detection of MTBE	7	13
At least one detection of MTBE	9	2

Table 7. Selected data for air samples and concentrations of MTBE in air, North Windham, December 1998 to July 1999

[L, liters; mm Hg, millimeters of mercury; °C, degrees Celsius; ppbv, parts per billion by volume; E, estimated concentration below the lowest daily standard (0.12 ppbv)]

Date	Sample volume, in L	Temperature, in °C	Atmospheric pressure, in mm Hg	MTBE in air, in ppbv
12/20/1998	4.68	1	764	E0.08
01/10/1999	5.01	-10.6	754	1.0
01/18/1999	5.01	3.9	758	0.18
01/28/1999	5.01	-11.4	758	.18
02/08/1999	5.01	-4	751	.88
02/19/1999	5.01	-1	751	.29
03/02/1999	5.01	1.1	740	.26
03/11/1999	5.01	-1.1	744	E.06
03/22/1999	5.01	3.9	742	E.07
04/01/1999	5.01	7.5	762	E.11
04/10/1999	5.01	3.9	754	E.09
04/26/1999	5.01	10.8	745	E.04
05/06/1999	5.01	14.7	758	E.03
05/16/1999	5.01	11.7	771	E.09
05/26/1999	5.01	12.5	746	.19
06/04/1999	5.01	12.5	750	E.10
06/13/1999	5.01	21.1	752	E.08
06/22/1999	5.01	20.6	754	E.09
07/03/1999	5.01	25.8	763	.12
07/21/1999	5.01	27.8	756	E.09

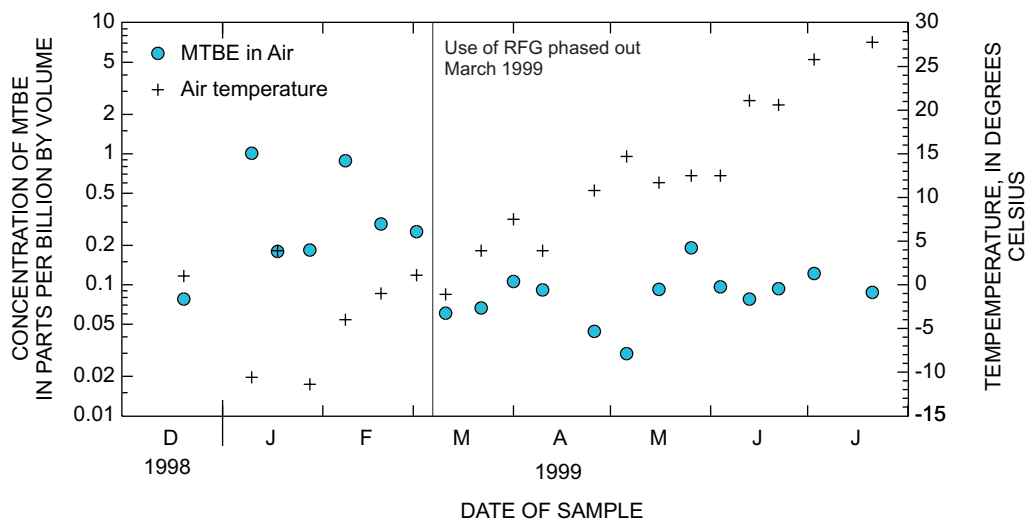


Figure 6. Concentrations of MTBE in air, and air temperature at the start of each time-composited sampling period in North Windham, Maine, December 1998 to July 1999.

The concentrations of MTBE in North Windham in air before and after the phaseout of RFG are significantly different ($p = 0.005$). Before the phaseout, the median air concentration of MTBE in air was 0.25 ppbv, which is similar to the 0.27-ppbv concentrations in air at the Rowan College medium-density urbanization site in New Jersey (A.L. Baehr, U.S. Geological Survey, written commun., 1999). After the RFG phaseout, air concentrations of MTBE in Windham decreased to a median of 0.09 ppbv.

