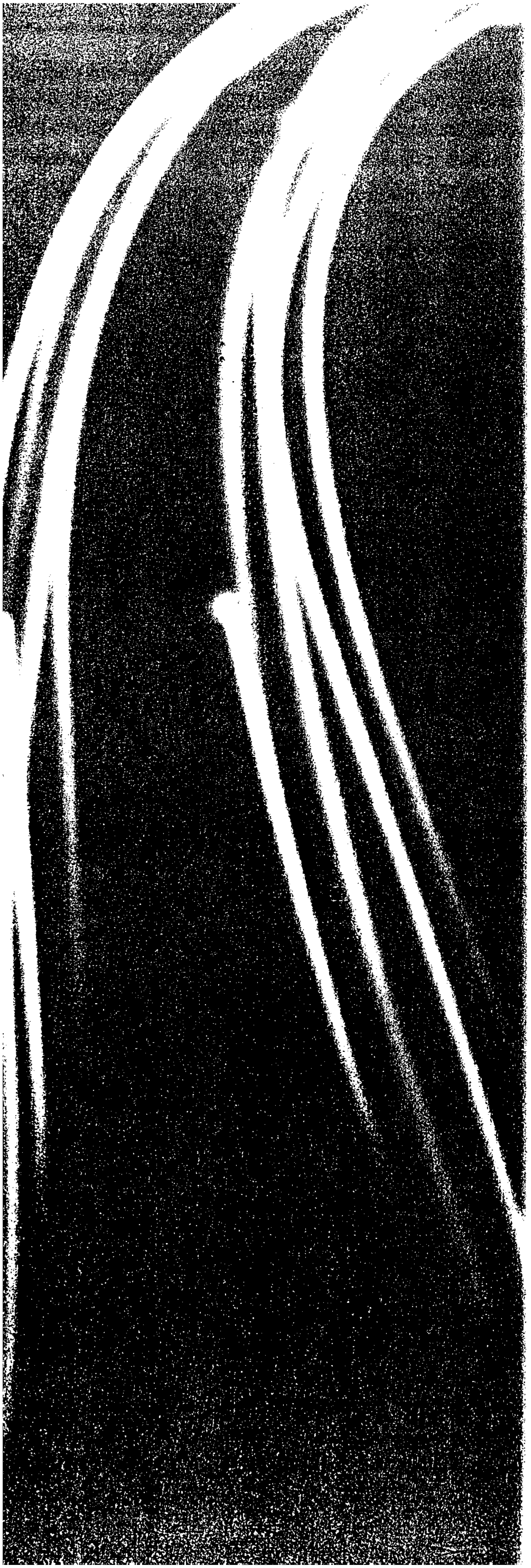

Fuel Oxygenates and Water Quality

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PREPARED BY

John S. Zogorski,
U.S. Geological Survey

Abraham Morduchowitz,
Texaco, Inc.

Arthur L. Baehr,
U.S. Geological Survey

Bruce J. Bauman,
American Petroleum Institute

Dwayne L. Conrad,
Texaco, Inc.

Robert T. Drew,
American Petroleum Institute

Nic E. Korte,
Oak Ridge National Laboratory

Wayne W. Lapham,
U.S. Geological Survey

James F. Pankow,
Oregon Graduate Institute for Science and Technology

Evelyn R. Washington,
U.S. Environment Protection Agency

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EXECUTIVE SUMMARY AND RECOMMENDATIONS

Introduction and Scope

At the request of the U.S. Environmental Protection Agency (USEPA), the Office of Science and Technology Policy, Executive Office of the President, has coordinated an interagency assessment of the scientific basis and efficacy of the Nation's winter oxygenated gasoline program. This program mandates that compounds referred to as oxygenates be added to gasoline in select metropolitan areas across the United States to reduce the amount of carbon monoxide in the atmosphere in the winter. Many other areas of the United States have voluntarily chosen to use oxygenated fuels to abate air pollution and in severe ozone non-attainment areas reformulated gasoline is required. Fuel oxygenates are also used to enhance the octane of conventional gasolines-a practice that started in the late 1970's and continues today.

Methyl *tert*-butyl ether (MTBE) is the most commonly used fuel oxygenate. The U.S. production was estimated to be 8.0 billion kilograms in 1995. Essentially all of MTBE produced is used for fuel oxygenation. Ethanol (EtOH) is the second most used oxygenate in gasoline blending. EtOH production in the U.S. was estimated to be 4.3 billion kilograms in 1994. No data are available to estimate the portion of this production used in gasoline. Gasoline in carbon monoxide non-attainment areas must contain no less than 2.7 percent oxygen by weight. By volume, this requirement for MTBE and EtOH corresponds to 14.8 and 7.3 percent, respectively. Oxygenates in limited commercial use include ethyl *tert*-butyl ether (ETBE), *tert*-amyl methyl ether (TAME), and diisopropyl ether (DIPE). Methanol (MeOH) is only being used as an oxygenate in a limited test program in California. *Tert* -butyl alcohol (TBA) has been added to gasoline in the past and is another potential fuel oxygenate, but is not currently produced for this purpose.

The purpose of this chapter is to address water-quality issues arising from the production, distribution, storage, and use of fuel oxygenates and their movement in the hydrologic cycle. It summarizes the scientific literature, data, and agency information on the sources, concentrations, behavior, and fate of fuel oxygenates, and their aqueous degradation products, in ground water and surface water. It also assesses the implications for drinking-water quality and aquatic life. Recommendations for further data-base compilation, monitoring, reporting of information, follow-up assessments, reports, and research efforts are also noted. Although the scope of this chapter is intended to cover all oxygenates and aqueous degradation products, little to no data and few scientific publications are available on the occurrence and behavior of oxygenates and their degradation products in ground water, surface water, and drinking water, except for MTBE. Some monitoring data are available for MTBE, however, these data sets are limited in scope.

Sources and Releases

Like hydrocarbon components of gasoline, fuel oxygenates are introduced to the environment during all phases of the petroleum fuel cycle, but the major sources of these compounds are likely associated with the distribution, storage, and use of oxygenated gasoline. Releases of gasoline containing oxygenates to the subsurface from, for example, underground storage tanks, pipelines, and refueling facilities provide point sources for entry of oxygenates as well as gasoline hydrocarbons into the hydrologic cycle. Urban and industrial runoff and wastewater discharges also represent potential sources of oxygenates to the environment. Water in contact with the spilled gasoline at the water table or in the unsaturated zone will solubilize oxygenates along with aromatic hydrocarbon constituents (e.g., benzene, toluene, ethylbenzene, and xylenes commonly referred to as BTEX). Such water can contain high oxygenate concentrations, for example, MTBE concentrations as high as 200,000 micrograms per liter[1] have been measured in ground water at a site of gasoline leakage. In a few instances (such as in Santa Monica, CA), high concentrations of MTBE have caused the shutdown of a drinking-water production well or well field, and the source of contamination was identified as a release from an underground gasoline storage tank.

Petroleum storage tanks represent the largest populations of potential point sources of alkyl ether oxygenates to natural waters. For example, in 1988 the USEPA estimated that there were about 2 million underground storage tanks (USTs) at over 700,000 facilities. In the last several years, USTs have been removed at many facilities, and the current EPA UST universe is an estimated 415,000 UST facilities (about 195,000 are service stations) with about 1.2 million tanks. USEPA's statistics show that slightly over 300,000 sites have been identified with contamination levels that require corrective action. Cleanup has been completed at about 130,000 of these sites. Because of the inherent difficulty in determining leak rates, leak durations, and the use of oxygenates in the released gasoline, it is difficult to develop a reliable estimate of past or current annual release of fuel oxygenates from these sources. USEPA and State requirements exist and require that USTs be fully upgraded to meet stringent release prevention and detection standards by December 1998. The concurrent improvement in the physical condition of USTs and release-detection capabilities, coupled with a reduction in the population of tanks, should contribute to a considerable reduction in the annual volume of oxygenated gasoline released to natural waters from this subset of point sources.

Estimated releases of MTBE, MeOH, and TBA during industrial activity are mostly to the atmosphere and are reported to the USEPA in annual Toxics Release Inventory (TRI) submissions by manufacturers. The release of MTBE to the environment is almost entirely associated with its production, distribution, storage, and use as a fuel oxygenate, whereas releases of MeOH and TBA occur from various other industrial and commercial uses. Industrial releases of other fuel oxygenates ETBE, TAME, DIPE, and most notably EtOH are not included in the TRI.

Annual estimates of exhaust emissions from vehicles, evaporative losses from gasoline stations and vehicles, and releases from storage tanks have not been reported in the scientific literature but are perceived to be important sources of oxygenates (as well as other fuel components) released to the environment. Fuel oxygenates in the atmosphere, because of the dispersive effect of weather patterns and occurrence in precipitation, are considered a non-point source to the hydrologic cycle.

Occurrence in Air and Water and Significance to Drinking Water and Aquatic Life

The Clean Air Act, Clean Water Act, and Safe Drinking Water Act do not require the monitoring of fuel oxygenates in air, ground water, surface water, or drinking water. Therefore, comprehensive data to document the occurrence of fuel oxygenates in the major

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[1] One microgram per liter is approximately equivalent to one part per billion.

compartments of the hydrologic cycle across the Nation are not available from these programs.

MTBE and other fuel oxygenates are not included in routine ambient air monitoring done by local and State agencies. An exception is the State of California, which just recently began to monitor for MTBE and other volatile organic compounds (VOCs) in ambient air. Air-quality data have been collected for MTBE in six cities as part of special studies. These data are not sufficient to provide a national perspective, however, MTBE was found in urban air and the median concentrations within these urban areas ranged between 0.13 and 4.6 parts per billion by volume. Concentrations of MTBE in air near known sources of MTBE (gasoline stations, roadways, parking lots and garages, and so forth) are higher, and in many cases considerably higher than ambient urban air.

Little data exist on the occurrence of any of the fuel oxygenates in surface-water bodies including streams, rivers, lakes, and reservoirs. Similarly, little data exist on oxygenate occurrence for drinking water derived from surface water.

Storm water was sampled and analyzed for MTBE in 16 cities during 1991-95. These studies were completed by various U.S. Geological Survey (USGS) Districts to characterize storm-water runoff in cities with population exceeding 100,000. These projects were not specifically designed to determine the occurrence and sources of MTBE or other oxygenates, or other VOCs originating from gasoline. Northeastern States and California, high-use areas of MTBE oxygenated gasoline, were not sampled in the USGS studies. The compilations, however, do provide insight on the occurrence of MTBE in storm water in select cities. MTBE was detected in about 7 percent of 592 storm-water samples. When detected, concentrations ranged from 0.2 to 8.7 micrograms per liter, with a median of 1.5 micrograms per liter. Eighty-three percent of the detectable concentrations occurred during the winter season. Statistical evaluation comparing MTBE concentrations for samples collected during an April 1 to September 30 time period versus an October 1 to March 31 time period yielded statistically significant differences. MTBE was detected both in cities using oxygenated gasoline to abate carbon monoxide non-attainment and in cities presumed to have used MTBE in gasoline for octane enhancement.

Water-quality criteria for oxygenates to protect aquatic life have not been established. For the alkyl ether oxygenates, chronic aquatic toxicity data are lacking, and only limited information exists on acute toxicity and bioconcentration. Considerably more acute toxicity studies have been completed for EtOH and MeOH. The maximum concentration of MTBE detected in storm water reported above is about five orders of magnitude below the median lethal concentration for the most sensitive species investigated to date. More toxicity studies of aquatic animals and plants, bioaccumulation information, and ambient levels in surface water are needed before the significance of MTBE to aquatic life can be assessed.

Two data sets provide information on the occurrence of MTBE in ground water and drinking water derived from ground water. Limited or no data are available for any other fuel oxygenate. The first data set was collected as part of the USGS's National Water-Quality Assessment Program. MTBE was included on a list of analytes for ground-water samples collected in 20 major basins across the country during 1993-94. In addition, retrospective efforts of this Program have summarized MTBE occurrence data from a few State and regional ground-water assessment programs. The second data set was assembled during the preparation of this report as USEPA requested, through its 10 Regions, information on drinking-water programs that have analyzed for MTBE. In response to this request, data on the occurrence of MTBE in public drinking-water supplies derived from ground water were provided by seven States, and four States provided data on private wells. It is likely that a significant number of large water utilities monitor for constituents such as MTBE as part of routine scans for VOCs, therefore, additional information on MTBE occurrence may exist but could not be compiled in the timeframe of this assessment.

At least one detection of MTBE has occurred in ground water in 14 of 33 States surveyed. These 14 States are located throughout the United States. MTBE was detected in 5 percent of over 1,500 wells sampled. Most of the detections occur in shallow ground water in urban areas. Ninety-nine percent of the samples from wells screened in shallow ground water in agricultural areas did not have MTBE. About 98 percent of the wells screened in deeper aquifers or deeper parts of shallow aquifers did not have detections of MTBE, and of the remaining 2 percent that had detections of MTBE, the highest concentration reported was 7.9 micrograms per liter. The mechanism for occurrence in the deeper wells is unknown. MTBE's presence in drinking water for one or more utility was reported in six of the seven States that provided data for public water supplies derived from ground water, and MTBE was reported in all four of the States that provided data for private drinking-water wells.

Because only a few States have information on MTBE in drinking water, it is not possible in this preliminary assessment to describe MTBE concentrations in drinking water nationwide. A Federal drinking-water standard has not been established for MTBE, however, the USEPA has issued a draft lifetime health advisory of 20 to 200 micrograms per liter. The health advisory is expected to be revised in 1997. MTBE has been detected in 51 public drinking-water systems to date based on limited monitoring, however, when detected, the concentration of MTBE was generally low and nearly always below the lower limit of the current draft USEPA health advisory. This indicates that the consumption of drinking water was not a major route of exposure for these few systems. Additional MTBE monitoring data for drinking water are needed, from both the States which provided information for this preliminary assessment and from States that were unable to provide said information, before the significance of drinking water as a route of exposure can be assessed for the Nation.

In the past, routine monitoring of ground water at gasoline USTs has focused on BTEX compounds and, as such, little monitoring information is available for fuel oxygenates. Past and recent releases from UST, however, are perceived to be an important source for the entry of high concentrations of fuel oxygenates to ground water. A California Senate Advisory Committee has initiated a request to collect MTBE concentration data for ground water at UST sites. This information should be helpful in understanding MTBE water-quality concerns from USTs. At least 10 States have established an action level and/or clean-up level for MTBE at sites where gasoline releases have occurred and are being remediated. MTBE monitoring data may be available from these and other States, and this information would provide insights on the potential significance of oxygenate releases from USTs, as well as MTBE concentrations in ground water at these sites.

Studies have been conducted to establish taste and odor thresholds for oxygenates in water. These studies provide useful information regarding the potential impacts on the palatability of drinking water, and the ability for the public to detect MTBE-containing water before it is ingested. These studies indicate that the taste threshold for MTBE, ETBE, and TAME are 39 to 134, 47, and 128 micrograms per liter, respectively. Similarly, the odor detection threshold of MTBE, ETBE, and TAME in water are 45 to 95, 49, and 194 micrograms per liter, respectively. The above-noted taste and odor threshold values for MTBE fall in the range of the USEPA's draft health advisory.

Behavior and Fate of Fuel Oxygenates in the Hydrologic Cycle
Water in contact with spilled gasoline at the water table or in the unsaturated zone will solubilize oxygenates along with aromatic hydrocarbon constituents. Water that is equilibrated with an oxygenated fuel can contain very high concentrations of the oxygenate. For example, for a gasoline that is 10 percent by weight MTBE, the concentration of MTBE in water in chemical equilibrium with the gasoline at room temperature would be on the order of 5,000,000 micrograms per liter and the total BTEX hydrocarbon concentration would be on the order of 120,000 micrograms per liter. Ground-water MTBE concentrations as high as 200,000 micrograms per liter have been observed in wells near gasoline spills. The fact that measured concentrations are typically lower than solubility levels for gasoline oxygenated with MTBE is due either to dilution by uncontaminated water or depletion of MTBE from the gasoline source. Alcohol oxygenates could occur at high concentrations in water adjacent to spilled gasoline because of the high solubility of alcohols, however, there are no published studies that report alcohol concentrations in ground water from releases of oxygenated fuels.

While oxygenated gasolines can lead to high concentrations of fuel oxygenates in water, these concentrations are typically not high enough to increase either the water solubilities (co-solvent effect) or the transport rates of the BTEX compounds. Gasolines containing very high amounts of ethers and alcohols are capable of causing this effect, but such fuels are not in widespread use.

MTBE and other alkyl ether oxygenates are much less biodegradable than BTEX hydrocarbons in ground water. Furthermore, the alkyl ether oxygenates sorb only weakly to soil and aquifer materials, therefore, their transport by ground water will not be retarded to any significant extent. These factors explain why MTBE has been observed to persist at higher concentrations and advance ahead of BTEX plumes in ground water at gasoline spill sites. Conversely, EtOH would be expected to degrade much more rapidly than BTEX hydrocarbons, therefore, EtOH is not expected to persist much beyond the source area and the immediate contaminant plume at a gasoline spill site. It should be noted, however, that no data exist on the occurrence of EtOH in ground water to verify the hypothesis of EtOH's non-persistence and non-migration at spill sites.

Abiotic degradation processes including hydrolysis, direct photolysis, and indirect photolysis are not expected to significantly alter the concentration of MTBE in natural waters.

Because of their occurrence in the atmosphere, and favorable and rapid partitioning to water, fuel oxygenates will occur in precipitation in direct proportion to their concentrations in air. Changes in the ambient air concentration of MTBE, due to increased or decreased usage of oxygenated gasoline, for example, will affect the level of MTBE in precipitation. Cooler temperatures imply larger concentration of MTBE in precipitation for a given atmospheric concentration. Assuming a concentration of 1 part per billion by volume MTBE in the atmosphere, the concentration of MTBE in precipitation would increase almost tenfold, from about 0.2 to 1.5 micrograms per liter, if the temperature decreases from 20 to 0 degrees Celsius. Based on this range of proportionality and MTBE atmospheric concentration data collected in a few cities, precipitation for general urban atmospheres could contain sub-microgram per liter to about 3 micrograms per liter of MTBE. Theory predicts that precipitation concentrations will be higher near roadways, parking lots and garages, and gasoline stations that consistently experience higher air concentrations of MTBE. Available data suggest that the alkyl ether oxygenates have lifetimes in the atmosphere that range from 4 days to 2 weeks. The main degradation pathway seems to be reaction with hydroxyl radical to form *tert*-butyl formate. In summary, the atmospheric source of alkyl ether oxygenates in urban areas is believed to be continual, and results in low concentrations of MTBE in water relative to point sources such as USTs. The atmospheric source is also areally extensive due to the dispersive effect of weather patterns.

Precipitation inputs oxygenates directly to streams, rivers, lakes, and reservoirs as it falls on these surface-water bodies or enters surface water through overland runoff and storm-water drainage. While they are volatile from water, the alkyl ether oxygenates, such as MTBE, in large rivers and some streams will not be lost quickly by volatilization. Precipitation falling on land and recharging aquifers, together with diffusion of oxygenates from the atmosphere through the unsaturated zone, inputs oxygenates to shallow ground water. From shallow ground water it is possible that dissolved alkyl ether oxygenates will move deeper into an aquifer system toward wells and surface-water discharge areas. The concentration of an oxygenate in ground water along a particular flow path depends upon the age of ground water, that is its residence time in the aquifer from recharge location, and the rate of biodegradation reactions. Dissolved MTBE and other alkyl ether oxygenates would advance deeper into the aquifer system than BTEX compounds because they are less degradable than BTEX compounds, however, the significance of this deeper migration is uncertain because of the paucity of in-situ monitoring and degradation studies.

Remediation

The chemical properties of oxygenates relative to BTEX compounds provide insight on the anticipated performance and costs of remediation techniques typically applied to remove BTEX at gasoline spill sites. The presence of MTBE and other alkyl ether oxygenates does not prevent the application of conventional (active) remedial methods (air stripping, carbon adsorption, and soil-vapor extraction) for fuel spills but it does raise the cost. For example, the alkyl ether oxygenates can be removed from water using aeration, but only with much higher air/water ratios than required for BTEX removal. The alcohol oxygenates cannot be removed from water by aeration in a cost-effective manner. Similarly, vacuum extraction and air-sparging techniques will be much less efficient for alkyl ether oxygenates than for BTEX, and infeasible for alcohol oxygenate remediation. The application of intrinsic (passive) bioremediation, an emerging, relatively inexpensive approach to the management of conventional gasoline spills, may be limited because of the slowness with which alkyl ether oxygenates are biodegraded and the tendency of these compounds to migrate from release sites. For contaminant plumes containing EtOH or MeOH, however, intrinsic bioremediation, or enhancements to in-situ bioremediation will remain effective.

Recommendations

This chapter has sought to provide an initial assessment of the water-quality consequences of the use of oxygenates in gasoline. The actions outlined in the specific recommendations given below will allow a more comprehensive understanding of those consequences. Specific recommendations are given for MTBE and the other alkyl ether oxygenates largely because of their extensive commercial use and their persistence in, and migration with ground water. Ethanol, the only alcohol currently in wide-scale commercial use as a gasoline oxygenate, is expected to undergo rapid biodegradation in ground water and surface water, except when concentrations are high enough to be toxic to microorganisms.

At the present time, sufficient monitoring data are not available in the Nation to characterize human exposure to the alkyl ether oxygenate compounds by the consumption of drinking water. Typical oxygenate concentrations are not known either for treated drinking waters, or for the surface- and ground-water sources of that drinking water, except for select States. Similarly, little information is available on either the concentrations of oxygenates in surface water to which aquatic animals and plants are typically exposed, or on the toxicities of those compounds to a broad range of aquatic species.

In order that resources directed to implement the recommendations outlined below be used wisely and efficiently, it is recommended that an ad hoc panel representing the public and private sectors develop a comprehensive and interdisciplinary monitoring, research, and assessment plan to determine the significance of the use of alkyl ether fuel oxygenates on drinking-water quality and aquatic life. The plan should identify lead agencies and organizations for various topics, and provide the necessary details which were beyond the scope of this initial assessment, such as: defining specific goals; establishing the timing and relative priority of research and monitoring needs; developing coordination between industry and various local, State, and Federal agencies; creating a national data base for analytical determinations; and selecting data sets for entry into the data base. Some components of the plan, such as monitoring and creating the national data base should be piloted for select cities and States to further work out details, such as common field sampling and analytical methods, and to make appropriate modifications if deemed necessary. Selecting cities and States that are actively engaged in monitoring for alkyl ether oxygenates in air and water would allow for the timely completion of the suggested pilot phase, with minimal additional expenditure.

Three broad recommendations are made based on this initial assessment:

1. Obtain more complete monitoring data and other information that would: (a) enable an exposure assessment for MTBE in drinking water, (b) characterize the relation between use of MTBE and other alkyl ether oxygenates in gasoline and water quality, and (c) identify and characterize major sources of MTBE to the environment.
2. Complete additional behavior and fate studies to expand current knowledge.
3. Complete aquatic toxicity tests to define the threat posed to aquatic life and establish, if warranted, a Federal water-quality criteria.

Completing the exposure assessment for MTBE in drinking water should be given priority. Monitoring of MTBE in drinking water for this purpose should initially be targeted to high MTBE use areas, and to those environmental settings that are otherwise thought to be most susceptible to contamination. State and Federal agencies and large public water utilities are encouraged to start voluntary monitoring of MTBE in drinking water immediately so that the drinking-water exposure assessment can be completed. Essential elements of each of the three recommendations are described below.

Better Characterize Ambient Concentrations, Oxygenated Gasoline Use, Sources to the Environment, and Relations Between Gasoline Use and Water Quality

- Add the alkyl ether oxygenates MTBE, ETBE, TAME, and DIPE to existing VOC analytical schedules and as USEPA routine target analytes for drinking water, wastewater, surface water, ground water, and remediation studies. This inclusion will provide considerable additional information on the occurrence of these oxygenates in water at little additional expense.

- Create a national data base of analytical determinations of the alkyl ether oxygenates in air, and in ground, surface, and drinking waters. The data base should also include, for example, information on sampling dates, locations, detection limits, analytical method, quality control, and the reporting agency. Carefully selected monitoring data obtained by Federal, State, and local agencies should be reported for inclusion in the data base. The difficulty and limited success in compiling monitoring data from the States for this preliminary assessment illustrates the need for the recommended data base. The goal should be to assemble a data base that allows exposure assessments for the alkyl ether oxygenates in drinking water and for aquatic life in surface water. The USEPA in late 1970's and 1980's completed similar drinking-water assessments for other VOCs.

- Characterize the seasonal volumes of gasoline containing the alkyl ether oxygenates that are sold in the major regions and cities of the Nation. Such usage information is presently unavailable in any systematic form and at the necessary scale, and this lack of data prevents attempts to correlate water-quality data with actual seasonal use. Establishing relations between the use of MTBE (and other alkyl ether oxygenates) and the oxygenate’s presence in ground water and surface water will enable the identification of those hydrologic and geologic settings that are most susceptible to contamination.

- Determine the annual releases of the alkyl ether oxygenates to air, land, and water from all sources (e.g., industrial releases, refueling losses, auto emissions, and storage-tank releases), both point and non-point in nature. Presently, estimates of this information are available only for MTBE, TBA, and MeOH, for some sources, and only for those industries which must file annual TRI reports. Precise estimates of annual releases will be difficult to make from currently available information but order-of-magnitude estimates should be made to identify major “data gaps” and to identify the primary source(s) of the alkyl ether oxygenates for air, surface water, ground water, and drinking water. Once characterized, the feasibility of further reducing these primary sources of fuel oxygenates to the environment should be determined.

- Annually review the information specified above and when adequate information is available, prepare interpretive report(s) on the water-quality consequences of the use of MTBE and other alkyl ether oxygenates. At a minimum, the report(s) should cover: (1) exposure assessment for drinking water and aquatic life; (2) relation between oxygenated fuel usage and the seasonal occurrence of alkyl ether oxygenates in surface water, for various climatic and hydrogeologic settings, and (3) the significance of various sources of fuel oxygenates to air, surface water, ground water, and drinking water. The continued need to collect information on alkyl ether oxygenates should be re-assessed after the above-noted report(s) is completed.

Expand the Current Understanding of the Environmental Behavior and Fate of Alkyl Ether Oxygenates

- Characterize, via field monitoring in select cities and regions of the Nation, the occurrence, movement, and mass fluxes of alkyl ether oxygenates between ambient air, precipitation, surface water, the unsaturated zone, and shallow and deep ground water. This monitoring is needed to: (1) determine the significance of urban atmospheres as non-point sources of contamination of alkyl ether oxygenates to surface and ground water; (2) identify climatic and hydrogeologic settings where movement of alkyl ether oxygenates in the hydrologic cycle will be of concern; and (3) evaluate the influence of drainage and storm-water management programs on contaminant movement. These studies should also determine the importance of overland runoff in altering the levels of alkyl ether oxygenates in urban streams and rivers, and in water recharged to shallow aquifers.

- Conduct additional laboratory and field research on the degradation of the alkyl ether oxygenates in the different compartments of the hydrologic cycle, under a variety of environmental conditions. Information is needed on degradation half-lives and pathways. It is especially important to clarify exactly how persistent the alkyl ether oxygenates can be in soil and ground water under a range of redox conditions, and to identify all of the important degradation products for possible monitoring and behavior/fate research. The potential for plants to uptake and otherwise alter the concentration of alkyl fuel oxygenates in the root zone should be determined.

- Conduct further theoretical modeling on the movement of the alkyl ether oxygenates from land surface to shallow ground water. This research should: (1) test the hypothesis that the frequent occurrence of MTBE in shallow urban ground water at low concentrations can be due to recharged precipitation or overland runoff; (2) identify the associated predominant transport mechanisms; and (3) provide insights on the climatic and hydrogeologic factors that favor such movement of alkyl ether oxygenates in the unsaturated zone.

Expand the Current Understanding of the Aquatic Toxicity of Alkyl Ether Oxygenates

- Initiate studies of the chronic toxicity of alkyl ether oxygenates to a broad range of aquatic animals and plants indigenous to surface waters. Additional acute toxicity tests should also be completed for the same species. These studies are needed to: (1) define the extent of any threat posed by the alkyl ether oxygenates to aquatic life; and (2) collect sufficient information to form the basis of a Federal water-quality criteria, if warranted.

SCOPE OF THE CHAPTER

This chapter summarizes the scientific literature, data, and agency information on the sources, concentrations, behavior, and fate of fuel oxygenates, and their aqueous degradation products, in ground water and surface water; and assesses implications for drinking-water quality and aquatic life. Conclusions and recommendations are also noted.

The chapter is intended to cover all oxygenates currently in commercial use in the United States including methyl *tert*-butyl ether (MTBE), ethanol (ETOH), ethyl *tert*-butyl ether (ETBE), *tert*-amyl methyl ether (TAME), and diisopropyl ether (DIPE) and their aqueous degradation products. Information also is presented for methanol (MeOH) and *tert*-butyl alcohol (TBA). These latter chemicals are included because they: (1) have been used in gasoline in the past (Conrad, 1995); (2) are being used currently in pilot programs; or (3) may be used in the future.

Little to no data are available on the occurrence of fuel oxygenates in ground water, surface water, and drinking water. Some data are available for MTBE, however, these data sets are limited in scope. The paucity of monitoring data for fuel oxygenates in natural waters is due to their lack of historical use (e.g., alkyl ether oxygenates) or their difficulty of analysis in water (e.g., alcohols). The available data sets for MTBE are discussed in this chapter and are a composite of monitoring results obtained from States and by the U.S. Geological Survey (USGS) as part of the National Water-Quality Assessment (NAWQA) Program, and other USGS District studies. Concentrations of MTBE detected in water are compared to U.S. Environmental Protection Agency's (USEPA) draft drinking-water lifetime health advisory. Also, the aquatic toxicity, taste and odor properties, environmental behavior, fate, and remediation of fuel oxygenates are discussed.

SOURCES, RELEASES, AND MOVEMENT OF FUEL OXYGENATES IN THE HYDROLOGIC CYCLE

Sources and Releases of Fuel Oxygenates

The origin of fuel oxygenates in natural waters can be classified as occurring from either point sources or non-point sources. A point source is a discharge from a discrete point location. Examples include an effluent discharged to a stream via a pipe, a leaking fuel tank, or a spill. In contrast, a non-point source is areally extensive, and is often associated with land use. Examples include agricultural runoff, urban runoff, automotive (mobile) emissions, and atmospheric deposition.

Point Sources. Point sources of fuel oxygenates include: (1) releases from storage tanks, pipelines, and landfills and dumps; (2) spillage at industrial plants and refueling facilities; and (3) accidental spilling during transport. These are the sources cited most often by State agencies in cases of MTBE contamination of soil and ground water. Other point sources of fuel oxygenates include evaporative emissions during fuel handling, such as refueling at gasoline stations, "water bottom" releases from storage tanks, municipal effluents, and industrial releases to air, land and water, and deep-well injection. Estimates of industrial releases of some fuel oxygenates are reported annually in the Toxics Release Inventory

(TRI) and are discussed in the section on "Industry Releases of MTBE, TBA, and MeOH."

Storage-Tank Releases. There is a large population of storage tanks that may contain oxygenated gasoline, and that could be point sources of oxygenate releases to soil and ground water. The USEPA estimated in 1988 that there were over 2 million underground storage tanks (USTs) at over 700,000 facilities, and that 95 percent of these tanks are used to store petroleum fuels (Lund, 1995). There are currently an estimated 195,000 retail service stations (National Petroleum News, 1995), and an estimated 220,000 non-retail UST facilities (Lund, 1995). Combined, these facilities have about 1.2 million tanks. Gasoline usage represents approximately 80 percent of the volume of motor-fuels consumption, thus many of these tanks have stored gasoline. MTBE has been used in some gasolines since 1979, and other oxygenates have come into use in recent years. It is expected that many of these tanks have contained oxygenated gasoline at some time in their history.

USEPA statistics indicate that over 300,000 sites have been identified with soil or ground-water contamination that would require corrective action (USEPA, 1995a). Corrective action has been completed at more than 130,000 of these sites, and is underway at almost all of the others. The number of these sites that may have released gasoline containing oxygenates is not known. Because of the inherent difficulty in determining leak rates, leak durations, and concentration of oxygenates in the gasoline stored in a UST, it is difficult to develop a reliable estimate of past or current annual releases of fuel oxygenates from these sources.

Monitoring and remediation activities are required at release sites, but typically focus on the hydrocarbons benzene, toluene, ethylbenzene, and xylenes (BTEX compounds) that represent known environmental and health hazards. A limited number of States require monitoring for MTBE as part of the UST corrective-action programs including Florida, Maine, Maryland, Massachusetts, Michigan, New Mexico, New York, North Carolina, South Carolina, Vermont, and Wisconsin (Oliver et al., 1995). Additional data on UST-related impacts from oxygenated gasoline should be forthcoming. A California Senate Advisory Committee has initiated a request to collect data on MTBE concentrations in ground water at UST sites in that State (John Farr, letter of August 1995). Up to this time there was not a State requirement to analyze for MTBE in regular monitoring programs at UST-release sites.

Also, USEPA and State requirements exist and require that UST systems be fully upgraded to meet stringent release prevention and detection standards by December 1998. A survey reported in National Petroleum News (1994) indicates that about 55 percent of all USTs had been upgraded to meet USEPA's 1998 new tank standards. USTs meeting these standards are at a greatly reduced risk of having a release. Also, all current USTs are required to have release detection systems capable of detecting a release within a 30-day period. Finally, USEPA estimates that over 700,000 USTs have been removed in the last 8 years. This concurrent improvement in the physical condition of the UST tank population and release-detection capabilities, coupled with a substantial reduction in the population of tanks, should contribute to a considerable decrease in the annual volume of gasoline released to the environment.

It is estimated that in the Nation's marketing, transportation, and refining industries, there are approximately 14,000 aboveground storage tank (AST) facilities with an estimated 70,000 tanks (API, 1989). Between 30 to 40 percent of ASTs are used for gasoline storage. There are no known industry-wide estimates or surveys of the frequency of releases from ASTs. A 1994 American Petroleum Institute (API) survey of 299 facilities shows that about 40 percent had identified subsurface contamination and were engaged in some form of corrective action to address ground-water impacts of fuel releases (API, 1994a).

In addition to leaks, historic waste-management practices at ASTs may also have contributed to releases of MTBE or other oxygenates at these facilities. As noted in Davidson et al. (1995), water that collects at the bottom of large storage tanks (referred to as "water bottoms") used to be routinely drained into the diked area around the tank, subsequently recharging local ground water or evaporating to the atmosphere. Because of its high solubility, concentrations of MTBE in this water can be very high. One industry study of wastewater at AST facilities measured MTBE concentrations of 280,000 µg/L (micrograms per liter) (API, 1994b). Another study has found concentrations ranging from 1,800,000 to 9,000,000 µg/L (Butillo et al., 1994). An API study of AST facilities (API, 1994b) notes that water bottoms are now treated with other wastewaters generated at these facilities and are no longer released to ground water. As with USTs, specific estimates regarding current or past annual releases of MTBE or other oxygenates are not available.

Point-source releases of gasoline containing MTBE may result in concentrations of MTBE above the draft drinking-water lifetime health advisory of 20 to 200 µg/L. Several authors have reported drinking-water systems affected by MTBE but have not specified the source of MTBE (Anderson, 1986; Angle, 1991; Davidson, 1987; Davidson *et al.*, 1995; Jaremn, 1987; Mason, 1987; McQuillan, 1987; Smith, 1987; Zibrua, 1987). In a few instances (such as in Santa Monica, CA), high concentrations of MTBE have caused the shutdown of a drinking-water production well or well field, and the source of contamination was identified as a release from an underground storage tank (Haslam, 1996; Rodriguez, 1997; Komex•H_2O Science, 1997). In other instances, contaminated ground water was treated to remove MTBE and then used for drinking water (Garrett *et al.*, 1986; McKinnon and Dyksen, 1984; New York State Department of Health and U.S. Department of Health and Human Services Public Health Service, 1995). Underground storage tank improvement programs underway by the States and USEPA should result in a reduction in the release of gasoline and fuel oxygenates to ground water from these potential sources (40 CFR 280.200 - 280.230 and 281.39, July 1, 1996).

<u>Industry Releases of MTBE, TBA, and MeOH.</u> The industry-wide release of MTBE, TBA, and MeOH to air, land, and water, and disposal by deep-well injection are summarized in Table 2.1 for 1993, the most current TRI reporting year. Estimates of releases of chemicals by manufacturing facilities meeting certain size and chemical-release thresholds are required to be reported in the annual TRI; however, Federal facilities were not required to report releases in 1993. Storage-tank releases at manufacturing facilities that must report are also included in the TRI and noted in the environmental compartment in which disposal takes place (land, air, surface water, etc.) (USEPA, 1993a). The 1993 TRI includes reports from 23,000 facilities for 316 chemicals and 20 chemical categories. TRI does not mandate that facilities monitor their releases, and therefore the quantities of reported releases are estimates (USEPA, 1995c). For MTBE, a total of 136 facilities (see Appendix 1)

consisting of 22 Standard Industrial Classification codes reported MTBE releases for that year. About half (78/136) of the reporting facilities were petroleum refineries. These refineries collectively accounted for 83.8 percent of the MTBE released by industry in 1993, or about 1,440,000 kg. Also, nearly all of the estimated release of

Table 2.1: *Estimated releases of MTBE, TBA, and MeOH for the United States for report year 1993.*

[MTBE, methyl *tert*-butyl ether; TBA, *tert*-butyl alcohol; MeOH, methanol. Source: U.S. Environmental Protection Agency, 1993b]

Release to	Reported releases (kilograms per year) by: Petroleum refineries	All other facilities	Total
	Methyl *tert*-butyl ether		
Atmosphere	1,398,026	274,571	1,672,597
Underground injection	288	3,979	4,267
Land	184	2	186
Water	41,799	74	41,873
Total releases	1,440,297	278,626	1,718,923
Percent	83.8	16.2	100
Number of facilities	78	58	136
	***Tert*-butyl alcohol**		
Atmosphere	40,498	705,127	745,625
Underground injection	253	138,410	138,663
Land	0	158	158
Water	5	79,051	79,056
Total releases	40,756	922,746	963,502
Percent	4.2	95.8	100
Number of facilities	8	59	67
	Methanol		
Atmosphere	369,895	77,544,790	77,914,685
Underground injection	9,670	12,645,520	12,655,190
Land	401	779,716	780,117
Water	17,134	4,523,137	4,540,271
Total releases	397,100	95,493,163	95,890,263
Percent	0.4	99.6	100
Number of facilities	67	2,198	2,265

MTBE by industry, about 97 percent, occurred to the atmosphere. It is important to note that the MTBE released by industry, as tallied from the TRI, represents only a small fraction of the total amount of MTBE produced. For example, the estimated release of MTBE by industry in 1992 in the United States accounted for only 0.03 percent of the MTBE that was produced (Squillace et al., 1995a). As noted previously, some sources of MTBE, such as automotive emissions and evaporative losses, evaporative losses at gasoline stations, accidental spills, and so forth are not well documented but could be important sources of oxygenates to the environment. Until these and other releases are accurately determined, it is not possible to put the industrial TRI release data for MTBE within a total release perspective.

The estimated release of TBA and MeOH to the environment by industry in 1993 was 963,500 and 95,890,000 kg, respectively. Similar to MTBE, the majority of the reported estimated releases of TBA and MeOH were to the atmosphere. In contrast to MTBE, petroleum refineries represented a very small amount, 4.2 and 0.4 percent, respectively, of the amount of reported industrial releases for TBA and MeOH (see 2.1). Non-industrial releases of TBA and MeOH also are not well known and thus a comparison of releases associated with the petroleum fuels industry to total releases is not possible. Industrial releases of other fuel oxygenates, including EtOH, ETBE, TAME, and DIPE are not included in the TRI.

Non-Point Sources. As previously noted, fuel oxygenates can enter natural waters from non-point sources, as well as from point sources. Many of the point sources characterized above, as well as exhaust and evaporative emissions from automobiles and trucks, will ultimately cause fuel oxygenates, like other volatile organic chemicals (VOCs), to enter the atmosphere, which can then act as a non-point source to water. The process of chemicals moving in the hydrologic cycle is subsequently described in the sections of this chapter on "Movement of Fuel Oxygenates in the Hydrologic Cycle" and "Behavior in the Ambient Hydrologic Cycle." Research on the atmospheric deposition of fuel oxygenates has not been reported in the scientific literature; however, the importance of this process has been extensively investigated for other VOCs and other chemical classes. Preliminary compilations on the occurrence of MTBE in urban storm-water runoff are discussed in the section on "MTBE in Urban Storm Water" and exhaust emissions of MTBE have been reported elsewhere (Calvert et al., 1993; Hoekman, 1992; Kirchstetter et al., 1996; Stump et al., 1990). The subjects of atmospheric deposition, storm-water runoff, and vehicular emissions as non-point sources of fuel oxygenates in water are discussed in the sections on "Partitioning Between Environmental Compartments" and "Behavior in the Ambient Hydrologic Cycle."

Movement of Fuel Oxygenates in the Hydrologic Cycle

MTBE and other fuel oxygenates are expected to move with water in the hydrologic cycle primarily because of their release to air, water, and land, and their favorable partitioning to water. A schematic depicting the movement of fuel oxygenates in the environment is shown in Figure 2.1. As shown, fuel oxygenates are released to the atmosphere from various point and non-point sources and, once present in the atmosphere, are expected to occur in precipitation because of partitioning from the gas phase to the water phase. Precipitation can then introduce oxygenates directly to streams, rivers, and lakes as it falls on these surface-water bodies, or enters through overland runoff and storm-water drainage. Precipitation falling on land and moving through the unsaturated zone (recharge), and the diffusion of the oxygenates from the atmosphere through the unsaturated zone, are potentially areally extensive, low-level sources of oxygenates to shallow ground water (Squillace et al., 1995a, 1995b, 1996). Dissolved oxygenates that are resistant to degradation can move deeper in aquifers as ground water flows towards wells or natural discharge areas, such as surface water. The extent, if any, to which fuel oxygenates undergo chemical or biological transformation to less harmful substances or chemicals of concern must be understood for each compartment of the hydrologic cycle. This topic is more fully addressed in the section on "Behavior in the Ambient Hydrologic Cycle."

Releases from gasoline storage sites represent important sources of fuel oxygenates to ground water because water in contact with the spilled product, at the water table or within the unsaturated zone, will solubilize the oxygenates as well as the BTEX compounds of the gasoline. Concentrations of oxygenates in ground water near such point sources would be high relative to concentrations in storm water and shallow ground water, that originated from precipitation containing MTBE.

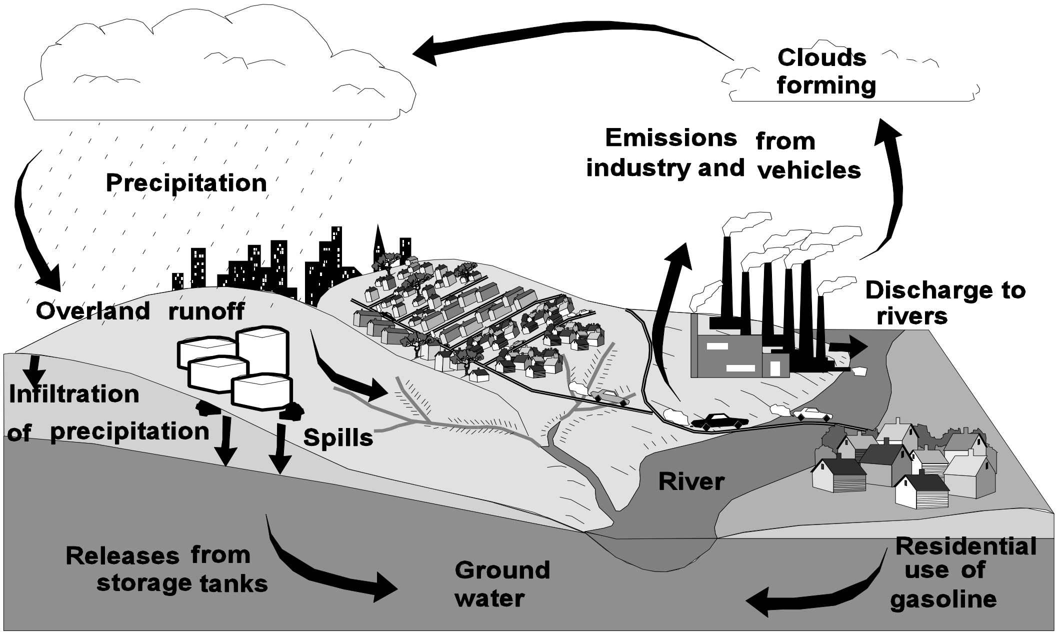

Figure 2.1. The movement of fuel oxygenates in the environment (adapted from Squillace *et al.*, 1995a)

OCCURRENCE AND SIGNIFICANCE OF FUEL OXYGENATES IN WATER

The occurrence of MTBE in ground water, storm water, and drinking water has been reported previously (Angle, 1991; Barks, 1994; Davidson, 1995a, 1995b; Davidson et al., 1995; Delzer et al., 1996; Dey et al., 1991; Garrett, 1987; Garrett et al., 1986; Lopes et al., 1995; McKinnon and Dyksen, 1984; New York State Department of Health and U.S. Department of Health and Human Services, 1995; Post, 1994; Squillace et al., 1995a, 1995b, 1996; Tangley, 1984; and U.S. Environmental Protection Agency, 1986, 1987a, 1987b). Collectively, these investigations document that MTBE occurs in water, especially in areas where this fuel oxygenate is extensively used, and where releases of MTBE to air, water, and land occur. These studies, especially the USGS's recent finding of MTBE's occurrence in shallow urban ground water (Squillace et al., 1995a), have increased national interest in better defining the occurrence and source(s) of fuel oxygenates in ground water, surface water, and drinking water, as well as the transport, biodegradation, fate, and remediation of these chemicals. Little information on the occurrence of other oxygenates in natural waters and drinking waters has been reported in the scientific literature.

Information on drinking-water standards, health advisories and guidelines, and ground-water action levels and protection standards for fuel oxygenates that have been set by the USEPA and the States is presented in this section. Also included is a summary of (1) taste-and-odor properties, (2) aquatic toxicity, (3) analytical methods, and (4) past monitoring in ambient air, storm water, ground water, and drinking water. Finally, recently compiled data on the occurrence of MTBE in urban storm water, drinking water provided from ground water and surface water, and in ground water is presented, along with a discussion of the significance of reported MTBE concentrations.

Drinking-Water and Ground-Water-Protection Regulations

The USEPA has not established a Federal drinking-water standard for any of the fuel oxygenates; however, the agency has issued a draft health advisory for MTBE (USEPA, 1995b). A drinking-water standard is a legally enforceable requirement that includes a maximum contaminant level for the protection of human health that public water supplies cannot exceed.

Health advisories describe non-regulatory concentrations of drinking-water contaminants at which adverse health effects would not be anticipated to occur over specific exposure durations, with a margin of safety. Health advisories serve as informal technical guidance for protecting public health when contamination situations occur. They are not to be construed as legally enforceable Federal standards. Health advisories for MTBE for various durations are reported elsewhere (USEPA, 1995b). The draft drinking-water lifetime health advisory for MTBE is 20 to 200 µg/L, and it is expected to be revised by the USEPA in 1997. The range reflects the uncertainty of the carcinogenicity of MTBE. Health advisories have not been developed by the USEPA for other fuel oxygenates.

Eleven States have established or are promulgating a standard, health advisory/guideline, or action level for MTBE in drinking water (see Table 2.2). An action level is the concentration, when exceeded in ground water, that triggers remediation or other appropriate action. The regulated level varies from State to State, and ranges between 35 to 230 µg/L. Vermont and New York have set standards for MTBE in drinking water at 40 and 50 µg/L, respectively.

At least ten States have established action levels and clean-up levels for MTBE in ground water (see Table 2.3). A clean-up level is the maximum concentration of a contaminant that can remain after remediation has occurred. As shown in Table 2.3, the action levels vary between 40 to 240 µg/L, and the clean-up levels vary between 12 to 700 µg/L (for a drinking-water designation). Some States do not distinctly set action levels or clean-up levels, but rather use standards or health advisory/guidance levels for drinking water to decide when remediation of ground water is needed and the clean-up level to be achieved. A comparison of standards, health advisories/guidelines, action levels, clean-up levels, and

Table 2.2: *Summary of MTBE drinking-water standards, health advisories/guidelines, and action levels established or being promulgated by select States.*

[MTBE, methyl *tert*-butyl ether. μg/L, micrograms per liter]

State	Type of requirement	Regulatory level (μg/L)	Reference	Remarks
California	Interim action level	35	(1,2)	Risk assessment is currently being updated.
Connecticut	Health advisory/guideline	100	(3)	Started about 1980.
Kansas	Health advisory/guideline	100	(3)	Not specific for MTBE; applies to total VOCs.
Illinois	Health advisory/guideline	230	(4)	--
Massachusetts	Health advisory/guideline	50	(3)	--
Maine	Health advisory/guideline	50	(3)	--
New Hampshire	Health advisory/guideline	200	(3)	--
New Jersey	Health advisory/guideline	50	(5)	
	Standard (proposed)	70	(5, 6)	Standard expected to be promulgated in 1996.
New York	Standard	50	(7, 8)	Not specific for MTBE; applies to unspecified organic contaminants.
Rhode Island	Health advisory/guideline	40	(3)	--
Vermont	Standard	40	(3)	--

[1] State of California, Division of Drinking Water and Environmental Management memo of 31 Oct 1995.