MTBE in precipitation

No MTBE was detected in the four precipitation samples. Rainfall samples were collected near the Arlington school on three sample dates: January 25, May 4 (two samples) and May 19, 1999. Samples were also collected on March 22 and May 26, but volumes were insufficient for analysis. Rainfall during March to May 1999 was far below normal, so few rainfall events were available to sample. Elevated detection limits were reported for three of the samples; this was caused by samples foaming in the laboratory. Samples that foam must be diluted to protect the analysis equipment, which limits their usefulness in any data analysis. The absence of detectable MTBE could indicate the lack of MTBE in the precipitation samples, or, that MTBE is present in concentrations below the elevated detection limits.

During a rainfall event, MTBE in precipitation is expected to equilibrate very quickly with ambient air concentrations of MTBE (Squillace, Zogorski, and others, 1996; Lopes and Bender, 1998). As a raindrop falls through air that contains MTBE, the MTBE partitions into the raindrop, and concentrations in the raindrop should achieve equilibrium with air concentrations within a few tens of meters as it falls (Lopes and Bender, 1998). The concentration in rainfall is governed by the ambient air temperature and by the Henry's Law Constant for MTBE. The equilibrium concentration of MTBE in water in contact with air is

$$C_a/C_w = H/RT, \quad (1)$$

where C_a is the concentration of MTBE in air (ppbv),
 C_w is the concentration in water ($\mu\text{g/L}$),
 H is the Henry's Law Constant (Pascal- m^3/mol),
 R is the universal gas constant (Joules/gmol-Kelvin), and
 T is temperature (degrees Kelvin).

The Henry's Law Constant, H , is temperature dependent, and as temperatures decrease, more MTBE will move into the water from the air, thus raising the aqueous concentration in the rainfall. The Henry's Law Constant used in the following calculations is in the form

$$H_{\text{MTBE}} = \text{EXP}(30.06 - 7721/T), \quad (2)$$

where H_{MTBE} is in Pascal- m^3/mol , and
 T is in degrees Kelvin (Robbins and others, 1993).

These equations were used to calculate the equilibrium concentrations of MTBE in water (precipitation) on a monthly basis (see below).

Because the data were insufficient to characterize MTBE concentrations in rainfall in North Windham, equilibrium concentrations of MTBE in water can be used in the discussion of possible MTBE sources to ground water. To estimate potential average rainfall concentrations during normal periods of recharge to the aquifer, hypothetical monthly MTBE concentrations were calculated. Because the comparison to groundwater MTBE concentrations involves recharge that would have taken place while RFG was being used in Maine, the median concentration of MTBE in air during the RFG period (0.25 ppbv) was used to calculate monthly hypothetical equilibrium rainfall concentrations (table 8). Hypothetical monthly MTBE concentrations in rainfall after the RFG phaseout in Maine also were calculated using the average monthly temperatures and the median MTBE air concentrations after the RFG phaseout (0.09 ppbv).

Before the phaseout of RFG, the calculated air-water equilibrium concentrations of MTBE for precipitation ranged from 0.05 $\mu\text{g/L}$ to 0.37 $\mu\text{g/L}$. During the months when recharge commonly takes place (March and April, and October through December), estimated concentrations ranged from

Table 8. Monthly predicted air-water equilibrium concentrations of MTBE (for precipitation) based on median measured MTBE concentration in air and average monthly temperatures

[°C, degrees Celsius; ppbv, parts per billion by volume, µg/L, micrograms per liter; RFG, reformulated gasoline]

Month	Average monthly temperature in Windham, in °C ¹	Temperature used for equilibrium calculations, in °C	Calculated air-water equilibrium concentrations (in µg/L)	
			With RFG (air 0.25 ppbv)	No RFG (air 0.09 ppbv)
January	-8	0	0.37	0.13
February	-7.1	0	.37	.13
March	-1.1	0	.37	.13
April	5.4	5.4	.21	.08
May	11.7	11.7	.12	.04
June	16.9	16.9	.07	.03
July	19.8	19.8	.05	.02
August	18.5	18.5	.06	.02
September	13.9	13.9	.09	.03
October	8.1	8.1	.16	.06
November	2.1	2.1	.3	.11
December	-5.5	0	.37	.13

¹Estimated on the basis of data from Maine National Weather Service station at E. Hiram, Maine.