[2] State of California, Pesticide and Environmental Toxicology Section, memo of 19 Feb 1991.

[3] Chemical Communication Subcommittee, 1990.

[4] Illinois Environmental Protection Agency, 1994.

[5] New Jersey Drinking Water Quality Institute, 1994.

[6] New Jersey DEP letter of July 24, 1995.

[7] New York DOH letter of July 6, 1995.

[8] New York State Department of Health, 1995.

Table 2.3: *Summary of MTBE ground-water action and clean-up levels established or being promulgated by select States.*

[MTBE, methyl *tert*-butyl ether. μg/L, micrograms per liter]

State	Regulatory level (μg/L)		Reference	Remarks
	Action level	Clean-up level		
Florida	--	50	Oliver, 1995	--
Maine	--	50	Association for Environmental Health of Soils, 1994; Benjamin and Belluck, 1994	Applies to stringent sites only. Site-specific remediation standards applied to other sites.
Massachusetts	Not specified in regulation	[a]700/[b]50,000/[c]50,000	Oliver, 1995	a - Actual/potential drinking water supply; b - Source of vapor emissions to building; c - Everywhere.
Michigan	Same as cleanup criteria	[d]240/[e]690	Oliver, 1995	d - Residential; e - Industrial/commercial.
New Mexico	100	100	Oliver, 1995; Benjamin and Belluck, 1994	--
New York	50	[f]50	Oliver, 1995	f - Clean-up level is the action level, or when not achievable, site specific.
North Carolina	>200	>200	Association for Environmental Health of Soils, 1994; Benjamin and Belluck, 1994	--
South Carolina	Site specific	40 (Recommended)	Oliver, 1995	--
Vermont	40	Site specific	Oliver, 1995	--
Wisconsin	60	12	Oliver, 1995	--

other information is summarized in Figure 2.2. Similar information for other oxygenates has not been compiled to date.

Taste and Odor Thresholds

The introduction of the oxygenated gasoline program in November 1992 resulted in complaints about the smell of gasoline. In an attempt to understand the nature of the complaints, industry assessed the taste and odor thresholds of the neat ethers and then of oxygenate-gasoline mixtures. The work was completed by TRC Corporation, and was sponsored by ARCO Chemical Company and the American Petroleum Institute. Three reports were issued (TRC Environmental Corporation, 1994; Vetrano, 1993a, 1993b). Standard protocols were used in which trained adult volunteers sipped water or smelled air containing known concentrations of the oxygenates being tested. The data were then used to calculate the taste threshold for water and odor thresholds for water and air. The taste threshold of MTBE in water for two studies was 39 and 134 µg/L. Taste thresholds for ETBE and TAME were 47 and 128 µg/L, respectively.

Odor thresholds are characterized by two numbers, a detection threshold and a recognition threshold. The detection threshold is the level at which people can notice a difference between the smell of clean water and the smell of water containing the test material, and the recognition threshold is the level at which they can describe the smell. In general, the recognition threshold is about twice the detection threshold. The odor threshold data for alkyl ether oxygenates in water are summarized in 2.4. The relative standard errors associated with these measurements were found to range up to about 15 percent but for brevity are not included. As shown in Table 2.4, the odor-detection threshold of MTBE for two studies was 45 and 95 µg/L, and ETBE and TAME have reported detection thresholds of 49 and 194 µg/L, respectively. The above range for MTBE is not unusual and reflects the results of two studies done at different times and by different panels. The odor-detection threshold for MTBE in water falls within the range of the draft drinking-water lifetime health advisory for MTBE of 20 to 200 µg/L (see Figure 2.2). Odor thresholds in air are not discussed in this chapter; the reader is referred to the previously noted reports for this information.

Table 2.4: *Odor thresholds for fuel oxygenates in water.*

[MTBE, methyl *tert*-butyl ether; ETBE, ethyl *tert*-butyl ether; TAME, *tert*-amyl methyl ether; µg/L, micrograms per liter]

Fuel oxygenate	Odor threshold (µg/L)		Reference
	Detection	Recognition	
MTBE	95	193	Vetrano, 1993a
MTBE	45	55	TRC Environmental Corporation, 1994
ETBE	49	106	Vetrano, 1993a
TAME	194	443	Vetrano, 1993b

Aquatic Toxicology of Oxygenates

Because it will not be included in the health effects chapter, aquatic toxicological information on fuel oxygenates is summarized below. Both published information and information available from industrial studies not yet published in the peer-reviewed literature are included.

Water-quality criteria to protect aquatic life have not been established by the USEPA. When developing numerical criteria for the protection of aquatic life, acute and chronic toxicity and bioconcentration data are used. The minimum data set for criteria derivation consists of eight families or organisms, and acute and chronic testing must be available using the same species in the same dilution of water, for the most sensitive life stages of a given species. Plant toxicity is also a factor considered when developing water-quality criteria. For the alkyl ether oxygenates, chronic-toxicity data for aquatic animals and plants are lacking, and limited information exists on acute toxicity and bioconcentration. For EtOH and MeOH, considerably more aquatic toxicity studies have been completed, especially to assess acute toxicity.

USEPA's AQUIRE data base was searched for toxicity data on fuel oxygenates and articles cited therein, and industrial studies were subsequently reviewed for additional information on toxicity. Only studies with an AQUIRE documentation code of 1 or 2 were used. The available information is summarized in Table 2.5. Median lethal concentrations, LC_{50}, and median effective concentrations, EC_{50}, are given in this table. LC_{50} and EC_{50} represent the estimated concentration that is expected to be lethal and to cause other effects, in 50 percent of the test species, respectively. Effects described in EC_{50} studies include, for example, behavior, growth, immobilization, reproduction, and equilibrium. Many study results were available for EtOH and MeOH in AQUIRE and, as such, entries in Table 2.5 for these oxygenates are for the test species that had the lowest and second lowest concentrations for LC_{50} and EC_{50} only. For other fuel oxygenates, all studies completed to date are listed.

Based on the species tested to date, TBA and MTBE appear to have lower toxicity than other fuel oxygenates with LC_{50} ranges of 2,450 to 6,410 and 672 to >1,000 mg/L (milligrams per liter), respectively. Greater toxicity has been reported for other oxygenates, for at least one test species, including: TAME, 14 mg/L for shrimp; ETBE, 37 mg/L for shrimp; MeOH, 37 mg/L for mussel; DIPE, 92 mg/L for fathead minnow; and EtOH, 454 mg/L for scud.

As is shown in Table 2.5, non-lethal effects have been studied for EtOH, MeOH, TBA, TAME, and DIPE. MeOH and TBA have lower toxicity, whereas greater toxicity has been reported for TAME, 0.11 mg/L for freshwater algae; EtOH, 2.0 to 2.5 mg/L for water flea; and DIPE, 476 mg/L for fathead minnow. The reader is reminded the acute toxicity values noted above and listed in Table 2.5 are reported in milligrams per liter, not micrograms per liter; the latter unit is used in most instances in this chapter.

Monitoring and Analysis of Fuel Oxygenates

Monitoring. The Clean Air Act (CAA), Clean Water Act (CWA), and Safe Drinking Water Act (SDWA) do not require the monitoring of fuel oxygenates in air, ground water, surface water, or drinking water and, as such, national monitoring data sets are not available for these chemicals with two exceptions. First, MTBE was measured in ground water in 1993-95 as part of the NAWQA program, and preliminary findings have been reported (Squillace et al., 1995a, 1995b, 1996). Second, MTBE was measured in storm water as part of USGS

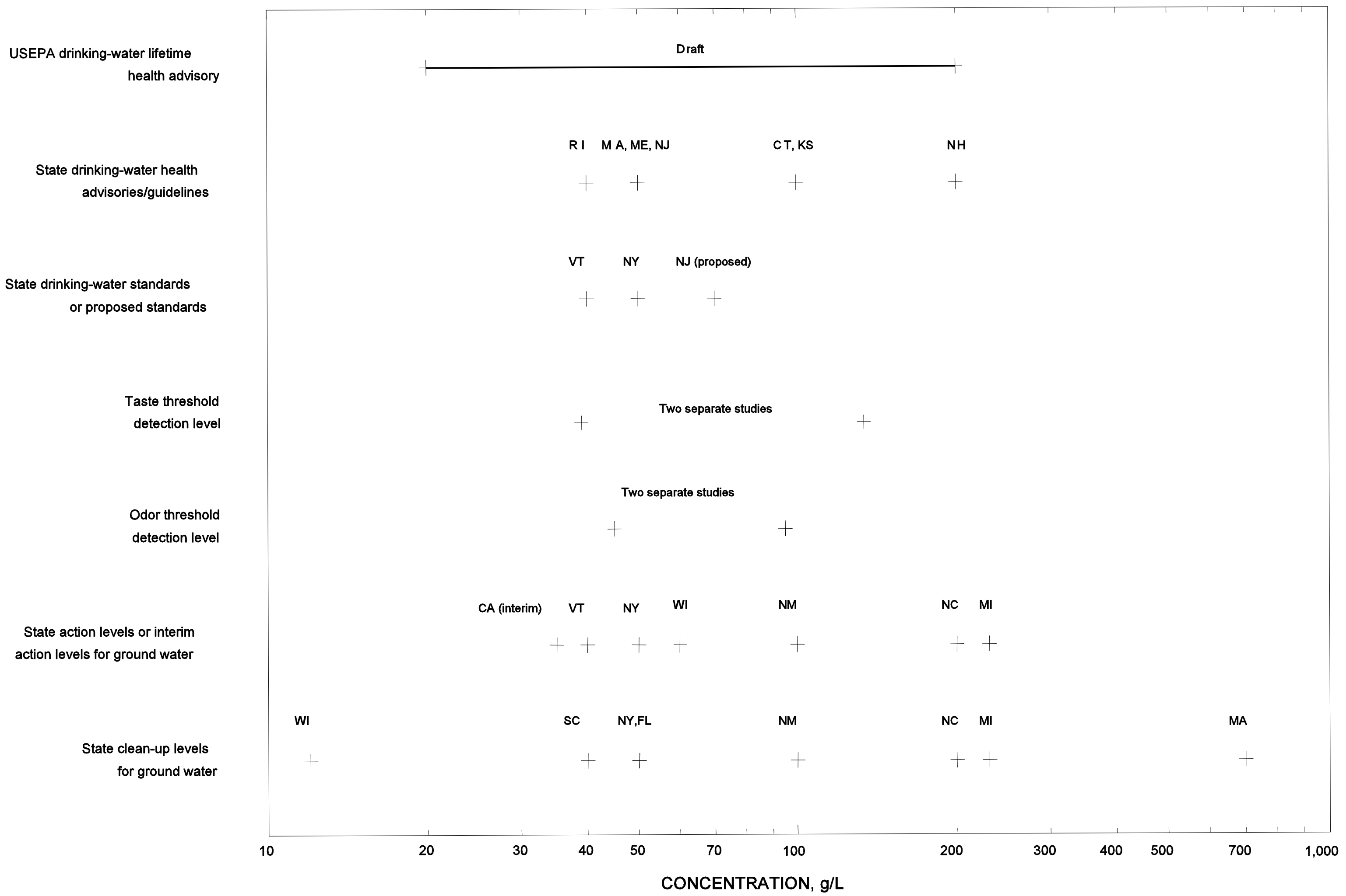

Figure 2.2. Comparison of MTBE health advisories/guidelines, drinking-water standards, taste and odor thresholds, action levels, and clean-up levels.

Table 2.5: *Acute toxicity of fuel oxygenates to freshwater aquatic life.*

[EtOH, ethanol; MeOH, methanol; TBA, *tert*-butyl alcohol; MTBE, methyl *tert*-butyl ether; ETBE, ethyl *tert*-butyl ether; TAME, *tert*-amyl methyl ether; DIPE, diisopropyl ether. BEH, behavior; GRO, growth; IMM, immobilization; PHY, physical; REP, reproduction; EQU, equilibrium, change in ability to maintain balance; mg/L, milligrams per liter]

Fuel oxygenate	Test species	$LC_{50}{}^{1}$ (mg/L)	$EC_{50}{}^{2}$ (mg/L)	Reference
$EtOH^{3}$	*Hyalella azteca* (Scud)	^{4}454		Cowgill and Milazzo, 1991
$EtOH^{3}$	*Daphnia magna* (Water flea)	^{5}8,210		Bowman *et al.*, 1981
$EtOH^{3}$	*Daphnia magna* (Water flea)		^{6}2.0-^{7}2.5 (PHY)	Lagerspetz *et al.*, 1993
$EtOH^{3}$	*Ceriodaphnia dubia* (Water flea)		^{8}26 (REP)	Cowgill and Milazzo, 1991
$MeOH^{3}$	*Anodonta imbecillis* (Mussel)	^{6}37		Keller, 1993
$MeOH^{3}$	*Lepomis macrochirus* (Bluegill)	^{9}15,400		Poirier *et al.*, 1986
$MeOH^{3}$	*Oncorhynchus mykiss* (Rainbow trout)		^{6}13,000-^{9}13,200 (EQU)	Poirier *et al.*, 1986
$MeOH^{3}$	*Lepomis macrochirus* (Bluegill)		^{6}16,000-^{7}16,100 (EQU)	Poirier *et al.*, 1986
TBA	*Carassius auratus* (Goldfish)	^{7}>5,000		Bridie *et al.*, 1979
TBA	*Daphnia magna* (Water flea)		^{6,7}5,504 (IMM)	Kuhn *et al.*, 1989
TBA	*Chironomus riparius* (Midge larvae)	^{6}5,800		Roghair *et al.*, 1994
TBA	*Pimephales promelas* (Fathead minnow)	^{9}6,410	^{9}4,430 (BEH)	Geiger *et al.*, 1988
TBA	*Xenopus laevis* (Clawed toad)	^{7}2,450		De Zwart and Slooff, 1987
MTBE	*Bleak* (European fish)	^{9}>1,000		Bengtsson and Tarkpea, 1983
MTBE	*Nitocra Spinipes* (Harpacticoid copepod)	^{9}>1,000		Bengtsson and Tarkpea, 1983
MTBE	*Pimephales promelas* (Fathead minnow)	^{9}706		Veith *et al.*, 1983a, 1983b

Table 2.5: *Acute toxicity of fuel oxygenates to freshwater aquatic life.-Continued*

Fuel oxygenate	Test species	LC_{50} [1] (mg/L)	EC_{50} [2] (mg/L)	Reference
MTBE	*Pimephales promelas* (Fathead minnow)	^{9}672		Geiger *et al.*, 1988
ETBE	*Cyprinodon variegatus* (Sheepshead minnow)	^{9}>2,500		Boeri *et al.*, 1994a
ETBE	*Mysidopsis bahia* (Shrimp)	^{9}37		Boeri *et al.*, 1994b
TAME	*Selenastrum capricornutum* (Freshwater algae)		^{9}0.11 (GRO)	API, 1995a
TAME	*Daphnia magna* (Water flea)		^{7}100 (IMM)	API, 1995b
TAME	*Mysidopsis bahia* (Shrimp)	^{9}14		API, 1995c
TAME	Oncorhynchus mykiss (Rainbow trout)	^{9}580		API, 1995d
DIPE	Pimephales promelas (Fathead minnow)	^{9}92		Veith *et al.*, 1983a, 1983b
DIPE	Carassius auratus (Goldfish)	^{7}380		Bridie *et al.*, 1979
DIPE	Lepomis macrochirus (Bluegill)	^{9}7,000		Dawson *et al.*, 1977
DIPE	Pimephales promelas (Fathead minnow)	^{9}786	^{9}476 (BEH)	Geiger *et al.*, 1988

[1] LC_{50}, the median lethal concentration, is the estimated concentration that is expected to be lethal to 50 percent of the test animals or plants. Only those studies with an AQUIRE documentation code of 1 and 2 are included.

[2] EC_{50}, the median effective concentration, is the estimated concentration that is expected to cause an effect other than death for 50 percent of the test animals or plants. Only those studies with an AQUIRE documentation code of 1 and 2 are included.

[3] Entries for EtOH and MeOH are for the test species that had the lowest and second lowest concentrations for LC_{50} and EC_{50}. For other fuel oxygenates, all studies completed to date are listed.

[4] 216-hr; [5] 18-hr; [6] 48-hr; [7] 24-hr; [8] 168-240-hr; [9] 96-hr.

cooperative projects with some of the Nation's larger cities, which completed monitoring as part of obtaining national permits for discharges of municipal storm-water runoff, and preliminary findings have been prepared (Delzer et al., 1996). Although used extensively as a fuel oxygenate, the lack of monitoring for EtOH is apparently a result of: (1) the difficulty of analyzing for this chemical in the aqueous phase, and (2) the ease of microbial degradation, which results in a short half-life in water. MTBE and MeOH are included on the CAA Hazardous Air Pollutant List, and information on these two oxygenates in urban air may become available via this voluntary program in the future. Also, MTBE is on the USEPA's Drinking Water Priority List, which means that it is a possible candidate for future Federal regulation and monitoring.

Some States have monitored for MTBE in public water systems, or a subset of systems, including Connecticut, Illinois, New Jersey, Rhode Island, and Texas. Other States, for example, Iowa, New York, Missouri, Rhode Island, and Wisconsin have completed monitoring of private wells and public water-supply systems. In some cases, the sampling program was conducted where contamination of ground water by MTBE was known to have occurred or was suspected. Although information on monitoring being completed by State agencies was sought as part of this assessment, additional information is needed to better characterize MTBE monitoring being completed by the States. Also, a number of large water utilities may monitor for MTBE as part of routine VOC monitoring, and the availability of this information needs to be determined. Very little monitoring of other fuel oxygenates in water has been completed by State agencies or water utilities.

MTBE and other fuel oxygenates are not included in routine ambient air monitoring done by local, State, and Federal agencies. An exception is the State of California, which just recently began to monitor for MTBE and other VOCs in ambient air. Air-quality data have been collected for MTBE, as part of special studies in Fairbanks, Alaska; Stamford, Conn.; Albany, N.Y.; Milwaukee, Wis.; Boston, Mass.; and Houston, Tex. (Table 2.6). Additional air-quality studies have been completed to determine human exposure, mostly at or near blending and distribution facilities, and gasoline stations (Johnson et al., 1995; McCoy and Johnson, 1995; NATLSCO, 1995). Some air-quality data are available for EtOH (Kelly et al., 1993; McCoy and Johnson, 1995), ETBE (Allen and Grande, 1995), and MeOH (Kelly et al., 1993), and none is known to exist for other fuel oxygenates.

The median concentration of MTBE in ambient air ("area" entries in Table 2.6) for the six cities listed in this table ranged between 0.13 to 4.6 ppb-v (parts per billion by volume), with the highest median value measured in Fairbanks, Alaska. Excluding Fairbanks, the maximum concentration measured in ambient air was 4.1 ppb-v in Milwaukee, Wisconsin. The median ambient air levels of MTBE in Milwaukee, Albany, Stamford, Boston, and Houston were typically at or below 1 ppb-v. While informative, air quality monitoring of fuel oxygenates completed to date is inadequate to characterize concentrations expected in ambient air across the United States. As shown in Table 2.6, concentrations of MTBE in air near gasoline stations, roadways, parking lots and garages, and blending and distribution facilities are higher, and in many cases considerable higher than ambient urban air.

Analysis. The widespread usage of fuel oxygenates will require that additional monitoring be performed. Analytical methods for EtOH, MeOH, and TBA in water have not been developed by the USEPA or USGS. However, alkyl ether oxygenates can be analyzed

Table 2.6: *Statististical summary of MTBE concentrations in urban air.*

[MTBE, methyl *tert*-butyl ether. Concentrations are parts per billion by volume (ppb-v); to convert to micrograms per cubic meters, multiply ppb-v values by 3.604]

City/State or special study		Minimum	Median	Maximum	Reference	Remarks
Milwaukee, Wis.	Area (n=11)[1]	0.0	0.13	4.13	Allen and Grande, 1995	
	Gas station (n=6)	0.25	1.59	4.58		Sampled at perimeter of gas station.
	Parking lot (n=8)		2.05			Average concentrations of the 8 samples.
	Roadway[2] (n=12)	0	0.50	1.06		
	Gas station (n=19)	50	70	2,930		Sampled at breathing zone while refueling.
Fairbanks, Alaska (Phase I: Dec. 1-12, 1992)	Area (n=2)	2.0	4.0	6.0	Roy Zweidinger, USEPA, written commun., 1995	Phase I was immediately prior to the phase out of 15% MTBE in gasoline.
	Gas station (n=1)	54	54	54		
	Roadway (n=7)	3.0	5.0	12.0		
Fairbanks, Alaska (Phase II: Dec. 18-22, 1992)	Area (n=11)	1.7	4.6	28	Roy Zweidinger, USEPA, written commun., 1995	Phase II was during the phase out of 15% MTBE in gasoline.
	Gas station (n=1)	37.4	37.4	37.4		
	Roadway (n=7)	4.2	9.7	17.9		
Fairbanks, Alaska (Phase III: Feb. 2 - Mar. 5, 1992)	Area (n=9)	0.2	0.9	2.5	Roy Zweidinger, USEPA, written commun., 1995	Phase III was after the phase out of 15% MTBE in gasoline.
	Gas station (n=5)	1.7	3.2	13.8		
	Roadway (n=9)	0.6	1.4	3.4		
Albany, N.Y. (May 5-27, 1993)	Area (n=6)	0.1	0.25	0.7	Roy Zweidinger, USEPA, written commun., 1995	MTBE was used in premium gasoline only.
	Gas station (n=6)	6.5	17.7	54.0		

Table 2.6: *Statistical summary of MTBE concentrations in urban air--Continued.*

City/State or special study		Mini-mum	Median	Maxi-mum	Reference	Remarks
Stamford, Conn. (Apr. 13-14, 1993)	Area (n=4)	0.3	0.85	2.8	Roy Zweidinger, USEPA, written commun., 1995	Another area where 15% MTBE in gasoline was used.
	Gas station (n=3)	2.1	5.5	7.4		
	Parking garage (n=4)	18.6	35.1	49.4		
	Area (x=1/22)[3]	<0.2	<0.2	0.49	Kelly *et al.*, 1993	Sampled at former Toxic Air Monitoring Study site.
Houston, Tex.	Area (x=8/22)	<0.2	<0.2	2.8	Kelly *et al.*, 1993	Sampled at former Tox ic Air Monitoring Study site.
Service station personnel exposure (long-term samples)	Attendant (Winter)	30	200	500	NATLSCO, 1995	Geometric means are used instead of the median values in this publication.
	Mechanic (Winter)	20	120	2,600		
	Attendant (Summer)	30	80	420		
	Mechanic (Summer)	20	30	180		
Area samplers	Blending - neat MTBE (x=32/38)	60	419	9,893	McCoy and Johnson, 1995	
	Blending - fuel mixtures (x=10/19)	40	200	2,100		
	Distribution (fuel) (x=3/4)	20	60	100		

Table 2.6: *Statistical summary of MTBE concentrations in urban air--Continued.*

City/State or special study		Mini-mum	Median	Maxi-mum	Reference	Remarks
New Jersey service stations Stage II full-service	Perimeter (x=15/16)	1	3	36	Johnson *et al.*, 1995	Stage II is a vapor recovery system used during refueling.
	Pumps (x=4/4)	120	440	1,600		
	Breathing zone (x=4/4)	84	245	520		
New York service stations Stage II self-service	Perimeter (x=24/24)	2	7	83	Johnson *et al.*, 1995	Stage II is a vapor recovery system used during refueling.
	Pumps (x=6/6)	14	48	80		
	Breathing zone (x=6/6)	77	205	780		
Connecticut service stations self-service	Perimeter (x=38/40)	1	14	140	Johnson *et al.*, 1995	
	Pumps (x=9/10)	9	170	1,500		
	Breathing zone (x=10/10)	170	1,500	2,600		

[1] n = number of samples.
[2] Roadway is defined as sites near highways or intersections of highways.
[3] x = number of detections/number of samples.

by purge and trap gas chromotography/mass spectrometry (GC/MS). USEPA Method 524.2 is one of the two required methods for the analysis of VOCs in drinking water, and it is the preferred method for measuring MTBE[2]. The other USEPA drinking water method for VOCs is 502.2. A revised version of Method 524.2 will officially replace the current version after July 1996. The estimated detection limit for reagent water spiked with 0.4 µg/L of MTBE for revised Method 524.2 is 0.09 µg/L (USEPA, 1992). Also, many laboratories have successfully used USEPA SW846 Methods, 8020 and 8240, to measure MTBE in water samples collected for remediation studies. Because existing GC/MS methods can be used, adding the alkyl ether oxygenates to monitoring programs should have only a minimal effect on cost.

MTBE was added as an analyte on routine VOC water schedules by the USGS in October 1991, and ETBE, TAME, and DIPE were added as target analytes in 1996. The method and its performance have been reported elsewhere (Raese et al., 1995; Squillace et al., 1995b, 1996). The estimated detection limit for reagent water spiked with 0.2 µg/L of MTBE is 0.06 µg/L (Raese et al., 1995). Methods used by the USGS to collect, preserve, and ship water samples are described elsewhere (Koterba et al., 1995).

Analytical results for MTBE described in the next two sections were completed by the USGS and a variety of States. USGS's analyses have a reporting level of 0.2 or 1.0 µg/L, whereas the reporting level for analyses done by the States are often unknown, and when known are usually similar to that noted for the USGS's analyses.

MTBE in Urban Storm Water

Storm water has been analyzed for MTBE and other non-oxygenate constituents in 16 cities and metropolitan areas from 1991 to 1995 (see Figure 2.3). These studies were completed by various USGS Districts to characterize storm-water runoff in cities with a population exceeding 100,000. These cities are required by provisions of the CWA to obtain National Pollution Discharge Elimination System (NPDES) permits for discharges from municipal separate storm-sewer systems. These projects were not specifically designed to assess the occurrence of fuel oxygenates in storm water, and many of the cities studied were not using MTBE in either oxygenated gasoline or reformulated gasoline during the sampling period. Also, MTBE may or may not have been used to enhance the octane of conventional gasoline in these cities. The compilations characterized herein provide some insights on the occurrence, or lack of occurrence, of MTBE in storm water in select cities in select States. MTBE was the only oxygenate analyzed. It is important to note that Northeastern States and California, high-use areas of MTBE oxygenated gasoline, were not sampled in the USGS investigations and, as such, the concentration of MTBE in storm water for these States has yet to be characterized.

The design of each study varied depending upon the requirements of each USEPA Region and the extent of monitoring desired by each municipality. A wide variety of conveyance types, such as culverts, concrete pipes, lined ditches, and channels was sampled. Some of the conveyances were open to the atmosphere and others were not. The drainage area of sampled sites was typically very small, with a range of 0.014 to 27.7 km^2 (kilometers

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[2] Drinking-water monitoring for MTBE is not required because a Federal drinking-water standard has not been established. Some States may complete MTBE analysis, however, because of existing or proposed State requirements.

squared). Most sampling sites had a predominant land use including highway, residential, commercial and industrial. Laboratory procedures (Raese et al., 1995) and preliminary study findings (Delzer et al., 1996) are reported elsewhere.

Compilations for All 16 Cities. Summary statistics were calculated on the occurrence and concentration of MTBE for each of the 16 cities where monitoring was completed (Appendix 2). The timeframe in which samples were collected in each city is also presented in Appendix 2. Tallies are provided for the entire calendar year and for the periods Oct. 1 to Mar. 31 and Apr. 1 to Sept. 30, to correspond with the expected seasonal use and non-use of MTBE in carbon monoxide non-attainment areas, respectively.

A total of 592 storm-water samples were collected and analyzed for MTBE and other VOCs (see Table 2.7), and about half were collected during each period. MTBE was detected in 6.9 percent of the 592 samples, or 41 detections. One or more detections were found for Birmingham, AL; Phoenix, AZ; Denver, CO; Colorado Springs, CO; Atlanta, GA; Dallas-Fort Worth, TX; San Antonio, TX; and Baton Rouge, LA. Eighty-three percent of the 41 detections occurred during the Oct. 1 to Mar. 31 period when MTBE would be used in greater volumes in carbon monoxide non-attainment areas, if it were the oxygenate of choice.

Table 2.7: *Occurrence of MTBE in storm water for all 16 cities where monitoring was completed.*

[MTBE, methyl *tert*-butyl ether]

Time period	Number of samples	Number of detections	Percent occurrence	Percent of total detections in the indicated time period
Apr. 1 - Sept. 30	305	7	2.3	17
Oct. 1 - Mar. 31	287	34	11.8	83
Entire year	592	41	6.9	--

The partitioning of MTBE from atmospheric gases to precipitation is very dependent upon air temperature and air concentrations of MTBE (Squillace et al., 1995b, 1996). The higher percent detection of MTBE in storm water during the winter season is attributable, in part, to the more favorable partitioning from air to precipitation, because of lower winter temperatures. Shorter atmospheric half-lives, lower atmospheric levels, reduced MTBE volumes in gasoline, and increased volatility from water during the summer season may also contribute to the observed difference in MTBE's occurrence in storm water between the two periods.

Concentrations of MTBE in storm water for all samples analyzed ranged from below the reporting level to 8.7 µg/L, with a median below the reporting level (Table 2.8). For just those samples in which MTBE was detected, the concentration ranged from 0.2 to 8.7 µg/L, with a median of 1.5 µg/L. As shown in Table 2.8, the median

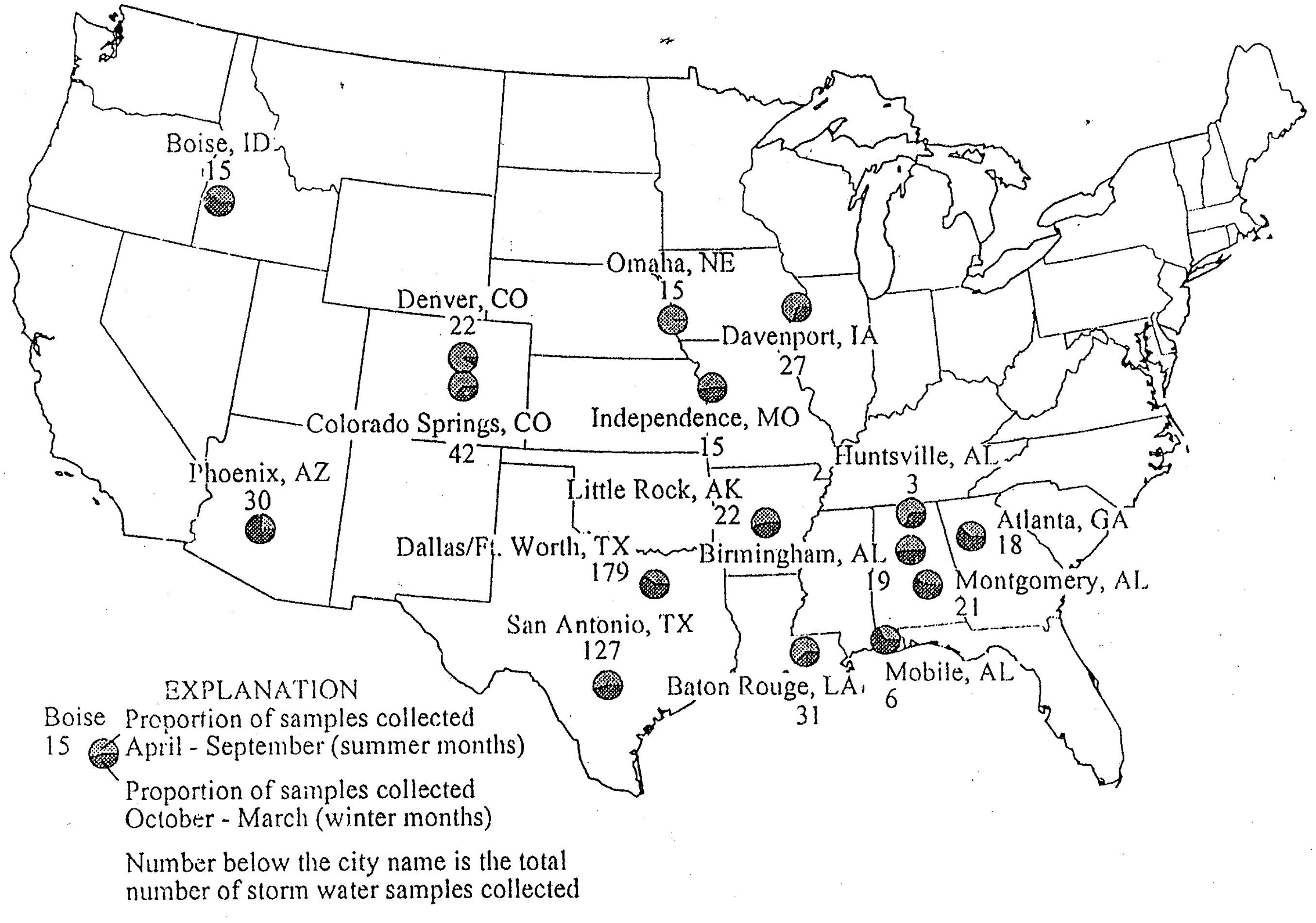

Figure 2.3. Cities and metropolitan areas where MTBE was sampled in urban storm water, 1991-95.

concentrations of MTBE detections were 1.8 µg/L during Apr. 1 to Sept. 30, and 1.5 µg/L during Oct. 1 to Mar. 31. The range of concentrations found was less during the Apr. 1 to Sept. 30 period when MTBE's use in reformulated gasoline and oxygenated gasoline is not expected to occur, except in severe ozone non-attainment areas. None of the cities where sampling was completed are so classified.

Table 2.8: *Concentration of MTBE in storm water for all 16 cities where monitoring was completed.*

[MTBE, methyl *tert*-butyl ether. µg/L, micrograms per liter]

	For all samples analyzed			
Time period	Number of samples	Concentration (µg/L)		
		Minimum1	Median[1]	Maximum
Apr. 1 - Sept. 30	305	<0.2	<1	3.4
Oct. 1 - Mar. 31	287	<0.2	<1	8.7
Entire year	592	<0.2	<1	8.7

	For samples with detection of MTBE			
Time period	Number of samples	Concentration (µg/L)		
		Minimum	Median	Maximum
Apr. 1 - Sept. 30	7	0.4	1.8	3.4
Oct. 1 - Mar. 31	34	0.2	1.5	8.7
Entire year	41	0.2	1.5	8.7

[1] Eighty-three percent of the storm-water samples were analyzed with a reporting level of 1.0 µg/L, 11 percent were analyzed at reporting level of 0.2 µg/L, and 6 percent of samples were diluted prior to analysis with varied reporting levels.

The median and mean concentrations of MTBE for all samples were shown to be statistically different during the Oct. 1 to Mar. 31 period, in comparison to the Apr. 1 to Sept. 30 period. The Wilcoxon rank sum test (one-sided p-value = 0.0000) and a modified t-test based on Tukey's bi-weight estimator (one-sided p-value = 0.0002) were used to establish the aforenoted statistical inferences. These tests are described elsewhere (Helsel and Hirsch, 1992).

The use of MTBE in oxygenated gasoline was confirmed by State air-pollution officials in Phoenix, AZ; Colorado Springs, CO; and Denver, CO; during the period when USGS's storm-water monitoring was completed. State officials also confirmed that MTBE was not being used in oxygenated fuel programs during the USGS sampling period for the other 13 cities listed in Appendix 2. MTBE may have been used in some of these latter cities as an octane enhancer, although this could not be confirmed. The detection of MTBE in Birmingham, AL; Baton Rouge, LA; Atlanta, GA; Dallas-Fort Worth, TX; and San

Antonio, TX; may be attributable to the use of MTBE as an octane enhancer in these cities. In total, 25 of the 41 MTBE detections, or 61 percent, occurred in cities that were not using oxygenated gasoline or reformulated gasoline.

Fuel oxygenates found in municipal storm water can originate from various point and non-point sources. Gasoline spills on land surfaces can enter storm water, and this source can potentially increase the levels of fuel oxygenates in storm water. Spills are transient events, however, and they would not be comprehensively characterized by the grab-sampling design used in the storm-water studies described above. This may explain, in part, why low levels of MTBE were found in these studies.

Compilations for Select Cities where MTBE was Used Seasonally in Oxygenated Gasoline. As noted previously, the use of MTBE in oxygenated gasoline was confirmed by State air-pollution officials in Phoenix, AZ, Colorado Springs, and Denver, CO, during the period when USGS's storm-water monitoring was completed. The occurrence and concentration of MTBE in storm-water samples for these three cities are summarized in Table 2.9. For each of the three cities, detections in storm-water samples occurred only during the period when oxygenated gasoline was in use. Again, the more favorable partitioning of MTBE to precipitation during colder temperatures, longer atmospheric half-lives in the winter, increased volume of MTBE in gasoline during the oxygenated gasoline season, and decreased volatility from storm water at winter temperatures may explain, in part, the strong seasonal detection pattern. MTBE was detected in 16 of 40 samples, or 40 percent of samples that were collected during the period when MTBE was used in oxygenated gasoline. The concentration of MTBE detections ranged from 1.0 to 4.2 µg/L, with a median concentration of 1.5 µg/L (Appendix 2).

MTBE in Ground Water and in Drinking Water Derived from Ground Water

The characteristics of the programs surveyed and used for this assessment, as well as the sources of the MTBE concentration data, are summarized in Appendices 3 and 4, by State, for ground water and for drinking water, respectively. The programs in Appendix 3 were compiled from (1) results of sampling by the NAWQA Program and (2) retrospective data compiled by the NAWQA Program for occurrence assessment. The information in Appendix 4 was compiled from responses to a request by USEPA's headquarters through the 10 EPA Regions to the States for information on drinking-water programs that have analyzed for MTBE. Samples collected in the NAWQA Program are from individual wells at or near the well head, regardless of the type of well. All drinking-water supplies that are listed in Appendix 4 have ground water as their source water, except for two Wisconsin drinking-water systems and at least one Rhode Island system, which used surface water as the source water.

Ground water and drinking water derived from ground water have been analyzed for MTBE in a number of States. MTBE has been analyzed in 1,516 wells in 33 States as part of 90 ground-water-resource assessment programs or studies (Table 2.10, Appendix 3). At least one detection of MTBE has occurred in 14 of the 33 States and in 25 of 90 assessment programs. From the data gathered by the USEPA request, seven States indicated that

Table 2.9: *Occurrence and concentration of MTBE in storm-water samples for select cities where MTBE was used seasonally in oxygenated gasoline.*

[MTBE, methyl *tert*-butyl ether. µg/L, micrograms per liter]

Study area	Time period	Number of samples	Number of detections	Percent occurrence	Median concentration of detections (µg/L)
Phoenix, Ariz.	Apr. 1 - Sept. 30	7	0	0	1.0
	Oct. 1 - Mar. 31	23	5	22	
	Entire year	30	5	17	
Colorado Springs, Colo.	Apr. 1 - Sept. 30	27	0	0	1.6
	Oct. 1 - Mar. 31	15	10	67	
	Entire year	42	10	24	
Denver-Lakewood-Aurora, Colo.	Apr. 1 - Sept. 30	20	0	0	1.5
	Oct. 1 - Mar. 31	2	1	50	
	Entire year	22	1	5	
All three cities	Apr. 1 - Sept. 30	54	0	0	1.5
	Oct. 1 - Mar. 31	40	16	40	
	Entire year	94	16	17	

MTBE had been sampled in public drinking-water systems and provided results of that sampling (Table 2.10, Appendix 4). Two of the seven States cited above also provided results on private drinking-water wells. In addition, two other States provided results of private well sampling. Six of the seven States reported at least one detection of MTBE in public water systems (Table 2.10). Also, all four States that provided MTBE results for private wells had at least one detection.

Ground Water. MTBE has been detected in ground water as a result of sampling of observation, monitoring, and water-supply wells (at the well head) by the NAWQA Program and other ground-water assessment programs (Appendix 3). Most of these ground-water-resource assessment programs were conducted by the NAWQA Program. The design of studies by NAWQA involves a well-selection strategy that results in a spatially distributed random sampling of a targeted ground-water resource. This approach, therefore, avoids skewing the characterization of water quality toward, for example, contamination plumes (Gilliom et al., 1995; Lapham et al., 1995; Scott, 1990; Squillace et al., 1995b, 1996).

<u>Detections for All Programs Sampled</u>. Detections of MTBE in ground water occurred in Colorado, Connecticut, Georgia, Massachusetts, New Jersey, New Mexico, Nevada, New York, Pennsylvania, Texas, Virginia, Vermont, Washington, and Wisconsin. Overall, about 5 percent (76 detections out of 1,516 samples) of the wells sampled in all networks had a detection of MTBE (Table 2.10). Most of the detections (27 percent of the shallow urban wells sampled–55 detections out of 204 samples) occur in shallow ground water in urban areas (described as NAWQA land-use studies in urban areas) and nearly half of these detections occurred in one urban area, Denver, CO. Only about 1.5 percent of samples from wells screened in shallow ground water in agricultural areas had detections of MTBE (7 detections out of 524 samples). One detection of MTBE occurred from seven samples of shallow ground water beneath an undeveloped land-use setting in Vermont. About 1.7 percent of the wells screened in deeper aquifers or deeper parts of shallow aquifers (13 detections out of 781 samples) had MTBE. The largest concentration of MTBE from deeper ground water was 7.9 µg/L from a well in New York State. These conclusions regarding frequency of detections are essentially the same as those reported by Squillace et al. (1995b, 1996).

The reason(s) for the frequent detection (23 of 29 wells) of MTBE in Denver's shallow ground water is not known. However, contributing factors likely include: (1) extended period of oxygenate use, (2) shallow depth from land surface to ground water, and (3) high vertical hydraulic conductivity. The alluvial aquifer sampled in Denver, and the overlying unsaturated zone, consist of very conductive sand and gravel, and the median depth to ground water is only 4.3 meters (Squillace et al., 1996). Further, MTBE has been used in Denver's oxygenated gasoline program since 1989 (and potentially longer to enhance the octane of conventional gasoline). Aquifers with similarly shallow depth to water and high vertical conductivity exist elsewhere in the Nation, and with extended use of MTBE or other alkyl ether oxygenates, these aquifers may also demonstrate a high frequency of occurrence pattern similar to MTBE in Denver's alluvial aquifer. As explained elsewhere, the high frequency of detection of MTBE in Denver's shallow ground water can not be

Table 2.10: *Summary information for MTBE in ground water and in drinking water derived from ground water for the States surveyed.*

[MTBE, methyl *tert*-butyl ether. NK, not known]

	Numbe r of States	**Number of program s**	**Number of wells (w) or drinking-water systems (s) sampled**	**Number of States surveyed**	**Number of programs surveyed**	**Number of wells (w) or drinking-water systems with a detection of MTBE**	**Percent of wells (w) or drinking-water systems with a detection of MTBE**
				In which there was at least one detection of MTBE			
				Ground water			
Ground-water resource assessment	33	90	1,516 (w)[1]	14	25	76 (w)[1]	5 (w)
				Drinking water derived from ground water			
Public	7	8	NK[2]	6	7	NK[2]	NK[2]
Private	4	4	NK[2]	4	4	NK[2]	NK[2]

[1] Includes sampling of several springs.

[2] The total number of systems or wells sampled was not reported for each State.

explained by the inclusion of six existing wells that were installed upgradient of point-source releases to define the quality of ambient ground water (Squillace et al., 1996).

The samples from the deeper ground water that had detections of MTBE indicate that MTBE can reach deeper ground water. The occurrence of MTBE in these deeper wells does not in itself explain the mechanism for migration. Possible reasons for the detections of MTBE in deeper ground water include, for example, short, natural ground-water flow paths between recharge areas and deeper ground water, faulty well construction resulting in vertical movement of recently recharged ground water along the well bore to deeper ground water, use of dry wells to rapidly recharge storm-water runoff, or nearby pumping that induces recently recharged ground water to deeper ground water (see the section on "Environmental Behavior and Fate of Fuel Oxygenates" for discussion of the environmental behavior and fate of MTBE in ground water).

Detections for Only Those Programs Where MTBE was Found. Results of monitoring ground water for MTBE for those 25 programs that had at least one detection of MTBE are given in Appendix 5 and the number of detections and percent occurrence are summarized in Table 2.11. Concentrations of MTBE in all samples with concentrations at or above the reporting level used for the summaries in Table 2.11 are given in Appendix 6. In those programs in which there was at least one detection of MTBE (Table 2.11), detection of MTBE occurred in 14 percent (76 of 540) of the wells and only seven wells had concentrations of MTBE that exceeded 10 µg/L. Concentrations of MTBE were below the reporting level in 90 percent of the private and 92 percent of the public-supply wells. None of the samples from private and public-supply wells had concentrations that exceeded 10 µg/L. Detections of MTBE in concentrations in excess of 20 µg/L, the lower limit of the draft drinking-water lifetime health advisory range, occurred at only a small percentage of other types of wells (Table 2.11).

Drinking Water. USEPA does not have the authority to require monitoring or data reporting for MTBE, and consequently the data reported by State agencies was voluntary (Appendix 4). Also, the data reported only represents a fraction of the drinking-water programs in which MTBE has been sampled, and the level of detail of the information reported varies among the States. The reader must also be made aware that the data in Appendix 4 and summarized in Table 2.10 for drinking water may be biased. A number of the sampling programs were conducted when contamination from a nearby point source was known or suspected. For example, in the New Jersey Department of Health data set, where samples were collected in response to consumer complaints, 19 of 31 samples had detections. Three of the eight public water-system sampling programs listed in Appendix 4 are known to have been conducted in response to known or suspected contamination. Also, all private well-sampling programs in Appendix 4 are known to have been conducted in response to consumer complaints.

Because of the small size of the data set for drinking water available for this assessment (only a few programs in a total of nine States), the interpretation of MTBE occurrence is limited only to presence and absence in those States reporting data. It is not possible to describe MTBE occurrence nationwide in drinking water. These data do verify, however, previously published reports that MTBE has been detected in drinking water (Davidson,

Table 2.11: *Summary of non-detection and detection of MTBE for several ranges of concentrations for different types of wells sampled as part of ground-water assessment in programs that had at least one detection of MTBE.*

[MTBE, methyl *tert*-butyl ether. Number of detections (percent detections of total for each well type); RL, reporting level; μg/L, micrograms per liter]

Well type	Number of wells sampled	< RL[1]	>= RL to <10 μg/L	>= 10 to <20 μg/L	>= 20 to <=200 μg/L	> 200 μg/L
Monitoring/observation	170	128 (75)	38 (22)	0 (0)	2 (~1)	2 (~1)
Private	106	95 (90)	11 (10)	0 (0)	0 (0)	0 (0)
Public supply	25	23 (92)	2 (8)	0 (0)	0 (0)	0 (0)
Other/not known	239	218 (91)	18 (8)	1 (<1)	1 (<1)	1 (<1)
All well types	540	464 (86)	69 (13)	1(<1)	3 (<1)	3 (<1)

[1] RL is 0.2 μg/L with the exception of two programs (see appendix 5).

1995a, 1995b; New York State Department of Health and U.S. Department of Health and Human Services, 1995; Post, 1994; Squillace et al., 1995a, 1995b, 1996; USEPA, 1986, 1987a, 1987b).

Results of monitoring drinking water for MTBE for those programs in Appendix 4 that had at least one detection of MTBE are given in Table 2.12, separated into public supplies and private supplies. The MTBE concentration measured in the most recent sampling event was used for the compilations in this table for those public systems or private wells that have been sampled multiple times. The approach of comparing the number of detections to total number of samples was not used as it would have inappropriately combined samples from single sampling events with those of multiple sampling events.

Table 2.12 does not summarize the data provided by Rhode Island for public water systems or private wells and by Texas for private wells. This is because of the lack of information necessary to determine if the data represent multiple samples from a system or well, or single samples from a number of systems or wells.

MTBE was detected in 51 public drinking-water systems in Colorado, Iowa, Illinois, New Jersey, and Texas (Table 2.12). Nearly all of the systems, 47 of 51 (92 percent), with detections of MTBE were at concentrations less than 20 µg/L, the lower limit of the USEPA draft health advisory. Concentrations as high as 63 µg/L in Iowa and 770 µg/L in Illinois have been detected, however (Appendix 7). MTBE was detected in private wells in Indiana, Missouri (Table 2.12), Rhode Island, and Texas. MTBE in five of the six private wells reported from Indiana and Missouri exceeded 200 µg/L, and the concentration of MTBE in the 6th well was within the range of 20 to 200 µg/L. MTBE concentrations in the two private wells in Indiana were 5,400 and 40 µg/L. MTBE concentrations in the four private wells in Missouri, using the latest sampling date, were 1,900, 1,100, 780, and 1,500 µg/L (Appendix 7). It is known from the data provided in Appendix 7 that public drinking-water systems in Rhode Island and private wells in Rhode Island and Texas have had detections of MTBE. However, because the number of unique systems or wells sampled from these two States was not identified, these data could not be included in the analysis in Table 2.12.

Because only a few States have information on MTBE in drinking water, it is not possible in this preliminary assessment to describe MTBE concentrations in drinking water nationwide. A Federal drinking-water standard has not been established for MTBE, however, the USEPA has issued a draft lifetime health advisory of 20 to 200 µg/L. The health advisory is expected to be revised in 1997. MTBE has been detected in 51 public drinking-water systems to date based on limited monitoring, however, when detected, the concentration of MTBE was generally low and nearly always below the lower limit of the current draft USEPA health advisory. This indicates that the consumption of drinking water was not a major route of exposure for these few systems. Additional MTBE monitoring data for drinking water are needed, from both the States that provided information for this preliminary assessment and from States that were unable to provide said information, before the significance of drinking water as a route of exposure can be assessed for the Nation.