0.16 to 0.37 µg/L. These concentrations would be detectable in ground water if MTBE in recharge through the unsaturated zone did not degrade. After the phaseout of RFG, the hypothetical concentrations of MTBE in precipitation ranged from 0.13 µg/L to 0.02 µg/L, and ranged from 0.06 to 0.13 µg/L during recharge months. These concentrations are all below the current reporting limit for MTBE of 0.2 µg/L.

As stated earlier, MTBE was not detected in the precipitation samples. Several factors may have contributed to this, but most importantly, three (of four) precipitation samples were collected in May, when air concentrations of MTBE were low. It is not expected that MTBE would be detectable in precipitation in this case (hypothetical concentrations of MTBE would be approximately 0.04 µg/L, below the 0.2 µg/L reporting limit).

POTENTIAL SOURCES OF MTBE IN GROUND WATER

Atmospheric Deposition

For the occurrence of MTBE in shallow ground water to be attributed to atmospheric deposition through recharge of rainfall, several conditions must apply: (1) sufficient MTBE must be present in rainfall to be detectable, (2) recharge of the rainfall to the aquifer must be sufficient, (3) MTBE in recharge must not degrade or be adsorbed onto the aquifer material enroute to the saturated zone, and (4) concentrations of MTBE in recharge must be limited by atmospheric levels. On the basis of the partitioning equilibrium calculations presented above, before the phaseout of RFG use there was at least the potential for sufficient MTBE in rainfall to be detected, especially during the months of the year when recharge to aquifers occurs in Maine (typically March-April and October-December). The amount of recharge to the aquifer (estimated to be 21 in/yr) would be sufficient to move MTBE through the unsaturated

zone (Pankow and others, 1997). Baehr and others (1999) discuss the potential for diffusion of gaseous MTBE from the atmosphere into pore water (potential recharge) in the unsaturated zone, and the degradation and adsorption of MTBE in the unsaturated zone. Their analysis suggests that under the conditions present in the Windham aquifer, it is possible for gaseous diffusion of MTBE to generate detectable concentrations of MTBE in the ground water nearly equal to atmospheric concentrations at 5 feet below the surface if decay rates are low. They also suggest that degradation and adsorption of MTBE in the unsaturated zone would be most sensitive to the total unsaturated thickness, which ranges from 5 ft to more than 50 ft in the Windham aquifer. Using average air concentrations of 0.25 ppbv (while Maine was using RFG) and 0.09 ppbv (after RFG was eliminated), their model predicts that at 50 ft below the surface, MTBE would have been detectable in ground water due to diffusion only while Maine was using RFG. At the lower air concentrations (after RFG was eliminated), MTBE would not be detectable at this depth. Degradation in this model is slow, and a more realistic degradation constant based on field data from New Jersey (Baehr and others, in press) would make the model predict much less MTBE in ground water due to diffusion. Thus, concentrations of MTBE in rainfall may be detectable, recharge is sufficient to

move MTBE through the unsaturated zone, and diffusion may help move MTBE into the unsaturated zone, but degradation in the unsaturated zone works to lessen the amount of MTBE that could reach the water table from atmospheric sources.

The air-water equilibrium partitioning principles described above can be used to calculate equilibrium concentrations of MTBE in water that correspond to the measured air concentrations (fig. 7). A comparison of these concentrations to the measured concentrations of MTBE in ground water shows that the detected MTBE in ground water is, on average, much higher than the air-water equilibrium precipitation concentrations. The median MTBE concentration in ground water is 1.13 $\mu\text{g/L}$, whereas the median of the air-water equilibrium concentrations is 0.08 $\mu\text{g/L}$. The average hypothetical recharge concentrations before RFG was phased out are calculated as 0.2 to 0.4 $\mu\text{g/L}$ (fig. 7). Both these numbers are much lower than the measured ground-water concentrations. Especially when considering that degradation of MTBE in the unsaturated zone is likely (Baehr and others, in press), another source is necessary to explain all but a few of the concentrations of MTBE in ground water. Given the fact that we did not measure any MTBE in precipitation and the possibilities for degradation of MTBE in