Table 2.12: *Occurrence and concentration ranges of MTBE in drinking water for those programs in which there was at least one detection of MTBE.*

[MTBE, methyl *tert*-butyl ether. NK, not known; µg/L, micrograms per liter]

State	Number of systems with detections[1]	Reporting level (µg/L)	Number of systems with detections of MTBE within indicated ranges of concentration			
			> reporting level to 10 µg/L	>=10 to <20 µg/L	>=20 to <=200 µg/L	>200 µg/L
Public water systems						
New Jersey	35	NK	34	1	0	0
Iowa	1	NK	0	1	0	0
Illinois	7	NK	3	1	2	1
Texas	7	NK	5	1	1	0
Colorado	1	0.2	1	0	0	0
Private wells						
Missouri	4	NK	0	0	0	4
Indiana	2	NK	0	0	1	1

[1] When multiple detections were reported for a single system or well, the most recent sample was used in this compilation. This table only includes those States where the number of unique public water systems or private wells could be identified. Public water-system data from the State of Rhode Island are not presented in this table, but Appendix 7 indicates MTBE has occurred in at least one public water system. Private well data for the States of Texas and Rhode Island are also not presented in this table, but Appendix 7 indicates MTBE has occurred in at least one private well in each State.

Occurrence and Variability of MTBE In Ground Water Over Time. An important issue relative to MTBE and other fuel oxygenates that remains unanswered is whether or not the frequency of detection and concentrations of these compounds in ground water will increase, remain constant, or decrease with time. This section focuses on existing monitoring data that provide an indication of temporal changes that may occur in wells in which MTBE has been detected. While the environmental behavior and fate of oxygenates in the subsurface is addressed later in this chapter, it is important to note that relative to the BTEX compounds, MTBE and other alkyl ether oxygenates are significantly less degradable.

Despite the extensive literature on UST releases and their impacts on ground water, case studies of the impacts on ground water over time of gasoline containing oxygenates are quite limited. When the source of MTBE in ground water is from a gasoline release, it is expected that the mass of residual gasoline at the water table or in the soil will remain a continuous source for years or possibly decades, depending on the size of the release and remedial efforts to remove the source. A recent study in North Carolina (Daniel, 1995) provides monitoring data for shallow ground water for 11 sampling events over a 26-month period (1/93 - 4/95) at a site where a small gasoline UST had been removed in 1990. Approximately 70 cubic meters of contaminated soil were also removed at that time, but some residual contamination remained present in the area of the water table. Multiple observation wells show consistent concentrations of MTBE over the entire sampling interval. For example, a well close to the area directly affected by the UST had concentrations that varied between 1,200 to 6,800 µg/L (well #3), and a well further downgradient (#17) had concentrations from 66 to 320 µg/L during that same period. Both wells also had measurable concentrations of BTEX from the release. No drinking-water wells were impacted at this site.

Figure 2.4 provides a detailed example of UST impacts on private water-supply wells, in this case MTBE concentrations in three private wells in Missouri, close to a UST that had released gasoline to a fractured bedrock aquifer. Although the tank had been removed before the sampling period shown, residual gasoline remained at or below the water table. Consistent detections of MTBE occurred in the three wells throughout the approximately 3-year periods of sampling, although concentrations and temporal variability differ among the three wells, especially well 3 (Figure 2.4). The range of MTBE concentrations reported was 700 to 14,000 µg/L, 510 to 17,000 µg/L, and 13 to 2,600 µg/L for wells 1, 2, and 3, respectively. These examples show that MTBE can remain at detectable levels near the source for years, although concentrations might vary by as much as several orders of magnitude during that time. The State of Connecticut has collected monitoring data over several years for its public water supplies and private wells. They have indicated that they are aware of multiple instances where MTBE continues to be detected, but that the data are not readily accessible, and were not included in this assessment.

Data characterizing MTBE and DIPE contamination of a New Jersey municipal water supply are presented in McKinnon and Dyksen (1984). The MTBE data reported in this reference are the earliest documentation of detections of MTBE in ground water found by the panel. McKinnon and Dyksen report that more than 25 water samples were collected

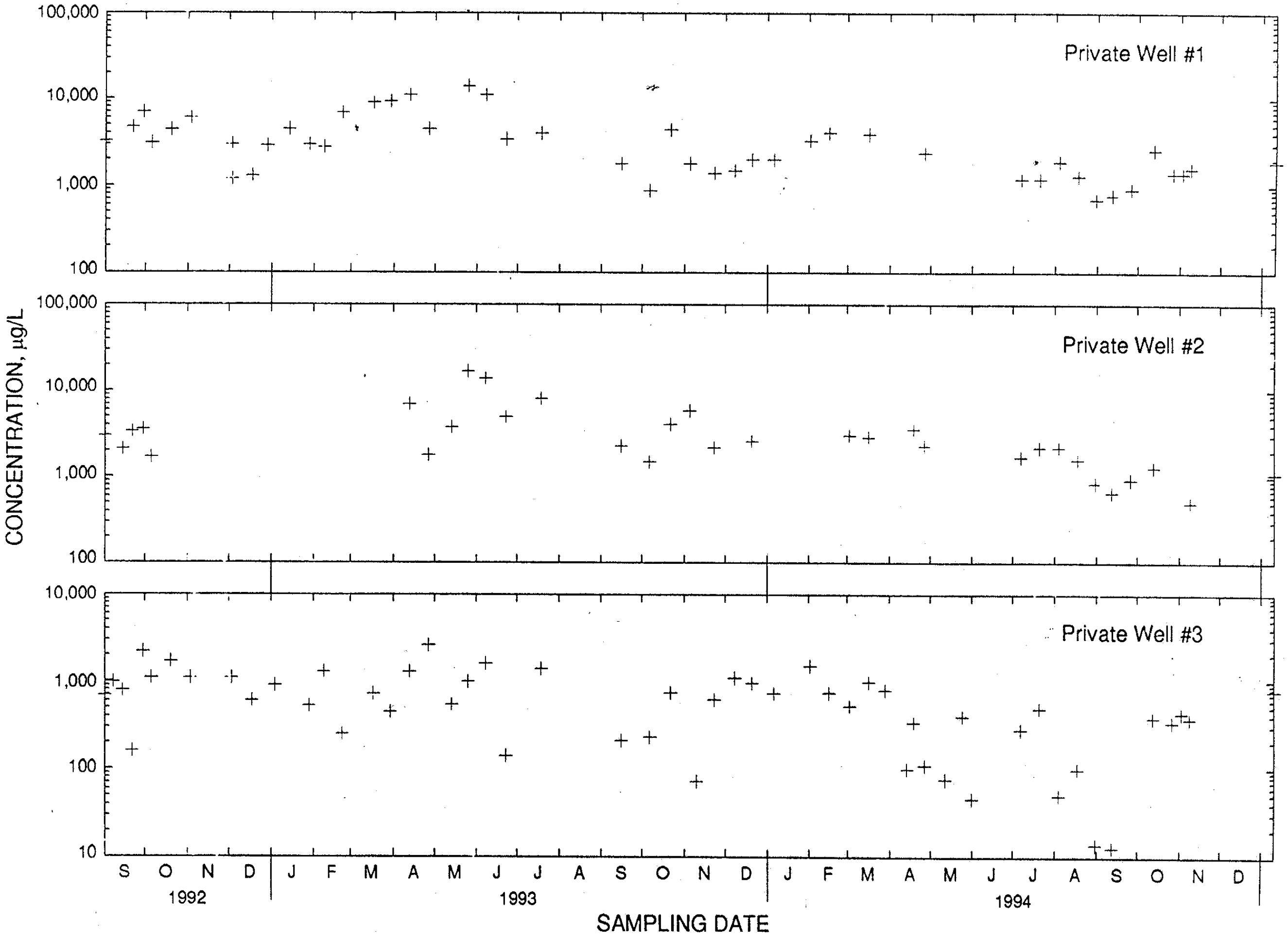

Figure 2.4. Temporal variation of the concentration of MTBE in three private wells in Missouri, 1992-95, which were contaminated by an underground storage tank.

from one well over a 29-month period from November 1980 to April 1983. DIPE concentrations in October 1980 ranged from 70 to 100 µg/L but decreased to below the detection limit by January 1983. MTBE concentrations ranged from 25 to 40 µg/L in October 1980 and declined to less than 10 µg/L by January 1983.

Limited temporal data on MTBE also were obtained for public-supply wells in Iowa, Illinois, and New Jersey. For these systems, MTBE concentration data are available for a sampling period of less than one year (Appendix 7). It is expected that regular monitoring of MTBE concentrations will continue at these facilities, and will provide further characterization of temporal changes.

A short-term data set that demonstrates continued areally extensive occurrence of MTBE in ground water, and its variability over time, is from an areally distributed network of 14 shallow urban wells sampled twice as part of the NAWQA Program in Denver, CO. These fourteen wells were sampled in July 1993 and in August 1995 (Table 2.13).

In the July 1993 sampling, 13 of the 14 shallow urban wells had detections of MTBE, ranging in concentration from 0.2 to 23,000 µg/L. In one well, MTBE was not detected above the reporting level of 0.2 µg/L. In the August 1995 sampling, MTBE was not detected above the same reporting level in three wells. Concentrations of MTBE ranged from 0.2 to 4,940 µg/L for the other 11 wells. MTBE was re-detected in August 1995 in 11 of the 13 wells in which it was detected in July 1993. Thus, the frequency of detection of MTBE did not change markedly. Also, for the 11 wells in which MTBE was detected during both sampling events, the concentration of MTBE decreased in six wells, remained the same in one well, and increased in four wells. Therefore, the number of wells in which concentrations increased over time was about equal to the number of wells in which concentrations decreased. Finally, changes in concentrations of at least one order of magnitude occurred in several wells between sampling events, with concentrations increasing in some of the wells and decreasing in other wells (Table 2.13). However, the median concentration of MTBE in all wells with concentrations above the reporting level remained essentially the same: 1.4 µg/L in July 1993 and 1.1 µg/L in August 1995. It is not known if all of the differences in concentration of MTBE at each well between the two sampling dates represent actual increases or decreases in concentration of MTBE in ground water at the screened interval. Some of the difference could be attributable to other factors; for example, difficulty in obtaining representative samples.

MTBE in Drinking Water Derived from Surface Water

In addition to the information provided by States on MTBE occurrence in drinking water derived from ground water, Wisconsin and Rhode Island provided data on drinking water derived from surface water. In Wisconsin, sampling was conducted during April 1995 at two drinking-water systems with surface-water sources. MTBE was not detected in either system (Appendix 4). In Rhode Island, an unknown number of surface-water samples have been analyzed for MTBE, and one detection of MTBE occurred at a system that used surface water as a source. The detection occurred in a sample collected in January 1994, and the concentration of MTBE was 1 µg/L (Appendix 7).

Table 2.13: *Concentration of MTBE in wells sampled in July 1993 and in August 1995 as part of the NAWQA Program in Denver, Colo.*

[MTBE, methyl *tert*-butyl ether. μg/L, micrograms per liter]

Well number	MTBE concentration measured in July 1993, in μg/L	MTBE concentration measured in August 1995, in μg/L
2	5.1	554
3	0.7	<0.2
4	0.2	3.6
5	3.5	3.7
7	1.4	0.2
15	<0.2	<0.2
16	0.3	0.3
17	1.3	0.7
19	800	70
20	33	<0.2
22	0.5	0.2
24	0.4	1.1
29	3.2	0.4
30	23,000	4,940

Significance of Measured Levels of MTBE for Drinking Water and Aquatic Life

The use of MTBE as an oxygenate and octane enhancer in gasoline has resulted in the compounds occurrence in the hydrologic cycle. This has been demonstrated for air, storm water, and ground water. Oxygenates with similar physical and chemical properties also would be highly mobile and potentially could be found in drinking-water supplies and affect aquatic life. The ease with which these chemicals move through the hydrologic cycle is of concern to some officials who are responsible for public and environmental health. The effect that MTBE and other alkyl ether oxygenates may have is difficult to ascertain because: (1) uncertainty exists about the carcinogenicity of these chemicals; (2) no data exist on the chronic effects that oxygenates may have when aquatic organisms are exposed to small concentrations; (3) few aquatic animals and plants have been tested for acute toxicity; (4) no data exist on synergistic effects of oxygenates with other chemicals that may co-occur; and (5) more data are needed on the sources, spatial distribution, pathways, and trends of concentrations in the environment. These and other unknowns have lead to established and proposed regulatory levels for MTBE in drinking water, for example, that vary from 20 to 230 µg/L (see Figure 2.2).

Existing data on the concentration on MTBE, described in the section on "MTBE in Ground Water and in Drinking Water Derived from Ground Water," indicate that drinking water supplied from ground water is a potential route for humans to be exposed to this chemical. Nearly all concentrations of MTBE measured in drinking-water systems to date were below 20 µg/L, the lower limit of USEPA's current draft lifetime health advisory, and below taste and odor thresholds. This indicates that the consumption of drinking water was not a major route of exposure for these few systems. The use of MTBE, however, has increased dramatically over the past 10 years. The continued increasing use of this oxygenate could increase its occurrence and spatial distribution in ground water, and thereby affect the occurrence and possibly the concentration of MTBE in drinking water derived from ground water.

As noted in the section, "*Drinking Water*," it is not possible to describe MTBE's occurrence in drinking water nationwide from available information. Although nearly all detections in public water-supply systems to date have been below the USEPA draft health advisory, the widespread use of MTBE, the past releases of gasoline from USTs and ASTs, and some instances of impact to drinking water wells, give reason for concern and provide the rationale for a comprehensive national assessment. The USEPA has completed similar assessments previously for other VOCs. Examples include the National Organics Reconnaissance Survey, 1975; the National Organics Monitoring Survey, 1976-77; the Community Water Supply Survey, 1978; the Rural Well Survey, 1978; and the Ground Water Supply Survey, 1981-82 (Pankow and Cherry, 1996). Additional MTBE monitoring data for drinking water are needed, from both the States which provided information for this preliminary assessment and from States that were unable to provide said information, before the significance of drinking water as a route of exposure can be assessed for the Nation.

Very little is known about the concentration of MTBE in surface water, except for the chemical's occurrence in urban storm water. As described previously, MTBE was detected at low concentrations in 40 percent of storm-water samples in the winter in three cities where MTBE was being used in oxygenated gasoline. MTBE was detected in storm water in five additional cities where the oxygenate was presumedly added as an octane enhancer. This illustrates that MTBE enters surface waters, at least during periods of overland runoff and storm-water discharge, and could be a pathway for MTBE to enter drinking-water supplies and ground water. The persistence of MTBE in surface water depends on the waters' velocity, depth, and temperature, and a wide range of half-lives may occur (see Tables 2.16 and 2.17). For deeper rivers, the predicted half-life of MTBE can be several days to three months (see the section on "Surface Waters and Storm Runoff"), which increases the exposure of MTBE to aquatic organisms and the potential for surface water with MTBE to infiltrate into aquifers. Because of the lack of adequate monitoring data and aquatic toxicity data, the significance of low levels of MTBE on drinking water provided from surface water and on aquatic life cannot be assessed.

ENVIRONMENTAL BEHAVIOR AND FATE OF FUEL OXYGENATES

This section relates the environmental behavior and fate of the fuel oxygenate compounds to their physical and chemical properties. It discusses: (1) the migration and partitioning characteristics of the fuel oxygenates; (2) their expected behavior in the ambient hydrologic cycle; (3) their biotic and abiotic degradation; and (4) their possible remediation at point-source release sites. Where appropriate, the properties of the oxygenates are contrasted with those of the BTEX compounds, because the latter are the most toxic compounds typically associated with conventional gasoline. Physical and chemical data for the compounds considered are presented in Tables 2.14 and 2.15. Information in these tables demonstrate that, relative to the BTEX compounds, the oxygenates are more water soluble and sorbed less strongly. Therefore, unless they undergo degradation, oxygenates will be transported with ground-water flow without significant retardation in the subsurface (Cline et al., 1991; Yeh and Novak, 1995). Multiple entries are given for some properties listed in Tables 2.14 and 2.15. This was done to illustrate the range of reported values, and to acknowledge that "best values" were not determined by the authors of this chapter.

Partitioning Between Environmental Compartments

The environment is comprised of a number of different compartments including water, soil, and air. The ways in which the different fuel oxygenate compounds behave in the environment is determined by how they distribute themselves among the different possible compartments. The behavior of an oxygenate compound in water is affected by its: (1) water solubility from gasoline; (2) partitioning between air and water, as occurs in the atmosphere during precipitation events and also in soil above the water table[3]; and (3) partitioning between water and soil materials. Each of these subjects is discussed below.

Solubility in Water from Gasoline. At a given temperature, the solubility of a pure organic liquid (e.g., benzene or MTBE) in water is a constant, represented here as c_s^0 (mg/L). The solubility of a compound from a mixture (i.e., gasoline) will be reduced from c_s^0 by the factor X_m, which is the fraction of the compound in the mixture on a mole-for-mole basis. An additional coefficient γ is needed when the chemical properties of the compound differ significantly from the properties of the mixture as a whole. The result is that the equilibrium water solubility of the compound from the mixture will be given by:

(1) $c_s(mg/L) = \gamma X_m c_s^0$ (all compounds)

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[3] Although it is not as important a process for the behavior of the fuel oxygenates in the water environment, vaporization from liquid gasoline to air can also affect the formation of vapor plumes in soil gas since vapor plumes can contaminate infiltrating water. It is therefore useful to point out that vaporization from gasoline is governed by relationships that are analogous with those presented here for solubility. For any compound of interest, these analogous relationships are obtained by substituting the partial pressure in the soil-gas phase and the pure compound vapor pressure for the solubility from the gasoline mixture and the pure compound solubility, respectively.

Table 2.14: *Reported chemical and physical properties of oxygenates and their degradation products.*

[Values are at 25°C unless otherwise stated. The ranges are from one reference and multiple listings are from multiple sources. Values in bold are values used in the narrative text. MeOH, methanol; EtOH, ethanol; TBA, *tert*-butyl alcohol; MTBE, methyl *tert*-butyl ether; ETBE, ethyl *tert*-butyl ether; TAME, *tert*-amyl methyl ether; DIPE, diisopropyl ether; TBF, *tert*-butyl formate. Sources: Budavari, 1989; Chiou *et al.*, 1979; Flick, 1991; Howard, 1990-93, 1991; Lide, 1994; Lyman *et al.*, 1990a, 1990b; Mackay *et al.*, 1991-93; McAuliffe, 1966; Montgomery and Welkom, 1990; Owen and Coley, 1990; Robbins *et al.*, 1993; Yeh, 1992]

Property	MeOH	EtOH	TBA	MTBE	ETBE	TAME	DIPE	TBF
Molecular weight (g/mole)	32.04	46.07	74.12	88.15	102.18	102.18	102.18	102.13
Specific gravity	0.796	0.794	0.791	0.744	0.73	0.77	0.736-0.7491	0.886
Boiling temp., °C	64.7	78-79	82.9	53.6-55.2	67	86	91 68-69	82
Water solubility, ($Cs_{(o)}$), mg/L	infinitely soluble	infinitely soluble	infinitely soluble	43,000-54,300 **50,000**	~26,000	~20,000	9,000 @ 20°C 2,039	~40,000
Vapor pressure @ 25°C, mm Hg	121.58	49-56.5	40-42	245-256	152	68.3	149-151@ 20°C	81@20°C
Log K_{ow}	-0.75	-0.16 -0.31	0.35	1.20	1.74		1.52	
Henry's Law constant, (H), (atm-m^3)/(g-mole)	4.42E-06	6.17E-6 5.13E-6 6.29E-6	1.175E-5 1.19E-5 1.04E-5 1.47E-5	5.87E-4 1.1E-3 1.4E-3 3E-3	2.66E-3	1.27E-3	9.97E-3 4.77E-3 5.87E-3	2.72E-4
Dimensionless Henry's Law constant (H/RT)	1.087E-4	2.522E-4 2.097E-4 2.571E-4	4.803E-4 4.864E-4 4.251E-4 5.927E-4 **4.8E-4**	2.399E-2 4.496E-2 5.722E-2 1.226E-1 2.6E-2 **0.018 @ 20°C**	1.087E-1	5.191E-2	4.075E-1 1.95E-1 2.399E-1	1.111E-2
Log Koc	0.921 0.44	1.21 0.20	1.57	1.091 1.035 1.049	2.2 0.95	2.2 1.27	1.82 1.46	1.11
CAS no.	67-56-1	64-17-5	75-65-0	1634-04-4	637-92-3	994-05-8	108-20-3	762-75-4

Table 2.15: *Reported chemical and physical properties of gasoline and BTEX compounds.*

[Values are at 25°C unless otherwise stated. The ranges are from one reference and multiple listings are from multiple sources. Values in bold are values used in the narrative text. Sources: Flick, 1991; Howard, 1990-93; Lide, 1994; Lyman *et al.*, 1990a, 1990b; Mackay *et al.*, 1991-93]

Property	Gasoline	Benzene	Toluene	Ethylbenzene	m-Xylene	o-Xylene	p-Xylene
Molecular weight (g/mole)	~100	78.11	92.13	106.16	106.16	106.16	106.17
Specific gravity	0.72-0.78	0.88 0.8765	0.8669	0.867	0.8842	0.8802	0.8611
Boiling temp., ˚C	27-225	80.1	110.6	136.25	139.3	144.4	137-138
Water solubility, ($C_{s(o)}$), mg/L	100-200	1,780	534.8	161	146	175	156
Vapor pressure @ 25˚C, mm Hg		76 95.19	28.4	9.53	8.3	6.6	8.7
Log K_{ow}		2.13 1.56-2.15	2.73 2.11-2.80	3.15	3.20	3.12 2.77-3.12	3.15 3.08-3.29
Henry's Law Constant, (H), (atm-m^3)/(g-mole)		5.43E-3	5.94E-3	8.44E-3	7.68E-3	5.1E-3	7.68E-3
Dimensionless Henry's Law Constant (H/RT)		2.219E-1 **0.22**	2.428E-1	3.45E-1	3.139E-1	2.084E-1	3.139E-1
Log K_{oc}		1.8-1.99 1.50-2.16 **$K_{oc} \cong 80$**	1.56-2.25	2.94 1.98-3.04	2.20 2.04-3.15 **$K_{oc} \cong 160$**	1.68-1.83	2.31 2.05-3.08
CAS no.		71-43-2	108-88-3	100-41-4	108-38-3	95-47-6	106-42-3

For a compound that has a molecular weight that is similar to the mean molecular weight of gasoline (~100 g/mol), X_m is closely approximated as the fraction of the compound on either a weight or volume basis. For example, for a gasoline that is 10 percent by weight MTBE, X_m for MTBE will be ~0.10. For the dissolution of low polarity compounds (like the BTEX group) from gasoline, γ will be close to 1 and equation 1 can then be approximated as:

(2) $c_s(mg/L)=X_m c_s^0$ (low polarity compounds)

The above equation assumes that dissolution is taking place into a water phase in which there are not large amounts of alcohols or other possible cosolvents that could increase the value of c_s^o. Since c_s^o values tend to decrease as the temperature decreases, predicted c_s values will also decrease as the temperature decreases.

Equilibrium solubility data obtained by Barker et al. (1991) indicate that equation 2 is also valid for the dissolution of the alkyl ether oxygenates from gasoline; for MTBE, their data indicate that $\gamma = 1.1$. For the alcohol oxygenates like TBA and EtOH, however, γ values will be significantly larger than one.

MTBE's high water solubility and its high concentration in an MTBE-oxygenated gasoline can result in high concentrations in water. For example, MTBE in a gasoline that is 10 percent (w/w) MTBE, has a solubility in water of approximately 5,000 mg/L at room temperature. By comparison, the total hydrocarbon water solubility for a non-oxygenated fuel is typically about 120 mg/L (Poulsen et al., 1992).

High concentrations of MTBE in ground water near gasoline-spill sites are consistent with experimental water-solubility data. Garrett et al. (1986) and Davidson (1995a) have observed MTBE concentrations as high as 200 mg/L. While these values are not as high (e.g. thousands of mg/L) as might be expected for water equilibrated with gasoline containing several percent MTBE, it is common for relatively uncontaminated water to dilute organic compounds to concentrations below what would be calculated with equation 2 (Feenstra et al., 1996). Also, lower levels in water can result because of depletion of MTBE in the gasoline by the dissolution process itself.

Cosolvent Effects. The high concentrations of fuel oxygenates that can occur in ground water at spill sites have raised the question as to whether or not they could enhance the subsurface transport velocities of the BTEX group through a "cosolvency effect." In fact, research has shown that cosolvency effects typically arise only when the cosolvent is present in water at 1 percent (10,000 mg/L) or more by volume (Pinal et al., 1990, 1991). Such concentrations are much higher than will typically be encountered in water in equilibrium with gasolines containing alkyl ether oxygenates. Gasoline that contains 15 percent MTBE by volume, when equilibrated with water, results in no more than 7,500 mg/L (~0.75% by volume) of MTBE in the water (Barker et al., 1991).

These conclusions regarding the potential for cosolvent effects are supported by laboratory research that employed gasoline to water ratios of 1:10 (v/v). No cosolvency effect was noted for gasolines containing any of the following: 15 percent MTBE, 10 percent EtOH, 10 percent TAME, and 10 percent isopropyl alcohol (Barker et al., 1991; Poulsen et al., 1992). In experiments with MeOH, no cosolvency effect was noted until the MeOH concentrations exceeded 8 percent by volume. As the aqueous concentration of MeOH increased from 8 to 50 percent, the aqueous BTEX solubility continued to increase as well (Barker et al., 1991; Horan and Brown, 1995; Poulsen et al., 1992).

Air/Water Partitioning. Air/water partitioning for a compound is described by its Henry's Law constant H which gives the ratio of the partial pressure of the compound in the gas phase to the concentration in the water that is at equilibrium with that partial pressure. Typical units for H are atm/(mol/m^3), or equivalently atm-m^3/mol.

When H is divided by the product of the gas constant R (8.2×10^{-5} atm-m^3/mol-K) and the temperature T (degrees K), the resulting H/RT value is referred to as the dimensionless Henry's Law constant. H/RT gives the ratio of the air to water concentrations at equilibrium, that is:

$$H/RT = \frac{\text{concentration in air}}{\text{concentration in water}} \tag{3}$$

A compound with a value of H/RT of 0.05 or larger will be very volatile from water. A compound with a low value of H/RT will tend to remain in the water phase, or viewed from another perspective, it will tend to partition strongly from the gas phase into the water phase if contaminated air is brought into contact with clean water.

At 25 °C, the H/RT values for MTBE and TBA are 0.026 and 0.00048, respectively. Other alkyl ether oxygenates exhibit H/RT values that are similar to that of MTBE. These values are the reason why the fuel oxygenates exhibit significant partitioning into water (e.g., into precipitation falling through the atmosphere, see the section on "*Air and Precipitation*"). These values also explain why MTBE and the other alkyl ether oxygenates are somewhat difficult to remove from water by aeration, and why TBA is exceedingly difficult to remove from water by aeration. In contrast, benzene exhibits an H/RT value of 0.22 at 25°C, making it rather volatile from water, as compared to the fuel oxygenates.

Water/Soil Partitioning. When a nonionic organic compound is dissolved in ground water and that ground water is moving in a porous subsurface medium, a primary factor determining the velocity of the compound relative to the ground-water velocity is the soil/water partition coefficient, K_d. The value of K_d gives the ratio of the concentration in/on the soil (in grams sorbed per gram of soil) to the concentration in water (in grams per mL).

The ratio of the water velocity to the velocity at which the compound is being transported is frequently referred to as the "retardation factor," R. A compound that is not retarded at all will move with the same velocity as the water, and so it exhibits an R value of 1. A compound that moves at one-half the velocity of the ground water exhibits an R value of 2. In porous media, R values can be calculated using the equation:

(4) $$R = 1 + \frac{\rho_b K_d}{n}$$

where ρ_b is the bulk density of the soil or aquifer material, and n is the porosity.

For nonionic compounds, K_d values are often estimated using the equation:

(5) $$K_d = f_{oc} K_{oc}$$

where f_{oc} is the weight fraction of the soil/aquifer material that is organic carbon, and K_{oc} is the organic-carbon-based partition coefficient. While the K_{oc} values of the BTEX compounds are not large enough to cause highly retarded transport (K_{oc} ~80 and ~160 for benzene and *m*-xylene, respectively), the K_{oc} values for the fuel oxygenates are even lower (K_{oc} ~11 and ~29 for MTBE and DIPE, respectively). Thus, under most circumstances, the fuel oxygenates will move at velocities that are similar to that of the local ground water (i.e., with R values fairly close to 1).

As an example, for a subsurface porous medium in which $f_{oc} = 0.005$ (0.5% by weight organic carbon), the predicted K_d values for benzene, *m*-xylene, MTBE, and DIPE will be 0.40, 0.80, 0.055, and 0.15, respectively. The corresponding R values will be about 2.9, 4.9, 1.3, and 1.7, respectively. Results exhibiting this pattern of relative mobilities have been observed in the field. In an injection study in the Borden aquifer conducted by Hubbard et al. (1994), benzene, ethylbenzene, and xylene were all slightly retarded (R = 1.1, 1.5, and 1.5, respectively). In contrast, MTBE movement was not retarded ($R = 1.0$). These results are in reasonable agreement with what would have been predicted based on the organic carbon content of the Borden aquifer ($f_{oc} \sim 0.0002$), namely R = 1.1, 1.8, and 1.2 for benzene, ethylbenzene, and the xylenes, respectively, and $R = 1.01$ for MTBE. Field data from actual spills have also demonstrated that MTBE migrates more rapidly than the BTEX compounds (Daniel, 1995; Davidson, 1995a).

Given the greater mobilities of the fuel oxygenates relative to the BTEX compounds, one can expect that the leading edge of a plume from an MTBE-oxygenated gasoline spill can contain significant levels of MTBE with very little or no BTEX contamination. This effect will be further amplified by the greater biodegradabilities of the BTEX compounds as compared to the alkyl ether oxygenates (see the section on “Biodegradation in the Environment”). In the ambient hydrologic cycle, for typical ground-water depths, the generally non-retarded movement of the alkyl ether oxygenates through the unsaturated zone can lead to the arrival at the water table of ambient levels of MTBE in precipitation within 5 to 10 years (see the section on “Ground Water”).

Behavior in the Ambient Hydrologic Cycle

Air and Precipitation. Similar to other VOCs in gasoline, the production, transport, and use of MTBE and other fuel oxygenates inevitably leads to the release of these compounds to the atmosphere. For example, releases to the atmosphere will occur due to vehicle refueling, evaporative emissions, and incomplete combustion. Once in the atmosphere, the compounds can be removed by chemical degradation and to a much lesser extent by precipitation.

Degradation in the Atmosphere. A limited amount of work has been conducted investigating the atmospheric lifetimes of selected fuel oxygenates. Wallington et al. (1988) and Tuazon et al. (1991) believe that it is reaction with hydroxyl radical (HO•) that is the main determining factor affecting the atmospheric fate of these compounds. For example, Wallington et al. (1988) point out that photolysis (Calvert and Pitts, 1966), reaction with ozone (Atkinson and Carter, 1984), and reaction with NO_3 radicals (Wallington et al., 1986, 1987) are all negligibly slow for ethers and alcohols like MTBE and TBA.

Wallington et al. (1988) studied the rate of reaction of both MTBE and TBA with HO• at 25 ° C. The main by-product of MTBE degradation is *tert* -butyl formate. Based on the values of the rate constants measured in that study and an average tropospheric HO• concentration of 10^6 radicals/cm^3, Wallington et al. (1988) predicted atmospheric lifetimes of about 4 and 11 days for MTBE and TBA, respectively[4]. These are much shorter lifetimes than result from partitioning to precipitation (see the section on "Partitioning to Precipitation"). The conclusions of Wallington et al. (1988) for MTBE were confirmed in a separate study by Smith et al. (1991). The lifetimes noted above apply to regional airsheds, in which the HO• concentration will approximate the 10^6 radicals/cm^3 value assumed by Wallington et al. (1988).

For DIPE, Wallington et al. (1993) found that the reactivity of this compound is higher than that of MTBE, ETBE, MeOH, and TBA. The primary by-products are isopropyl acetate and formaldehyde. If DIPE receives widespread use as a fuel oxygenate in the future, the implications of increased atmospheric levels of these two by-products in the atmosphere would need investigation.

Partitioning to Precipitation. Like other VOCs in the atmosphere, MTBE and other fuel oxygenates will tend to partition into atmospheric water, including precipitation. As discussed in "*Air/Water Partitioning*," the pertinent equilibrium constant for this partitioning is the Henry's Law constant H, or alternatively the dimensionless Henry's Law constant H/RT. Table 2.14 gives H and H/RT values for MTBE and other fuel oxygenates.

For the organic compounds of interest here, current knowledge indicates that partitioning equilibrium can be expected between precipitation arriving at ground surface and the concurrent atmospheric concentrations, also at ground surface (Slinn et al., 1978). A fall distance of only about 10 m (meters) is required to achieve partitioning equilibrium. This means that the assumption of a gas-phase concentration at the surface can be used to predict the corresponding concentration in the precipitation arriving at the surface. As a result, when concentrations immediately surrounding local sources are high when

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[4] Lifetime and half-life are not synonymous terms. Lifetime values can be converted to half-life values by multiplying the lifetime value by the natural logarithm of 2. For example, the atmospheric lifetime for MTBE of about 4 days is equivalent to a half-life of about 2.8 days.

averaged over timeframes of months to years, then rainfall passing through those concentrations may be expected to be similarly elevated. Conversely, a measured precipitation concentration can be used to calculate a corresponding atmospheric gas-phase concentration. For such calculations, the temperature dependence exhibited by *H* and *H/RT* for all compounds must be considered.

For an alkyl ether oxygenate like MTBE, falling precipitation will remove (i.e., wash out) only a negligible amount of the gas- phase compound. This may be shown as follows. Since *H/RT* is the air/water concentration ratio, the air/water mass ratio is obtained by multiplying *H/RT* by the air/water volume ratio:

$$(6) \quad \frac{mass\ in\ air}{mass\ in\ water} = H/RT \times \frac{volume\ \ of\ air}{volume\ \ of\ water}$$

For a 1-m^2 (meter squared) area at ground surface and a tropospheric mixing height of 1,000 m, the air volume is 1,000 m^3 (cubic meter). For a precipitation event of 0.025 m (1 inch), the water volume is 0.025 m^3. At 20 °C, H/RT for MTBE is 0.018. Thus, the air/water mass ratio for the single event will be 0.018 x (1,000/0.025) = 720. Only one part in 720 (0.14%) will be removed by the precipitation event. Similar calculations can be made for the other fuel oxygenates.

Based on the above discussion, we conclude that even multiple precipitation events will not provide an important loss conduit for fuel oxygenates from the atmosphere. However, even when little net loss occurs from the atmosphere, it may nevertheless be important as a source since natural waters have not, of course, historically contained the fuel oxygenates. What concentrations are typical for the fuel oxygenates in airsheds and around local sources then becomes the most important issue determining the strength of the atmosphere as a source of these compounds to surface water and ground water.

Surface Waters and Storm Runoff. MTBE and other fuel oxygenates will enter surface waters when water (e.g., urban storm-water runoff or ground water) containing these compounds become surface water. Direct spills of gasoline and the pure oxygenates themselves to surface water are also possible. Concentrations of MTBE that have been found in storm-water runoff were described previously and are summarized in Tables 2.8 and 2.9.

Many variables will affect the occurrence and concentrations of fuel oxygenates in storm water, as well as those in streams and rivers. These variables include fuel-use patterns, weather, unpredicted spill events, and so forth. Comments can, nevertheless, be made concerning the length of time that would be required for fuel oxygenate compounds to be lost by volatilization from flowing surface water, be it a stream, river, or storm-water channel.

Volatilization from flowing water is affected by the rate of mass transport from the bulk water to the air/water interface, and by the rate of mass transport from the air/water interface up into the bulk air (Rathbun, 1990). The inherent volatility of the compound from water as measured by the dimensionless Henry's Law constant also plays a role, as does the temperature. High compound volatility tends to favor dominance of the volatilization process by the transport through the water phase and losses then occur readily at the air/water interface. This condition leads to: (1) rate-determining concentration gradients in the water phase; and (2) volatilization rates which do not depend on compound volatility (e.g., MTBE and benzene can volatilize to the atmosphere at essentially the same rate). Three factors affect the water-side transport process: the water velocity, the water depth, and the temperature. Two factors affect the air-side transport: the wind speed and the temperature.

Using methods outlined by Schwarzenbach et al. (1993), it is possible to carry out calculations yielding the half-life ($t_{1/2}$) values for MTBE, TBA, and benzene from flowing surface waters to a clean atmosphere as a function of water velocity and water depth. Biodegradation of the compounds is not included in the analysis, and the air to which volatilization is occurring is assumed to have negligible amounts of MTBE, TBA, and benzene. Table 2.16 gives results for MTBE at a winter temperature of 5 °C under calm air conditions[5]. For very deep, slow-moving rivers or lakes, the half-lives can be significant [e.g., $t_{1/2}$ = 52 days or 450 km (kilometers) of travel distance for a depth of 10 m and a velocity of 0.1 m/s (meter per second). MTBE entering a river under such conditions will largely remain in the water for months. Corresponding calculations for a summer temperature of 25 °C are given in Table 2-17. For any half-life of about 1 day or greater at 5 °C (Table 2.16), increasing to a summer temperature of 25 °C reduces the half-life as found in Table 2.17 by a factor of about 3. Somewhat greater reductions are predicted for very short half-life conditions as occur in fast-moving, shallow streams and urban-runoff channels. The alkyl ether oxygenates ETBE, TAME, and DIPE can be expected to behave very much like MTBE as described in these two tables. Calculations

Table 2.16: *Estimated half-life of MTBE in a stream or river under calm air conditions at 5 °C.*

[MTBE, methyl *tert*-butyl ether]

Water depth (meters)	Half-life (days) for the following water velocities, meters/second				
	0.032	0.1	0.32	1.0	3.2
0.1	0.17	0.14	0.12	0.11	0.10
0.32	0.72	0.54	0.43	0.37	0.34
1.0	3.3	2.3	1.7	1.4	1.2
3.2	16	11	7.2	5.4	4.3
10	85	52	35	23	17

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[5] The rate of volatilization of MTBE (and other alkyl ether oxygenates) described above and characterized in tables 2.16 and 2.17 will be reduced when the overlying atmosphere contains significant concentrations of the oxygenate. In contrast, biodegradation will reduce the half-life values, however, no information is known to exist on the biodegradation of MTBE in surface water.

for windy conditions yield results that are similar to the results for calm conditions. This is due to the dominance of the mass transport by liquid-side transport for all but the shallowest, fastest moving streams.

Predicted half-lives for benzene are very similar to those for MTBE, with the higher volatility of benzene from water causing the benzene $t_{1/2}$ values to be a little shorter than those for MTBE. For the alcohol TBA, the low *H/RT* value of this compound causes its half-lives to be increased by about 50 percent as compared to MTBE[6].

Table 2.17: *Estimated half-life of MTBE in a stream or river under calm air conditions at 25 °C.*

[MTBE, methyl *tert*-butyl ether]

Water depth (meters)	Half-life (days) for the following water velocities, meters/second				
	0.032	**0.1**	**0.32**	**1.0**	**3.2**
0.1	0.063	0.042	0.031	0.024	0.021
0.32	0.32	0.20	0.13	0.10	0.077
1.0	1.7	1.0	0.63	0.42	0.31
3.2	8.9	5.2	3.2	2.0	1.3
10	49	28	16	10	6.3

Ground Water. As noted previously, there are two source types for the entry of fuel oxygenates into the subsurface: point sources and non-point sources. For the latter, which are the focus here, one needs to consider the movement of fuel oxygenates from the atmosphere through the unsaturated zone[7] and into the ground-water zone by infiltration and diffusion.

Infiltration will be tied to the precipitation events in the area of interest; diffusion will occur independently of filtration. In order for there to be net downward transport of fuel oxygenates, these two processes require the existence of a concentration gradient between the atmosphere and the subsurface air. As a result, once the local ground water reaches equilibrium with the local ambient air concentration of MTBE at some mean temperature, then the ground-water concentration of MTBE will not build up further, although continued infiltration of the MTBE-containing water will cause the volume of the contaminated water to increase when shallow ground water moves laterally or deeper[8].

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[6] For MTBE half-lives of a day or longer.

[7] No scientific literature was identified as part of this assessment on root uptake of MTBE and other alkyl ether oxygenates. The significance of the process remains to be assessed.

[8] We note in this context that it is now well known that chlorofluorocarbon (CFC) compounds present in the atmosphere can also partition to ground water, and that analyses of ground water for the CFC compounds can even be used to distinguish recent from old ground water (Busenberg and Plummer, 1992; Plummer et al.,

Increases of MTBE in ambient air levels would, of course, cause an increase in the ground-water concentration. When the depth to the water table is around 5 m, modelling done for this assessment indicates that water which has equilibrated with the atmosphere, can occur at the water table in times as short as 5 to 10 years[9]. In some areas of the Nation, dry wells are used to recharge storm water directly to ground water. In such areas, MTBE and other fuel oxygenates are expected to occur in ground water much more rapidly.

Based on the data in Table 2.6, median concentrations of MTBE in urban air studied to date seem to be of the order of a part per billion by volume or less. For a mean winter temperature of 5°C, H for MTBE is 1 x 10^{-4} atm-m^3 /mol (Robbins *et al.*, 1993). Therefore, for an atmospheric concentration of 1 ppb-v, the equilibrium concentration of MTBE will be about 1 µg/L. Similarly, if a specific city had a high MTBE median concentration, say 3 ppb-v, then the equilibrium concentration in water will be about 3 µg/L. If the atmospheric concentrations are systematically much higher around certain source areas such as parking garages, gas stations, or roadways, then precipitation falling near those areas is predicted to have higher levels, which could lead to ground water near these sites having higher levels of MTBE. For example, if the ambient air concentration near a parking garage remained consistent at 30 ppb-v, then 30 µg/L could occur in ground water (and storm water) immediately around the parking garage.

Biodegradation in the Environment

This subsection briefly reviews the literature regarding the biodegradability of fuel oxygenates and their degradation products. Only a limited amount of work has been accomplished for most of the compounds. Moreover, the studies are difficult to compare because they have been performed under a wide variety of experimental conditions. Both aerobic and anaerobic experiments have been conducted. In general, the investigations have demonstrated that the alkyl ether oxygenates (MTBE, TAME, ETBE, DIPE) are difficult to biodegrade. In contrast, BTEX, EtOH and MeOH are readily biodegraded. The difficulty with which alkyl ether oxygenates (and TBA) degrade is due to the resistance to microbial attack of tertiary or quaternary carbon atoms (Suflita and Mormile, 1993; Yeh and Novak, 1994) and the very stable and chemically unreactive ether linkage (Harada and Nagashima, 1975; Salanitro *et al.*, 1994). This subsection also discusses the effects of fuel oxygenates on biodegradation of other gasoline components.

Fuel Oxygenates and By-Products.

Methyl *tert*-butyl ether. Most studies have demonstrated that MTBE is not biodegraded easily. For example, various workers have found MTBE biodegradation did not occur under conditions described as follows: anaerobic microcosms, denitrifying conditions, sulfate-reducing conditions, methanogenic conditions, and anaerobic conditions in landfill aquifer material, soils, and sludges (Fujiwara *et al.*,1984; Moller and Arvin, 1990; Mormile *et al.*, 1994; Salanitro *et al.*, 1994; Suflita and Mormile, 1993; Yeh, 1992; and Yeh and Novak, 1991, 1994, 1995). It has also been reported that there was no

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1993).

[9] The model used in this simulation is briefly described in Appendix 8.

degradation of MTBE in aerobic microcosms after more than 100 days of incubation (Yeh and Novak, 1995). In the only controlled release that has been reported, MTBE was "recalcitrant in the aquifer, exhibiting no mass loss over a sixteen month period" (Hubbard *et al.*, 1994).

In contrast to the preceding observations, degradation of MTBE has been recorded on occasion. In a recent study of an actual fuel spill, MTBE was observed to degrade (decay rate of 0.18 percent per day), but only near the source area (Daniel, 1995). In addition, laboratory studies performed as part of that project showed some degradation in aerobic microcosms prepared from soil collected at the spill's source. TBA was produced in the microcosms but degradation ceased when the concentration of MTBE reached 1 mg/L. Degradation has also been reported in oxygen-limited microcosms after 4 weeks of incubation (Thomas *et al.*, 1988) and in one of three microcosms similarly prepared with Ohio River sediment (Mormile *et al.*, 1994). In the latter experiment, the degradation product was TBA which was then persistent. Other laboratory studies have observed degradation under conditions described as anaerobic or methanogenic, but only within a limited pH range (near pH 5.5), and only when more easily degraded organic matter was not present (Yeh and Novak, 1991).

Ethyl *tert*-butyl ether. ETBE, while also fairly recalcitrant, is less resistant to biodegradation than MTBE. Similar to their work with MTBE, Mormile *et al.* (1994) studied the susceptibility of ETBE to anaerobic (sulfate and/or nitrate reducing conditions and methanogenic conditions) biodegradation. They observed no degradation when ETBE was incubated with various inocula, regardless of the electron acceptor status. Anaerobic degradation was observed, however, in one study after a lag period of approximately 120 days. TBA accumulated and degradation decreased rapidly as the pH was increased (Yeh and Novak, 1991). In more detailed subsequent studies, ETBE was observed to degrade at a slower rate under denitrifying conditions and TBA accumulation was not observed. Some enhancement of degradation was observed under methanogenic conditions, but there was not a direct relationship which suggests that other factors are involved. It was concluded that anaerobic degradation occurred only under limited conditions and when more easily degradable organic matter was not present (Yeh and Novak, 1995). In contrast, under aerobic conditions, after 30 days of incubation, ETBE was degraded rapidly (2.5 mg/L/d per gram of soil) and TBA accumulated.

tert-Amyl methyl ether. The susceptibility of TAME to anaerobic (sulfate and/or nitrate reducing conditions and/or methanogenic conditions) biodegradation has been evaluated. No degradation was observed when the microcosms were incubated with various inocula, regardless of the electron acceptor status (Mormile *et al.*, 1994). TAME (3 mg/L) was also not degraded in 60 days when incubated with aquifer material, soil, or activated sludges (Moller and Arvin, 1990).

Diisopropyl ether. Mormile *et al.* (1994) also studied the susceptibility of DIPE to anaerobic (sulfate and/or nitrate reducing conditions and/or methanogenic reducing conditions) biodegradation. No degradation was observed when the microcosms were incubated with various inocula, regardless of the electron acceptor status. Similar results have been reported in other investigations (Fujiwara *et al.*, 1984; Suflita and Mormile, 1993).

tert-Butyl alcohol. Yeh and Novak (1995) reported that TBA persists in active microbial systems, even in microcosms where ETBE is undergoing rapid degradation. The resistance of TBA to biodegradation is consistent with reports by Hickman *et al.* (1989) and Suflita and Mormile (1993). When it does occur, anaerobic degradation of TBA is strongly dependent on the initial concentration, and the indigenous microbial activity (Hickman and Novak, 1989).

tert-Butyl formate. MTBE, the most commonly used oxygenate, is subject to photo-oxidation in the atmosphere. Several by-products are generated as a result of this process with a major product being *tert*-butyl formate (TBF). Other products are TBA, acetone, formaldehyde, methyl acetate, carbon dioxide, and water.

Because TBF is resistant to further photo-oxidation, and because its structure suggests resistance to biodegradation, it is a potential ground-water contaminant. No literature citations regarding its degradability have been located.

Methanol. In contrast to MTBE, which showed no mass loss for 16 months in a controlled release, rapid methanol utilization occurred following a three-and-a-half month lag period (Hubbard *et al.*, 1994). After 16 months, and only 45 m of travel, less than 1 percent of the original methanol remained. Insufficient oxygen was present in the plume to account for all of the removal, so methanol is believed to have biodegraded by first aerobic, then anaerobic mechanisms. In another study, methanol degraded rapidly after an acclimation period of only 5 days (Suflita and Mormile, 1993). The rapid degradability is not surprising, because there are at least eleven known species of methanogenic bacteria that can utilize methanol as a sole carbon source (Mormile *et al.*, 1994).

Ethanol. Simple alcohols, such as ethanol, as opposed to structurally complex compounds such as TBA, can be degraded by anaerobic respiration or, in the presence of sufficient oxygen, by aerobic processes (Chapelle, 1992). For example, the previous paragraph discussed the rapid degradability of methanol under anaerobic conditions. In the same experiment, ethanol was also degraded readily, but the acclimation period increased from 5 to 25 days (Suflita and Mormile, 1993). This information suggests that ethanol added to the environment as part of a gasoline spill would readily degrade, albeit slower than methanol.

Effects of Fuel Oxygenates on Biodegradation of Other Gasoline Components. Concern has been expressed that fuel oxygenates would have an inhibitory effect on the degradation of other fuel hydrocarbons such as BTEX. Consequently, several studies have evaluated this possibility. In the study by Hubbard *et al.* (1994), it was noted that the presence of MTBE had no measurable effect on the degradation of BTEX in an aquifer. Similarly, no effect on the BTEX respiration rate of sludge was observed for a hydrocarbon mixture that contained MTBE (Fujiwara *et al.*, 1984). In contrast, 200 mg/L of MTBE reportedly caused a weak inhibitory effect on the biodegradation of BTEX (Moller and Arvin, 1990) and 740 mg/L inhibited the mineralization of the fuel component hexadecane (Horan and Brown, 1995). An inhibitory effect of methanol on BTEX degradation also has been demonstrated (Hubbard *et al.*, 1994). Inhibition can occur because of the toxic effect of high methanol concentrations on microbial populations, oxygen depletion due to methanol biotransformation, and preferential microbial utilization of methanol as a substrate.