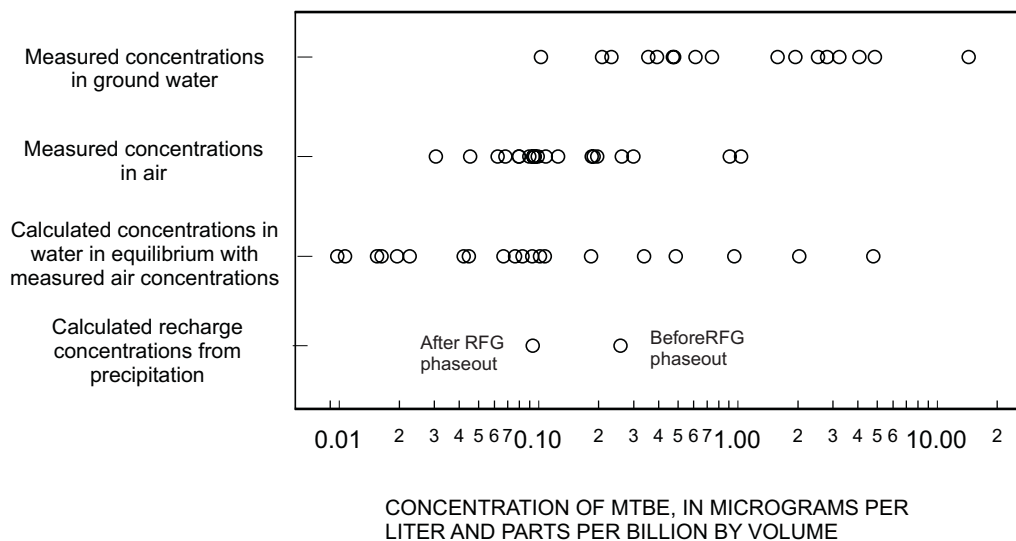


Figure 7. Concentrations of MTBE in air, water concentrations of MTBE in equilibrium with measured air concentrations, and measured concentrations of MTBE in ground water.

the unsaturated zone, we conclude that MTBE in precipitation is not a likely candidate for low levels of MTBE in the Windham aquifer. It is also worth noting that since Maine opted out of the RFG program, there is a greatly reduced potential for atmospheric deposition of MTBE in recharge that took place after March 1999.

Other sources

Other possible sources of low-level MTBE detections include stormwater runoff (Lopes and Bender, 1998; Delzer and others, 1996), small homeowner spills of gasoline (Dr. Andrew Smith, Maine Department of Public Health, written commun., 1999), and lake water contaminated with MTBE (Baehr and Zapecza, 1998). The Maine State study of MTBE tentatively identified very small spills of gasoline associated with filling of lawn-care equipment fuel tanks, recreational vehicle tanks, and automobile tanks as likely being responsible for the majority of the low levels of MTBE found (Dr. Andrew Smith, written commun., 1998). The study linked distance from the well to areas where any kinds of engines are used or where gasoline is stored as a major explanatory factor in the occurrence of MTBE in homeowner wells. The wells in the Windham aquifer study were not evaluated in this way, but the statistical relationship with developed areas and MTBE occurrence reported would support a similar conclusion for this study.

Another possible source would be recharge from surface-water bodies. Baehr and Zapecza (1998) have investigated the concentrations of MTBE in lakes in Sussex County, N. J., where watercraft use oxygenated fuel. Some lakeside wells in this area have been contaminated with MTBE. MTBE concentrations in two lakes ranged from 1.6 $\mu\text{g/L}$ to 29 $\mu\text{g/L}$ in samples collected from 3 to 10 ft below the water surface. Median concentrations ranged from 12.0 $\mu\text{g/L}$ to 20.7 $\mu\text{g/L}$. Samples were collected during the summer when the lakes showed strong temperature stratification. In the case of the Windham aquifer, recharge may enter from Little Sebago Lake,

where watercraft used oxygenated gasoline from 1995 to 1998. If MTBE were present in shallow lake water in areas adjacent to the discharge zone to the aquifer during those years, it is possible that Little Sebago Lake could have contributed to MTBE in the eastern part of the Windham aquifer during the summer months of those years.