Abiotic Degradation in Natural Waters

Based on estimated physical-chemical properties or analogies to other structurally related aliphatic ethers, it has been reported that in water MTBE is not expected to significantly adsorb to bed sediments or suspended sediments, hydrolyze, directly photolyze, or photooxidize via reaction with photochemically produced hydroxyl radicals in the water (Prager, 1992). MTBE has been reported to be chemically unstable in acidic solutions (Budavari, 1989), however, hydrolosis is not expected to be significant in natural waters under normal conditions (pH 5-9) (Lyman *et al.*, 1990b). MTBE may be abiotically transformed via Fenton's reaction (see the section on "Remediation at Point-Source Release Sites"), however, conditions under which this reaction would occur rarely are seen in natural waters.

Remediation at Point-Source Release Sites

Point-source contributions of gasoline to ground water will continue to occur from releases at refineries, fuel distribution centers, during transportation and from refueling stations. Currently, the primary remedial technology for ground water contaminated with gasoline is removal by pumping followed by aboveground treatment. Another commonly used method, soil vapor extraction (SVE), often used in conjunction with pumping, relies on the high vapor pressure and biodegradability of gasoline. With SVE, a vacuum is used to remove the volatile hydrocarbons. The increased air flow resulting from the induced vacuum provides additional oxygen to enhance naturally occurring biodegradation. Consequently, the presence of fuel oxygenates, because of their greater water solubility and resistance to biodegradation, may complicate remedial activities.

There have been several evaluations of remedial technologies for fuel oxygenates, but these have typically indicated low efficiency and high costs. For example, Garrett *et al.* (1986) concluded that filtration through activated carbon is not cost effective: a 0.06-m^3 (cubic meter) bed lasts only a month or less on a household treatment system with an influent concentration of MTBE of only a few milligrams per liter. In more comprehensive studies, it was concluded that MTBE-contaminated water could be remediated and that air stripping, and air stripping with carbon adsorption had the lowest treatment costs (International Technology Corporation, 1991; Truong and Parmele, 1992). A recent survey of fifteen field air-stripping installations indicated that 56 to 99.9 percent of the MTBE was being removed with a median removal rate of 91 percent (API, 1990). Because of the relatively low efficiency of air stripping for MTBE, it may be cost effective to increase the Henry's Law constant (H) by heating the process water (Butillo *et al.*, 1994). Heating the air stripper influent stream to 80 °F over a 30-ft (foot) packed column was equivalent to using 50 °F water and a 60-ft packed column. When there can be no air emissions, use of oxidation with UV/peroxide/ozone is also a feasible treatment alternative. This latter approach, however, has high capital and operating costs.

Addition of hydrogen peroxide, provided initially as a source of oxygen to support microbial degradation, has been found to hydrolyze MTBE and ETBE with the immediate formation of TBA and some acetone (Yeh, 1992; Yeh and Novak, 1995). ETBE was oxidized faster than MTBE when hydrogen peroxide was added (Yeh and Novak, 1995), and the conversion of these two oxygenates was faster in organically rich soils, in comparison to organically poor soils (Yeh, 1992). The reaction only occurred when iron was added to act as a catalyst for the release of hydroxyl radicals from the hydrogen peroxide. The oxidation, therefore, occurs by means of Fenton's reaction. This reaction, however, does not have wide applicability because it is inefficient in aerobic or near-neutral ($pH > 6.5$) to alkaline environments.

An increasingly common method for managing gasoline spills is intrinsic bioremediation, also termed passive remediation. For this approach, protocols are being developed that demonstrate whether or not the activity of the indigenous microbial population is containing the spill. When such is the case, active remediation is not performed and the site is merely monitored to ensure that containment and natural removal continues. The presence of alkyl ether oxygenates will complicate use of this approach either by inhibiting degradation of the fuel components or because of their own resistance to degradation (Horan and Brown, 1995; Yeh and Novak, 1991). Although degradation in natural systems can be observed, slightly acidic conditions and very low levels of organic matter are required (Yeh and Novak, 1991). Those conditions are common in drinking-water aquifers, but such systems typically lack the nutrients that would be needed to sustain biodegradation.

Despite the resistance of MTBE to indigenous bacteria, it may be possible to develop biotreatment methods. Recent research has demonstrated that both mixed bacterial populations and certain pure bacterial strains, isolated from biotreater sludges and other sources, have the ability to utilize MTBE as a sole carbon source (Mo et al., 1995; Salanitro et al., 1994).

The preceding discussion has focused on the alkyl ethers but circumstances are much different for MeOH and EtOH. For both of these alcohols, biological treatment and intrinsic bioremediation are effective alternatives. However, high concentrations (>10%) may not be biodegradable (Brusseau, 1993) and lesser concentrations have an inhibitory effect on BTEX degradation (Butler et al., 1992).

CONCLUSIONS

Conclusions are based on a review of the scientific literature, data, other agency information, and calculations summarized in this chapter. Except for MTBE, there are little to no monitoring data on fuel oxygenates in commercial use for ground water, surface water, and drinking water. As such, many of the conclusions are specific for MTBE. The following conclusions are made:

Sources and Releases

1. The sources of MTBE and other alkyl ether oxygenates to surface water and ground water are the same as those associated with the production, transport, storage, and use of conventional gasoline.
   - Examples of point sources include releases from refineries and gasoline storage tanks, spillage, and evaporative emissions during fuel handling.
   - Examples of non-point sources include precipitation, overland runoff, and vehicular mobile emissions.
2. The release of MTBE to the environment (water, land, and air) is almost entirely associated with the production, transport, storage, and use of this chemical as a fuel oxygenate.
   - Annual releases from vehicular emissions, evaporative losses from gasoline stations and vehicles, and storage tanks have not been reported in the scientific literature. However, such releases are perceived to be important sources for the entry of MTBE into the hydrologic cycle.
   - Petroleum storage tanks represent the largest population of potential point sources of alkyl ether oxygenates. Localized concentrations in ground water from these sources may be in the thousands of micrograms-per-liter range and some instances of impact to drinking-water wells have been reported. There are no current Federal or State summary data that characterize the frequency or scale of MTBE water-quality impacts from these sources.
   - Estimates of industrial releases reported via the TRI for 1993 totaled about 1.7 million kilograms:
     - About 84 percent of these known releases were from refineries.
     - About 97 percent of these releases were to the atmosphere.

Monitoring and Regulations

3. Comprehensive national monitoring to describe the occurrence of MTBE and other fuel oxygenates in all compartments of the hydrologic cycle and drinking water has not been completed to date.
   - USGS has measured MTBE in ground water in select areas of the Nation and in storm water in 16 large cities.
   - USEPA and others have measured MTBE in ambient air and in air near gas stations, parking lots and garages, roadways, and at or near blending and distribution facilities, as part of special studies.
4. Although information on MTBE monitoring is being compiled by the States and associated findings were sought as part of this assessment, only a few States were able or willing to compile and report their data within the allowable time frame.
   - Additional information is needed from the States and large water utilities to better

characterize monitoring of fuel oxygenates being done nationwide.
- At least eight States have monitored their public water-supply systems or a subset of systems for MTBE.
- Some States have monitored for MTBE in select private wells and public water-supply systems where contamination of ground water was known or suspected.

5. A Federal drinking-water standard or ground-water protection standard has not been established for MTBE or other fuel oxygenates, however, the USEPA has issued a draft drinking-water lifetime health advisory for MTBE of 20 to 200 µg/L.
- At least 11 States have established or are promulgating a drinking-water standard or health advisory/guideline for MTBE.
- At least 10 States have established action levels and/or clean-up levels for releases of gasoline containing MTBE to ground water.

Occurrence in Compartments of the Hydrologic Cycle

6. Available monitoring data show that the use of MTBE as a fuel oxygenate (or as an octane enhancer) can result in the introduction of MTBE to air, storm water, shallow ground water, and to a lesser extent to deeper ground water, in those cities or States where it is used.
- Low concentrations of MTBE have been measured in urban air in six special studies, typically at median levels at or below 1 ppb-v. Higher levels were found near gasoline stations, roadways, parking lots and garages, and blending and distribution facilities.
- MTBE was detected in about 7 percent of 592 storm water samples collected in 16 cities between 1991-1995.
  - When detected the concentration ranged between 0.2 to 8.7 µg/L, with a median of 1.5 µg/L.
  - A strong seasonal pattern of detection was evident; 83 percent of MTBE detections were found during the winter season.
  - MTBE was detected both in cities using oxygenated gasoline to abate carbon monoxide non-attainment, and in cities presumed to have used MTBE in gasoline for octane enhancement.
- MTBE was detected in about 5 percent of over 1,500 wells which were sampled as part of ground-water assessments, and at least one detection was found for 14 of 33 States surveyed to date.
  - Most of the detections occurred in shallow ground water in urban areas.
  - Less than 2 percent of the wells screened in deeper aquifers or deeper parts of shallow aquifers had MTBE, however, these data show that MTBE can reach deeper ground water. The mechanism for this deeper migration is not known.
  - Concentrations of MTBE in ground water greater than about 30 µg/L originate from point sources, whereas lower concentrations may originate from point sources, non-point sources, or both.

7. MTBE has been detected in public and private drinking-water supplies derived from ground water, however, data available for this initial assessment are inadequate to characterize MTBE occurrence in drinking water nationwide.
- MTBE was detected in 51 public drinking-water systems, and in 6 of 7 States that provided information. Nearly all the detections of MTBE in public water-supply systems were at concentrations less than 20 µg/L.

- MTBE has been detected in a few private wells in at least four States. Typically, high levels of MTBE (>200 µg/L) were evident in these wells, which were sampled because of known or suspected point-source contamination.
- Additional MTBE monitoring data for drinking water are needed before the significance of drinking water as a route of exposure can be assessed for the Nation.

Significance of Measured Concentrations to Drinking Water and Aquatic Life

8. Monitoring data indicate the presence of MTBE in some ground-water samples and, as such, drinking water derived from ground water represents a potential exposure route for humans to this chemical. Little information exists on MTBE in drinking water derived from surface water and, therefore, the potential for this exposure route remains to be shown by monitoring.

- When detected, the concentration of MTBE in public drinking-water systems was nearly always below 20 µg/L, the lower limit of USEPA's current draft drinking-water lifetime health advisory. This indicates that the consumption of drinking water was not a major route of exposure for these systems.
- With continued increased use, the occurrence and spatial distribution of MTBE in ground water may change from today's understanding, and alter the occurrence and possibly the concentration of this chemical in drinking water derived from ground water.

9. Taste and odor threshold values (for water) have been reported for MTBE, ETBE, and TAME, and the detection values for MTBE fall in the range of the USEPA's drinking-water lifetime health advisory for this chemical, 20 to 200 µg/L.

- The taste detection thresholds for MTBE from two studies are 39 and 134 µg/L.
- The odor detection thresholds for MTBE from two studies are 45 and 95 µg/L.

10. Inadequate information exists to assess the significance of MTBE and other alkyl ether oxygenates on aquatic life.

- Water-quality criteria to protect aquatic life have not been established at the national level.
- Chronic toxicity data are lacking, and limited information exists on acute toxicity to aquatic animals and plants.
- Little monitoring data exist to determine the concentration of MTBE present in surface waters, to which aquatic life is exposed.

Environmental Behavior and Fate

11. Water that is equilibrated with an oxygenated fuel can contain a very high concentration of the oxygenate.

- The water solubility of MTBE will be about 5,000 mg/L at room temperature for a gasoline that is 10 percent MTBE by weight. In contrast, the total hydrocarbon water solubility is typically about 120 mg/L for conventional gasoline.
- Ground water MTBE concentrations as high as about 200 mg/L have been observed in wells near gasoline spills. The fact that these concentrations are typically lower than saturation levels for gasoline oxygenated with MTBE is likely due to either dilution by uncontaminated water as the contaminated water flows towards and into wells and/or a depletion of the MTBE levels in the gasoline by the dissolution process itself.

12. While gasoline containing alkyl ether oxygenates can lead to high concentrations of

fuel oxygenates in water, these concentrations are not typically high enough to increase either the water solubilities or the transport rates of the BTEX compounds in ground water.

- Gasolines containing very high percentages of EtOH and MeOH are capable of causing this effect, but such fuels are not in widespread use.

13. The fuel oxygenates sorb only weakly to soil and aquifer materials. Therefore, sorption to those materials will not retard their transport by ground water to any significant extent.

14. Relative to the BTEX compounds, MTBE and other alkyl ether oxygenates are significantly less degradable, while EtOH and MeOH are more easily degradable.

- MTBE, ETBE, TAME, and DIPE are not rapidly biodegraded.
- Except when present in concentrations high enough (>10%) to be toxic to microorganisms, EtOH and MeOH are readily degraded. Degradation of EtOH and MeOH may inhibit degradation of other gasoline components because they can be a preferred or competing substrate for indigenous microbes.
- For the limited conditions under which biodegradation has been observed, TBA, also difficult to degrade, is often formed from MTBE and ETBE.

15. MTBE and other alkyl ether oxygenates have lifetimes in the atmosphere that range from 4 days to 2 weeks. The main degradation pathway seems to be reaction with hydroxyl radicals.

16. Washout of gas-phase MTBE by precipitation will not by itself significantly alter the gas-phase concentration of this compound in the atmosphere. As such, washout by precipitation is not an important mechanism for the removal of this oxygenate from the atmosphere. Nevertheless, the partitioning of MTBE to water (precipitation) is strong enough to allow for measurable inputs of MTBE to surface water and ground water.

- For general atmospheric levels of MTBE in urban areas, based on limited available information, the concentration of MTBE in precipitation can range from sub micrograms per liter to about 3 µg/L.
- Near gasoline stations, roadways, and parking lots and garages, that experience consistently high sources of MTBE to the atmosphere, the concentration of MTBE in precipitation can be increased above the 3 µg/L level noted above.

17. The concentration of MTBE in ground water, that originates from atmospheric sources, is expected to change in response to increases or decreases in the concentration of MTBE in urban air. Several years or longer will be required before such changes are evident in ground water.

18. While MTBE is volatile from water, in large rivers and some streams this compound will not be lost quickly (e.g. half-lives >1 day) by volatilization, especially at low temperature. The rate of volatilization will frequently be controlled by mass-transport limitations in the water phase, and under such circumstances MTBE and other alkyl ether oxygenates will exhibit volatilization rates (half-lives) that are similar to those of the BTEX compounds.

19. Abiotic degradation processes, including hydrolysis, direct photolysis and indirect photolysis (e.g., reaction with hydroxyl radicals) are not expected to significantly alter the concentration of MTBE in natural waters.

Remediation

20. The presence of MTBE and other alkyl ether oxygenates does not prevent the application of conventional (active) remedial methods (air stripping, carbon adsorption,

and soil vapor extraction) for gasoline spills but it does raise the cost.

- Considering the equilibrium partitioning between air and water, the alkyl ether oxygenates are less volatile from water than the BTEX compounds.
- The alkyl ether oxygenates can be removed from water using aeration, but only with high air/water ratios.

21. The application of intrinsic (passive) bioremediation, an emerging, inexpensive approach to the management of gasoline spills, may be limited because of the difficulty with which alkyl ether oxygenates are biodegraded and the tendency of these compounds to migrate from release sites. For contaminant plumes containing EtOH or MeOH, however, intrinsic bioremediation, or enhancements to in-situ bioremediation will remain effective.

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Appendix 1: *Estimated releases of MTBE for report year 1993.*

[Source: U.S. Environmental Protection Agency, 1995c]

			Reported releases (kilograms per year):			
Name	**City**	**State**	**Air**	**Under-ground**	**Land**	**Water**
Bayway Chemical Plant Refining & Marketing Terminal	Linden	New Jersey	34,700	0	0	5
Amerada Hess Corp. Port Reading	Port Reading	New Jersey	14,224	0	0	2
Amerada Hess Corp. Second Reserve Terminal	Port Reading	New Jersey	5,126	0	0	0
Merck & Co. Inc.	Rahway	New Jersey	249	0	0	0
Shell Oil Co. Sewaren Plant	Sewaren	New Jersey	9,266	0	0	16
Ciba-Geigy Corp. Pharmaceuticals Div.	Summit	New Jersey	23	0	0	0
Sandoz Pharmaceuticals Corp.	East Hanover	New Jersey	1,709	0	0	0
Mobil Oil Paulsboro Refinery	Paulsboro	New Jersey	1,792	0	0	1,043
Coastal Eagle Point Oil Co.	Westville	New Jersey	1,089	0	0	0
Ford Motor Co. Edison Assembly Plant	Edison	New Jersey	160	0	0	0
GMC Chevrolet Pontiac Canada Group	North Tarrytown	New York	590	0	0	0
American Refining Group Inc.	Indianola	Pennsylvania	354	0	0	2
United Refining Co.	Warren	Pennsylvania	3,515	0	0	0
Witco Corp. Bradford Operations	Bradford	Pennsylvania	1,043	0	0	0
BP Exploration & Oil Inc. Marcus Hook Refinery	Trainer	Pennsylvania	1,369	0	0	0
Sun Refining & Marketing Co.	Marcus Hook	Pennsylvania	19,187	0	0	0
Chevron USA Products Co.	Philadelphia	Pennsylvania	6,318	0	0	0
Sun Refining & Marketing Co.	Philadelphia	Pennsylvania	4,427	0	0	0
Star Ent. Delaware City Refinery	Delaware City	Delaware	2,445	0	2	236
Primary Corp.	Richmond	Virginia	3,719	0	0	0
U.S. Doe Savannah River Site	Aiken	South Carolina	245	0	0	0
Citgo Asphalt Refining Co. Savannah Refinery	Savannah	Georgia	658	0	0	113
Petro Chemical Inc.	Jacksonville	Florida	780	0	0	0
Hunt Refining Co.	Tuscaloosa	Alabama	4,834	0	0	0
Wellborn Cabinet Inc.	Ashland	Alabama	2	0	0	0
Nissan Motor Mfg. Corp. USA Corp. USA	Smyrna	Tennessee	1,375	0	0	0
Saturn Corp.	Spring Hill	Tennessee	113	0	0	0
Tecumseh Prods. Co. Dunlap Ops.	Dunlap	Tennessee	113	0	0	0
Mapco Petroleum Inc.	Memphis	Tennessee	1,911	0	0	0
Chevron Products Co. Pascagoula Refinery	Pascagoula	Mississippi	28,894	0	0	0
Ashland Petroleum Co. Catlettsburg Refinery	Catlettsburg	Kentucky	6,858	0	0	504
GMC NAO Bowling Green Plant	Bowling Green	Kentucky	1,096	0	0	0
Honda of America Mfg. Inc.	Marysville	Ohio	2,320	0	0	0
Eli Lilly & Co. Lilly Industrial Center 1555	Indianapolis	Indiana	454	0	0	0
Rhone-Poulenc Basic Chemicals Co.	Hammond	Indiana	116	0	0	0

Appendix 1: *Estimated releases of MTBE for report year 1993.—Continued*

[Source: U.S. Environmental Protection Agency, 1995c]

Name	City	State	Reported releases (kilograms per year): Air	Under-ground	Land	Water
Amoco Chemical Co.	Whiting	Indiana	1,163	0	0	0
Amoco Oil Co. Whiting Refinery	Whiting	Indiana	4,758	0	0	0
Subaru-Isuzu Automotive Inc.	Lafayette	Indiana	116	0	0	0
Eli Lilly & Co. Tippecanoe Labs.	Shadeland	Indiana	6,260	0	0	0
Saturn Corp.	Madison Heights	Michigan	113	0	0	0
Autoalliance Intl. Inc.	Flat Rock	Michigan	227	0	0	0
Marathon Oil Co.	Detroit	Michigan	2,011	0	0	0
Marathon Oil Co.	Detroit	Michigan	1,589	0	0	0
GMC Truck & Bus Group Flint Assembly	Flint	Michigan	1,383	0	0	0
GMC Lansing Automotive Plant 1	Lansing	Michigan	141	0	0	0
Upjohn Co. Production Facility	Portage	Michigan	22,339	0	0	0
Warner-Lambert Co. Parke-Davis Div.	Holland	Michigan	295	0	0	0
Baxter Diagnostics Inc. Burdick & Jackson Div.	Muskegon	Michigan	227	0	0	0
Sealed Power Div.	Muskegon Heights	Michigan	10	0	0	0
Tecumseh Prods. Co. Engine & Transmission Group	New Holstein	Wisconsin	116	0	0	0
Aldrich Chemical Co. Inc.	Sheboygan Falls	Wisconsin	454	0	0	0
Briggs & Stratton Corp.	Wauwatosa	Wisconsin	7,342	0	0	0
Aldrich Chemical Co. Inc.	Milwaukee	Wisconsin	454	0	0	0
Koch Refining Co.	Rosemount	Minnesota	1,170	0	0	0
Kraft General Foods Kraft USA	Melrose	Minnesota	113	0	0	0
Exxon Billings Refinery	Billings	Montana	2,994	0	0	0
U.S. Doe Argonne Natl. Lab	Argonne	Illinois	113	0	0	0
Shell Oil Co. Wood River Mfg. Complex	Roxana	Illinois	15,876	0	0	0
Marathon Oil Co.	Robinson	Illinois	1,021	0	0	0
BP Oil Co. Alliance Refinery	Belle Chasse	Louisiana	11,839	0	0	3
Evans Cooperage Co. Inc.	Harvey	Louisiana	84	0	0	0
Shell Norco Mfg. Complex E. Site	Norco	Louisiana	6,305	0	24	5
Mobil Oil Corp. Chalmette Refinery	Chalmette	Louisiana	7,303	0	0	0
Canal Refining Co.	Church Point	Louisiana	27	0	0	0
Citgo Petroleum Corp.	Lake Charles	Louisiana	16,057	0	0	0
Conoco Lake Charles Refinery	Westlake	Louisiana	9,163	0	0	0
Star Ent. Inc.	Union	Louisiana	30,890	0	0	23
Phibro Energy Usa Inc.	Krotz Springs	Louisiana	57,766	0	0	101
Ciba-Geigy Corp.	Saint Gabriel	Louisiana	469	0	0	0
Exxon Baton Rouge Refinery	Baton Rouge	Louisiana	140,160	0	40	14,969
Exxon Chemical Baton Rouge Chemical Plant	Baton Rouge	Louisiana	3,973	0	0	18

Appendix 1: *Estimated releases of MTBE for report year 1993.—Continued*

[Source: U.S. Environmental Protection Agency, 1995c]

Name	City	State	Reported releases (kilograms per year): Air	Under-ground	Land	Water
Sinclair Oil Corp. Tulsa Refinery	Tulsa	Oklahoma	41	0	0	0
Conoco Ponca City Refinery	Ponca City	Oklahoma	6,394	0	0	21
La Gloria Oil & Gas Co.	Tyler	Texas	417	0	0	0
GMC Midsize Car Div.	Arlington	Texas	263	0	0	0
Texas Ind. Inc.	Midlothian	Texas	5	0	0	0
Phibro Energy USA Inc.	Houston	Texas	41,232	0	18	140
Lyondell-Citgo Refining Co. Ltd.	Houston	Texas	2,381	0	0	0
Texas Petrochemicals Corp.	Houston	Texas	20,263	0	0	39
Platzer Shipyard Inc.	Houston	Texas	50,698	0	0	0
Phillips 66 Co. Freeport Terminal I	Sweeny	Texas	10,827	0	0	0
Phillips 66 Co. Sweeny Complex	Old Ocean	Texas	29,897	0	0	0
Crown Central Petroleum Corp. Houston Refinery	Pasadena	Texas	9,869	0	0	0
Hoechst-Celanese Chemical Group Inc. Clear Lake Pl	Pasadena	Texas	816	0	0	0
Monsanto Co.	Alvin	Texas	68	0	0	0
Occidental Chemical Corp.	Alvin	Texas	7,044	0	0	0
Exxon Baytown Refinery	Baytown	Texas	48,277	0	0	0
Exxon Chemical Americas Baytown Chemical Plant	Baytown	Texas	13,608	0	0	0
Howell Hydrocarbons & Chemicals Inc.	Channelview	Texas	363	0	0	0
Lyondell Petrochemical Co.	Channelview	Texas	21,319	0	0	0
Arco Chemical Co.	Channelview	Texas	13,370	3,979	0	0
Global Octanes Corp.	Deer Park	Texas	1	0	0	0
Shell Oil Co. Deer Park Mfg. Complex	Deer Park	Texas	51,983	0	0	0
EGP Fuels Co.	La Porte	Texas	16,185	0	0	0
Amoco Oil Co. Texas City Refinery	Texas City	Texas	10,342	0	0	19,958
Phibro Energy USA Inc.	Texas City	Texas	12,322	0	0	267
Chevron USA Prods. Co. Port Arthur Refinery	Port Arthur	Texas	130,181	0	0	0
Texaco Chemical Co.	Port Neches	Texas	38,570	0	0	0
Mobil Oil Beaumont Refinery	Beaumont	Texas	57,198	0	0	0
Mobil Chemical Co. BCSP	Beaumont	Texas	16	0	0	0
Mobil Chemical Co. O/A	Beaumont	Texas	7	0	0	0
Coastal Refining & Marketing Inc.	Corpus Christi	Texas	253,070	0	0	0
Citgo Refining & Chemicals Inc.	Corpus Christi	Texas	3,019	0	0	0
Southwestern Refining Co. Inc.	Corpus Christi	Texas	13,372	0	51	1
Valero Refining Co.	Corpus Christi	Texas	11,193	0	0	0
Phillips 66 Co. Philtex/Ryton Complex	Borger	Texas	1,186	0	2	2
Diamond Shamrock Inc. Mckee Plants	Sunray	Texas	24,630	288	4	0