SUMMARY AND CONCLUSIONS

A study was conducted on the occurrence and distribution of the fuel oxygenate MTBE (methyl *tert*-butyl ether) in a glacial sand and gravel aquifer in southern Maine, and samples of air and precipitation were analyzed and evaluated as a possible source of MTBE to the aquifer. Thirty-one wells in the Windham aquifer, in North Windham, Maine, were sampled for analysis of MTBE from July 1998 to May 1999. MTBE was detected in 35 percent of the wells sampled; however, 82 percent of wells with detectable concentrations of MTBE were in an area of the aquifer designated as a "high-yielding" aquifer (Neil, 1998). MTBE was much more commonly detected in wells with measured hydraulic conductivities more than 5 ft/d (9 of 16 wells) than in wells with hydraulic conductivities less than 5 ft/d (2 of 15 wells) ($p = 0.013$). Land use also was found to be associated with MTBE in the wells in the study area, with the urban and low-density residential areas having more MTBE detections than undeveloped areas. The median concentration in wells with detectable MTBE was 1.13 $\mu\text{g/L}$.

Air and precipitation samples were collected at a central location in North Windham. MTBE was present in all 20 air samples collected, at concentrations ranging from 0.03 ppbv to 1.0 ppbv. Before Maine opted out of the RFG (reformulated gasoline) program in March 1999, median concentrations of MTBE in air at the North Windham site were 0.25 ppbv, which is similar to concentrations measured at a site in New Jersey. After Maine stopped using RFG, the median concentration in air dropped to 0.09 ppbv. Technical difficulties and lack of rainfall during the

study period prevented the study from collecting a significant number of precipitation samples and no MTBE was detected in the four precipitation samples obtained.

On the basis of the equilibrium partitioning of MTBE from the air into rain, the predicted average concentration of MTBE in rainfall during months when recharge typically takes place (October-December and March-April) is approximately 0.2 to 0.4 $\mu\text{g/L}$ when Maine was using RFG and approximately 0.1 $\mu\text{g/L}$ after the phaseout of RFG. The concentration before the phaseout would be detectable in ground water if the recharge reached the water table with no degradation of MTBE. After the phaseout, it is unlikely that MTBE from recharge would be detectable in ground water.

An analysis of the distribution and concentrations of MTBE that were detected in ground water indicates that recharge from precipitation

containing MTBE is not a likely explanation for the occurrence of MTBE in the Windham aquifer. The median concentration of MTBE found in ground water is 1.13 $\mu\text{g/L}$, while the median air-water equilibrium concentration for the 20 air samples was 0.08 $\mu\text{g/L}$, and the hypothetical equilibrium concentration of rainfall during recharge months would have been, at the highest, 0.4 $\mu\text{g/L}$ when RFG was in use. In addition, the strong association of MTBE with land use and aquifer transmissivity/hydraulic conductivity suggests a land-based source. The mechanisms by which MTBE enters the aquifer were not differentiated in this study. The Maine State study of MTBE tentatively identified very small spills of gasoline associated with filling of lawn-care equipment fuel tanks, recreational vehicle tanks, and automobile tanks as likely being responsible for the majority of the low levels of MTBE found.

REFERENCES CITED

- Baehr, A.L., Charles, E.G., and Baker, R.J., in press, Methyl tert-butyl ether degradation in the unsaturated zone and the relation between MTBE in the atmosphere and shallow ground water: Water Resources Research.
- Baehr, A.L., Stackelberg, P.E., and Baker, R.J., 1999, Evaluation of the atmosphere as a source of volatile organic compounds in shallow groundwater: Water Resources Research, v. 35, no. 1, p. 127-136.
- Baehr, A.L., and Zapezca, O.S., 1998, Methyl tert-butyl ether (MTBE) and other volatile organic compounds in lakes in Byram Township, Sussex County, New Jersey, summer 1998: U.S. Geological Survey Water Resources-Investigations Report 98-4264, 8 p.
- Barker, J.F., Gillham, R.W., Lemon, L., Mayfield, C.I., Poulsen, M., and Sudickey, E.A., 1991, Chemical fate and impact of oxygenates in groundwater—Solubility of BTEX from gasoline—Oxygenate compounds: Washington, D.C., American Petroleum Institute Publication 4531, 90 p.
- Bouwer, H. and Rice, R.C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: Water Resources Research, v. 12, p. 423-428.
- Delzer, G.C., Zogorski, J.S., Lopes, T.J., and Bosshart, R.L., 1996, Occurrence of the gasoline oxygenate MTBE and BTEX compounds in urban stormwater in the United States, 1991-1995: U.S. Geological Survey Water-Resources Investigations Report 96-4145, 6 p.
- Gerber, Robert G. Inc., 1997, Windham ground water resource evaluation, Phase 2: Freeport, Maine, Robert G. Gerber, Inc., Freeport, Maine, report dated May 15, 1997, 26 p. plus tables, figures, appendixes, sheets.
- Grady, S.J., 1997, Distribution of MTBE in ground water in New England by aquifer type and land use, in American Chemical Society Division of Environmental Chemistry preprints of extended abstracts, 213th, San Francisco, Calif., April 1997, v. 37, no. 1, p. 392-394.
- Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: New York, New York, Elsevier Science Publishing Company, Inc., 522 p.
- Knox, C.E., and Nordenson, T.J., 1955, Average annual runoff and precipitation in the New England-New York area: U.S. Geological Survey Hydrologic Investigations Atlas HA-7, 3 sheets, scale 1:1,000,000.
- Koterba, M.T., Wilde, F.D., and Lapham, W.W., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program—Collection and documentation of water quality samples and related data: U.S. Geological Survey Open-File Report 95-399, 113 p.
- Lopes, T.J., and Bender, D.A., 1998, Nonpoint sources of volatile organic compounds in urban areas—relative importance of land surfaces and air: Environmental Pollution, v. 101, p. 221-230.
- Lyford, F. P., and Cohen, A. J., 1988, Estimation of water available for recharge to sand and gravel aquifers in the glaciated Northeastern United States, in Randall, A.D. and Johnson, A. I., eds., 1988, Regional aquifer systems of the United States—the northeast glacial aquifers: American Water Resources Association Monograph Series 11, 156 p.
- Maine Department of Human Services, 1995, An assessment of the health affects of reformulated gasoline in Maine, a report presented by the task force on health effects of reformulated gasoline: Augusta, Maine, April 1995, 35 p.
- Maine, State of, 1998, The presence of MTBE and other gasoline compounds in Maine's drinking water—Maine MTBE drinking water study, preliminary report, October 13, 1998: Augusta, Maine, Maine Bureau of Health, Department of Human Services; Bureau of Waste Management and Remediation, Department of Environmental Protection; Maine Geological Survey, Department of Conservation, 15 p., 8 figures.
- Moran, M.J., Zogorski, J.S., and Squillace, P.J., 1999, MTBE in ground water of the United States—Occurrence, potential sources, and long-range transport, in Water Resources Conference, American Water Works Association, Norfolk, Va., Sept. 26-29, 1998 [Proceedings]: American Water Works Association, Denver, Colo.
- National Oceanic and Atmospheric Administration, 1979-97, Climatological data, annual summaries, New England, 1979-97: Asheville, North Carolina, National Oceanic and Atmospheric Administration, v. 91-110, various pagination.
- Neil, C.D., 1998, Significant sand and gravel aquifers in the North Windham quadrangle, Maine: Maine Geological Survey, Open-File Map 98-158, scale 1:24,000.
- Nichols, W.J., and Silverman, P.N., 1998, Hydrologic data for the Presumpscot River Basin, Cumberland and Oxford Counties, Maine 1995 to 1996: U.S. Geological Survey Open-File Report 98-265. 53 p.
- Ott, L.R., 1993, An introduction to statistical methods and data analysis—4th ed.: Belmont, Calif., Wadsworth Publishing Co., 1038 p., appendixes.
- Pankow, J.F., Luo, W., Isabelle, L.M., Bender, D.A., and Baker, R.J., 1998, Determination of a wide range of volatile organic compounds in ambient air using multisorbent adsorption/thermal desorption and gas chromatography/mass spectrometry: Analytical Chemistry, v. 70, no. 24, p. 5213-5221.

- Pankow, J.F., Thompson, N.R., Johnson, R.J., Baehr, A.L., and Zogorski, J.S., 1997, The urban atmosphere as a nonpoint source for the transport of MTBE and other volatile organic compounds (VOCs) to shallow ground-water: *Environmental Science and Technology* v. 31, no. 10, p. 2821-2828.
- Pluhowski, E.J., and Kantrowitz, I.H., 1964, Hydrology of the Babylon-Islip area, Suffolk County, Long Island, New York: U.S. Geological Survey Water-Supply Paper 1768, 119 p.
- Puls, R.W., and Barcelona, M.J., 1995, Low-flow (minimal drawdown) ground-water sampling procedures: U.S. Environmental Protection Agency Research Brief EPA/540/S-95/504.
- Robbins, G.A., Henebry, B.J., Schmitt, B.M., Bartolomeo, F.B., Green, A., and Zack, P., 1999, Evidence for MTBE in heating oil: *Ground Water Monitoring and Remediation*, v. 19, no. 2, p. 65-69.
- Robbins, G.A., Wang, S., and Stuart, J.D., 1993, Using the headspace method to determine Henry's Law constants: *Analytical Chemistry*, v. 65, no. 3, p. 615-631.
- Shaw, D., 1995, Multi-resolution land characteristics documentation notebook, MRLC consortium unpublished document. [Available on the World Wide Web at <http://www.epa.gov/docs/grd/mrlc>.]
- Squillace, P.J., Pankow, J.F., Korte, N.E., and Zogorski, J.S., 1996, Environmental behavior and fate of methyl *tert*-butyl ether (MTBE): U.S. Geological Survey Fact Sheet FS-203-96, 6 p.
- Squillace, P.J., Pankow, J.F., Korte, N.E., and Zogorski, J.S., 1997, Review of the environmental behavior and fate of methyl *tert*-butyl ether: *Environmental Toxicology and Chemistry*, v. 16, no. 9, Sept. 1997, p. 1836-1844.
- Squillace, P.J., Pope, D.A., and Price, C.V., 1995, Occurrence of the gasoline additive MTBE in shallow ground water in urban and agricultural areas: U.S. Geological Survey Fact Sheet FS-114-95, 4 p.
- Squillace, P.J., Zogorski, J.S., Wilber, W.G., and Price, C.V., 1996, Preliminary assessment of the occurrence and possible sources of MTBE in groundwater in the United States, 1993-1994: *Environmental Science and Technology*, v. 30, no. 5, p. 1721-1730.
- Stackelberg, P.E., O'Brien, A.K., and Terracciano, S.A., 1997, Occurrence of MTBE in surface and ground water, Long Island, New York, and New Jersey, *in* American Chemical Society Division of Environmental Chemistry preprints of extended abstracts, 213th, San Francisco, Calif., April 1997, v. 37, no. 1, p. 394-397.
- Vogelman, J.E., Sohl, T., Campbell, P.V., and Shaw, D.M., 1998, Regional land cover characterization using Landsat thematic mapper data and ancillary data sources: *Environmental Monitoring and Assessment*, v. 51, p. 415-428.
- Zogorski, J.S., Delzer, G.C., Bender, D.A., Squillace, P.J., Lopes, T.J., Baehr, A.L., Stackelberg, P.E., Landemeyer, J.E., Boughton, C.J., Lico, M.S., Pankow, J.F., Johnson, R.L., and Thompson, N.R., 1998, MTBE—Summary of findings and research by the U.S. Geological Survey, *in* Annual Conference of the American Water Works Association—Water Quality, June 21-25, 1998, Dallas, Tex., [Proceedings]: AWWA, Denver Colo., p. 287-309.