Appendix 1: *Estimated releases of MTBE for report year 1993.—Continued*

[Source: U.S. Environmental Protection Agency, 1995c]

			Reported releases (kilograms per year):			
Name	**City**	**State**	**Air**	**Under-ground**	**Land**	**Water**
Pride Refining Inc.	Abilene	Texas	6,659	0	0	0
Fina Oil & Chemical Co.	Big Spring	Texas	123,831	0	0	0
El Paso Refinery L.P.	El Paso	Texas	816	0	0	0
Colorado Refining Co.	Commerce City	Colorado	5,474	0	0	15
Conoco Denver Refinery	Commerce City	Colorado	6,804	0	0	399
Frontier Refining Inc.	Cheyenne	Wyoming	166	0	0	0
Coastal Chem. Inc.	Cheyenne	Wyoming	13,406	0	0	0
Little America Refining Co.	Casper	Wyoming	2	0	0	0
Pennzoil Prods. Co. Roosevelt Refinery	Roosevelt	Utah	721	0	0	0
Amoco Oil Co.	Salt Lake City	Utah	683	0	0	0
Giant Refining Co. Ciniza	Jamestown	New Mexico	8,066	0	0	0
Bloomfield Refining Co.	Bloomfield	New Mexico	1,474	0	2	0
Chevron USA Prods. Co. El Segundo Refinery	El Segundo	California	19,051	0	37	3,992
Mobil Oil Torrance Refinery	Torrance	California	1,474	0	0	0
Paramount Petroleum Corp.	Paramount	California	1	0	0	0
Texaco Refining & Marketing Inc. Lap	Wilmington	California	7,575	0	0	0
Unocal Louisiana Refinery Wilmington Plant	Wilmington	California	2,627	0	0	0
Arco Prods. Co. Louisiana Refinery	Carson	California	6,849	0	0	0
U.S. Doe Naval Petroleum Reserves of California	Tupman	California	514	0	0	0
Texaco Refining & Marketing Inc.	Bakersfield	California	3,543	0	0	0
Exxon Co. USA Benicia Refinery	Benicia	California	9,616	0	0	0
Pacific Refining Co.	Hercules	California	113	0	0	0
Shell Oil Co. Martinez Mfg. Complex	Martinez	California	17,690	0	5	0
Tosco Refining Co.	Martinez	California	463	0	0	0
Unocal Corp. San Francisco Refinery	Rodeo	California	2,971	0	0	0
Chevron Research & Technology Co.	Richmond	California	26	0	0	0
Chevron USA Prods. Co. Richmond Refinery	Richmond	California	12,428	0	0	0
Arco Cherry Point Refinery	Ferndale	Washington	2,631	0	0	0
Mapco Alaska Petroleum Inc.	North Pole	Alaska	1,100	0	0	0

Appendix 2: *Statistical summary of the occurrence and concentration of MTBE in storm water from select USGS studies.*

[Oct. 1 - Mar. 31 is the most frequent time for oxygenated gasoline usage throughout the United States. The only detailed record of usage of oxygenated gasoline for this summarization of the USGS storm-water data are for Arizona (oxygenate use during Oct. 1 - Mar. 31) and Colorado (oxygenate use during Oct. 1 - Mar. 31). NA, not applicable; µg/L, micrograms per liter]

City/study period[1]	Sampling period	Reporting level (µg/L)[2]	Number of samples	Number of samples with detections	Percent occurrence	Detected concentrations (µg/L)		
						Minimum	Median	Maximum
Montgomery, Ala. (6/92 - 3/93)	Apr. 1 - Sept. 30	1.0	9	0	0	N/A	N/A	N/A
	Oct. 1 - Mar. 31	1.0	12	0	0	N/A	N/A	N/A
	Total		21	0	0	N/A	N/A	N/A
Birmingham, Ala. (2/92 - 3/93)	Apr. 1 - Sept. 30	1.0	10	0	0	N/A	N/A	N/A
	Oct. 1 - Mar. 31	1.0	9	1	11.1	2.0	2.0	2.0
	Total		19	1	5.3	2.0	2.0	2.0
Mobile, Ala. (2/93 - 4/95)	Apr. 1 - Sept. 30	0.2, 1.0	2	0	0	N/A	N/A	N/A
	Oct. 1 - Mar. 31	0.2, 1.0	4	0	0	N/A	N/A	N/A
	Total		6	0	0	N/A	N/A	N/A
Huntsville, Ala. (2/93 - 6/93)	Apr. 1 - Sept. 30	1.0	2	0	0	N/A	N/A	N/A
	Oct. 1 - Mar. 31	1.0	1	0	0	N/A	N/A	N/A
	Total		3	0	0	N/A	N/A	N/A
Little Rock, Ark. (6/92 - 1/94)	Apr. 1 - Sept. 30	1.0	12	0	0	N/A	N/A	N/A
	Oct. 1 - Mar. 31	1.0	10	0	0	N/A	N/A	N/A
	Total		22	0	0	N/A	N/A	N/A
Phoenix, Ariz. (Maricopa County) (10/91 - 9/94)	Apr. 1 - Sept. 30	0.2, 1.0	7	0	0	N/A	N/A	N/A
	Oct. 1 - Mar. 31	1.0	23	5	21.7	1.0	1.0	2.5
	Total		30	5	16.7	1.0	1.0	2.5
Denver-Lakewood, Colo. (3/92 - 8/92)	Apr. 1 - Sept. 30	1.0	20	0	0	N/A	N/A	N/A
	Oct. 1 - Mar. 31	1.0	2	1	50	1.5	1.5	1.5
	Total		22	1	4.5	1.5	1.5	1.5
Colorado Springs, Colo. (5/92 - 12/92)	Apr. 1 - Sept. 30	1.0	27	0	0	N/A	N/A	N/A
	Oct. 1 - Mar. 31	1.0	15	10	66.7	1.0	1.6	4.2
	Total		42	10	23.8	1.0	1.6	4.2

Appendix 2: *Statistical summary of the occurrence and concentration of MTBE in storm water from select USGS studies.—Continued*

[Oct. 1 - Mar. 31 is the most frequent time for oxygenated gasoline usage throughout the United States. The only detailed record of usage of oxygenated gasoline for this summarization of the USGS storm-water data are for Arizona (oxygenate use during Oct. 1 - Mar. 31) and Colorado (oxygenate use during Oct. 1 - Mar. 31). NA, not applicable; µg/L, micrograms per liter]

City/study period[1]	Sampling period	Reporting level (µg/L)[2]	Number of samples	Number of samples with detections	Percent occurrence	Detected concentrations (µg/L)		
						Minimum	Median	Maximum
Atlanta, Ga. (7/92 - 2/93)	Apr. 1 - Sept. 30	1.0	7	1	14.3	1.2	1.2	1.2
	Oct. 1 - Mar. 31	1.0	11	2	18.2	1.0	1.05	1.1
	Total		18	3	16.7	1.0	1.1	1.2
Boise, Idaho (10/93 - 10/94)	Apr. 1 - Sept. 30	0.2, 1.0	6	0	0	N/A	N/A	N/A
	Oct. 1 - Mar. 31	0.2, 1.0	9	0	0	N/A	N/A	N/A
	Total		15	0	0	N/A	N/A	N/A
Davenport, Iowa (7/92 - 11/94)	Apr. 1 - Sept. 30	0.2, 1.0	19	0	0	N/A	N/A	N/A
	Oct. 1 - Mar. 31	0.2, 1.0	8	0	0	N/A	N/A	N/A
	Total		27	0	0	N/A	N/A	N/A
Baton Rouge, La. (4/93 - 6/95)	Apr. 1 - Sept. 30	0.2, 1.0	20	1	5	0.4	0.4	0.4
	Oct. 1 - Mar. 31	0.2, 1.0	11	0	0	N/A	N/A	N/A
	Total		31	1	3.2	0.4	0.4	0.4
Independence, Mo. (no Rfg/oxy-fuels usage in State) (7/92 - 2/93)	Apr. 1 - Sept. 30	1.0	8	0	0	N/A	N/A	N/A
	Oct. 1 - Mar. 31	1.0	7	0	0	N/A	N/A	N/A
	Total		15	0	0	N/A	N/A	N/A
Omaha, Nebr. (no Rfg/oxy-fuels usage in State) (5/93 - 8/93)	Apr. 1 - Sept. 30	1.0	15	0	0	N/A	N/A	N/A
	Oct. 1 - Mar. 31	1.0	0	0	0	N/A	N/A	N/A
	Total		15	0	0	N/A	N/A	N/A
Dallas-Fort Worth, Tex. (2/92 - 6/93)	Apr. 1 - Sept. 30	1.0	71	4	5.6	1	2.7	3.4
	Oct. 1 - Mar. 31	1.0	108	9	8.3	1.4	3.4	8.7
	Total		179	13	7.3	1	3.3	8.7
San Antonio, Tex. (1/93 - 6/95)	Apr. 1 - Sept. 30	0.2, 1.0	70	1	1.4	1.8	1.8	1.8
	Oct. 1 - Mar. 31	0.2, 1.0	57	6	10.5	0.2	0.7	1.8
	Total		127	7	5.5	0.2	1.0	1.8

Appendix 2: *Statistical summary of the occurrence and concentration of MTBE in storm water from select USGS studies.—Continued*

[Oct. 1 - Mar. 31 is the most frequent time for oxygenated gasoline usage throughout the United States. The only detailed record of usage of oxygenated gasoline for this summarization of the USGS storm-water data are for Arizona (oxygenate use during Oct. 1 - Mar. 31) and Colorado (oxygenate use during Oct. 1 - Mar. 31). NA, not applicable; µg/L, micrograms per liter]

City/study period[1]	Sampling period	Reporting level (µg/L)[2]	Number of samples	Number of samples with detections	Percent occurrence	Detected concentrations (µg/L)		
						Minimum	Median	Maximum
Composite of all samples	Apr. 1 - Sept. 30	0.2, 1.0	305	7	2.3	0.4	1.8	3.4
	Oct. 1 - Mar. 31	0.2, 1.0	287	34	11.8	0.2	1.5	8.7
	Total		592	41	6.9	0.2	1.5	8.7

[1] Timeframe in which storm-water samples were collected and analyzed for MTBE.

[2] A change in the reporting level for MTBE occurred between Apr. 3, 1994 and Apr. 9, 1994. The reporting level changed from 1.0 µg/L to 0.2 µg/L.

Appendix 3: *Summary of general characteristics and results of programs that have analyzed for MTBE in ground water, by State and by program in each State.*

[Data were compiled by NAWQA VOC National Synthesis from the data sources indicated. SUS, Study-Unit Survey; LUS, Land-Use Study; Ag, Agricultural; Ur, Urban; SU, Study Unit; µg/L, micrograms per liter]

State	Data source	Program description[1]	Sampling year(s)	Reporting level, in µg/L	Number of detections of MTBE	Number of wells tested
Arkansas	nawqa.ozrksus	SUS: Ozark Plateau SU	1993	0.2	0	11
California	nawqa.sanj (1)	Ag LUS: San Joaquin-Tulare Basins SU	1993	0.2	0	20
California	nawqa.sanj (2)	Ag LUS: San Joaquin-Tulare Basins SU	1994	0.2	0	20
Colorado	nawqa.splt	Ag LUS: South Platte River Basin SU	1994	0.2	0	33
Colorado	nawqa.spltlusur	Ur LUS: South Platte River Basin SU	1993	0.2	23	29
Connecticut	nawqa.connlus31	Ur LUS: Connecticut, Housatonic, and Thames River Basins SU	1994	0.2	5	10
Connecticut	nawqa.connlus33	Ur LUS: Connecticut, Housatonic, and Thames River Basins SU	1994	0.2	1	3
Connecticut	nawqa.connlus34	Ur LUS: Connecticut, Housatonic, and Thames River Basins SU	1993-94	0.2	1	2
Connecticut	nawqa.connsus	SUS: Connecticut, Housatonic, and Thames Riuver Basin SU	1995	0.2	5	18
Florida	nawqg.gaflsus	SUS: Georgia-Florida Coastal Plain SU	1993	0.2	0	7
Georgia	nawqa.acfb	Ag LUS: Apalachicola-Chattahoochee-Flint River Basin SU	1993	0.2	0	32
Georgia	nawqa.gafl	Ag LUS: Georgia-Florida Coastal Plain SU	1994	0.2	0	23
Georgia	nawqa.gaflsus	SUS: Georgia-Florida Coastal Plain SU	1993	0.2	1	26
Georgia	nawqa.acfblusur1[2]	Ur LUS: Apalachicola-Chattahoochee-Flint River Basin SU	1994	0.2	2	23
Iowa	USGS.midcontinent	Quality of water (QW) in near-surface aquifers	1992	1.0	0	23
Iowa	USGS.midcontinent	QW in near-surface aquifers	1993	1.0	0	23
Idaho	nawqa.usnk (1)	Ag LUS: Upper Snake River Basin SU	1993	0.2	0	31
Idaho	nawqa.usnk (2)	Ag LUS: Upper Snake River Basin SU	1993	0.2	0	28
Idaho	nawqa.usnk (3)	Ag LUS: Upper Snake River Basin SU	1994	0.2	0	30
Idaho	nawqa.usnksus1	SUS: Upper Snake River Basin SU	1992-93	0.2	0	4
Illinois	USGS.midcontinent	QW in near-surface aquifers	1992	1.0	0	32
Illinois	USGS.midcontinent	QW in near-surface aquifers	1993	1.0	0	32
Indiana	USGS.midcontinent	QW in near-surface aquifers	1992	1.0	0	4
Indiana	USGS.midcontinent	QW in near-surface aquifers	1993	1.0	0	4
Kansas	nawqa.ozrksus	SUS: Ozark Plateaus SU	1993	0.2	0	1

Appendix 3: *Summary of general characteristics and results of programs that have analyzed for MTBE in ground water, by State and by program in each State.—Continued*

[Data were compiled by NAWQA VOC National Synthesis from the data sources indicated. SUS, Study-Unit Survey; LUS, Land-Use Study; Ag, Agricultural; Ur, Urban; SU, Study Unit; μg/L, micrograms per liter]

State	Data source	Program description[1]	Sampling year(s)	Reporting level, in μg/L	Number of detections of MTBE	Number of wells tested
Kansas	USGS.midcontinent	QW in near-surface aquifers	1992	1.0	0	1
Kansas	USGS.midcontinent	QW in near-surface aquifers	1993	1.0	0	1
Massachusetts	nawqa.conn	Ag LUS: Connecticut, Housatonic, and Thames River Basins SU	1993-94	0.2	2	23
Massachusetts	nawqa.connlus33	Ur LUS: Connecticut, Housatonic, and Thames River Basins SU	1994	0.2	1	6
Massachusetts	nawqa.connlus34	Ur LUS: Connecticut, Housatonic, and Thames River Basins SU	1994	0.2	4	7
Maryland	nawqa.poto	Ag LUS: Potomac River Basin SU	1993	0.2	0	16
Maryland	nawqa.lsussus2	SUS: Lower Susquehanna River Basin SU	1994	0.2	0	2
Michigan	USGS.midcontinent	QW in near-surface aquifers	1992	1.0	0	1
Michigan	USGS.midcontinent	QW in near-surface aquifers	1993	1.0	0	1
Minnesota	nawqa.rednsus2	SUS: Red River of the North SU	1993	0.2	0	26
Minnesota	nawqa.rednsus4	SUS: Red River of the North SU	1993	0.2	0	11
Minnesota	USGS.midcontinent	QW in near-surface aquifers	1992	1.0	0	16
Minnesota	USGS.midcontinent	QW in near-surface aquifers	1993	1.0	0	16
Missouri	nawqa.ozrksus	SUS: Ozark Plateaus SU	1993	0.2	0	32
Missouri	nawqa.ozrksus1	SUS: Ozark Plateaus SU	1993	0.2	0	9
Missouri	USGS.midcontinent	QW in near-surface aquifers	1992	1.0	0	9
Missouri	USGS.midcontinent	QW in near-surface aquifers	1992	1.0	0	9
North Carolina	nawqa.albe	Ag LUS: Albemarle-Pamlico Drainage SU	1994	0.2	0	20
North Carolina	nawqa.albesus1	SUS: Albemarle-Pamlico Drainage SU	1994	0.2	0	8
North Carolina	nawqa.albesus2	SUS: Albemarle-Pamlico Drainage SU	1994	0.2	0	10
North Carolina	nawqa.albesus4	SUS: Albemarle-Pamlico Drainage SU	1994	0.2	0	5
North Carolina	nawqa.albesus5	SUS: Albemarle-Pamlico Drainage SU	1994	0.2	0	2
North Dakota	nawqa.rednsus1	SUS: Red River of the North SU	1993	0.2	0	10
North Dakota	nawqa.rednsus3	SUS: Red River of the North SU	1993	0.2	0	3
North Dakota	USGS.midcontinent	QW in near-surface aquifers	1992	1.0	0	1
North Dakota	USGS.midcontinent	QW in near-surface aquifers	1993	1.0	0	1

Appendix 3: *Summary of general characteristics and results of programs that have analyzed for MTBE in ground water, by State and by program in each State.—Continued*

[Data were compiled by NAWQA VOC National Synthesis from the data sources indicated. SUS, Study-Unit Survey; LUS, Land-Use Study; Ag, Agricultural; Ur, Urban; SU, Study Unit; µg/L, micrograms per liter]

State	Data source	Program description[1]	Sampling year(s)	Reporting level, in µg/L	Number of detections of MTBE	Number of wells tested
Nebraska	USGS.midcontinent	QW in near-surface aquifers	1993	1.0	0	38
Nebraska	USGS.midcontinent	QW in near-surface aquifers	1993	1.0	0	38
New Jersey	nawqa.linj01 (1)	Various USGS projects and monitoring networks	1994	0.2	1	5
New Jersey	nawqa.linj01 (2)	Various USGS projects and monitoring networks	1995	0.2	0	1
New Jersey	nawqa.linj01 (3)	Various USGS projects and monitoring networks	1993	1.0	0	1
New Mexico	nawqa.riog (1)	Ag LUS: Rio Grande Valley SU	1994	0.2	0	20
New Mexico	nawqa.riog (2)	Ag LUS: Rio Grande Valley SU	1993	0.2	1	35
New Mexico	nawqa.rioglusur	Ur LUS: Rio Grande Valley SU	1993	0.2	1	24
Nevada	nawqa.nvbrlusur	Ur LUS: Nevada Basin and Range SU	1993	0.2	4	33
Nevada	nawqa.nvbr	Ur LUS: Nevada Basin and Range SU	1994	0.2	6	28
Nevada	nawqa.nvbrsus	SUS: Nevada Basin and Range SU	1995	0.2	1	14
New York	nawqa.hdsnlusur	Ur LUS: Hudson River Basin SU	1993	0.2	4	22
New York	nawqa.hdsnsus	SUS: Hudson River Basin SU	1994	0.2	1	46
New York	nawqa.linj01	Various USGS projects and monitoring networks	1992	5.0	1	15
Ohio	USGS.midcontinent	QW in near-surface aquifers	1992	1.0	0	1
Ohio	USGS.midcontinent	QW in near-surface aquifers	1992	1.0	0	1
Oklahoma	nawqa.ozrksus	SUS: Ozark Plateaus SU	1993	0.2	0	7
Oregon	nawqa.will (1)	Ag LUS: Willamette Basin SU	1993	0.2	0	15
Oregon	nawqa.will (2)	Ag LUS: Willamette Basin SU	1993	0.2	0	26
Oregon	nawqa.willsus	SUS: Willamette Basin SU	1993	0.2	0	64
Pennsylvania	nawqa.lsus	Ag LUS: Lower Susquehanna River Basin SU	1993	0.2	4	30
South Dakota	USGS.midcontinent	QW in near-surface aquifers	1992	1.0	0	3
South Dakota	USGS.midcontinent	QW in near-surface aquifers	1992	1.0	0	3
Texas	nawqa.trinlusur1	Ur LUS: Trinity River Basin SU	1993	0.2	3	17
Texas	nawqa.trinsus1	SUS: Trinity River Basin SU	1994	0.2	0	21
Texas	nawqa.trinsus2	SUS: Trinity River Basin SU	1994	0.2	0	13

Appendix 3: *Summary of general characteristics and results of programs that have analyzed for MTBE in ground water, by State and by program in each State.—Continued*

[Data were compiled by NAWQA VOC National Synthesis from the data sources indicated. SUS, Study-Unit Survey; LUS, Land-Use Study; Ag, Agricultural; Ur, Urban; SU, Study Unit; µg/L, micrograms per liter]

State	Data source	Program description[1]	Sampling year(s)	Reporting level, in µg/L	Number of detections of MTBE	Number of wells tested
Texas	nawqa.trinsus3	SUS: Trinity River Basin SU	1994	0.2	0	18
Virginia	nawqa.albesus1	SUS: Albemarle-Pamlico Drainage SU	1994	0.2	1	4
Virginia	nawqa.albesus2	SUS: Albemarle-Pamlico Drainage SU	1994	0.2	0	4
Virginia	nawqa.albesus4	SUS: Albemarle-Pamlico Drainage SU	1994	0.2	0	2
Vermont	nawqa.connlus32	Undeveloped LUS: Connecticut, Housatonic, and Thames River Basins SU	1994	0.2	1	7
Washington	nawqa.ccpt (1)	Ag LUS: Central Columbia Plateau SU	1993-94	0.2	0	43
Washington	nawqa.ccpt (2)	Ag LUS: Central Columbia Plateau SU	1993-94	0.2	0	21
Washington	nawqa.ccptsus	SUS: Central Columbia Plateau SU	1994	0.2	1	35
Wisconsin	nawqa.wmic (1)	Ag LUS: Western Lake Michigan Drainage SU	1993-94	0.2	0	28
Wisconsin	nawqa.wmic (2)	Ag LUS: Western Lake Michigan Drainage SU	1994	0.2	0	30
Wisconsin	USGS.midcontinent	QW in near-surface aquifers	1992	1.0	0	5
Wisconsin	USGS.midcontinent	QW in near-surface aquifers	1993	1.0	0	5
Wisconsin	nawqa.umis07	Ground-water quality monitoring network Wisconsin	1990-94	5.0	1	78

[1] For descriptions of ground-water studies designed for NAWQA, see Gillom and others (1995).

[2] Some springs were also sampled as part of this data.

Appendix 4: *Summary of general characteristics and results of State monitoring programs that have analyzed for MTBE in drinking water.*

[NK, not known; NA, not applicable; µg/L, micrograms per liter]

a. Drinking water derived from ground water – public water systems

State	Data source	Sampling year(s)	Reporting level (µg/L)	Number of detections	Number of systems with detections	Number of			Source of contamination	Reference	Remarks
						Wells sampled	Samples	Systems sampled			
New Jersey	cert labs	1994-95	NK	63	20	NK	1,269	NK	NK	Letter from New Jersey DEP, 24Jul95	--
New Jersey	NJ DOH	1992-94	NK	19	18	NK	31	NK	NK	Letter from New Jersey DEP, 24Jul95	Samples collected in response to consumer complaints.
Iowa	Alvord PWS	1994	NK	3	1	1	NK	NK	Believed to be leaking UST.	Memo from EPA Region 7, 26Jul95	--
Illinois	IL EPA	1990-95	NK	29	7	NK	NK	NK	UST or pipeline contamination from refinery or bulk terminal, source of Roanoke under investigation.	Letter from Illinois EPA, 09Jun95	Oakdale has abandoned its wells, water is piped in from nearby community. Island Lake uses the one-contaminated well minimally.
Wisconsin	WI DNR	1995	NK	0	0	NK	NK	3	NK	Letter from Wisconsin DNR, 14Jun95	Sampling conducted in April 1995 at 3 systems with ground-water source.
Texas	EPA Region VI	1988-93	NK	8	7	NK	15,352	NK	NK	Note from Texas State Water Program, 28Jul95	The 15,352 samples represent the total of PWS and private well samples, however, the majority are from PWS. Note that samples are not verified (i.e., systems with detections were not resampled for confirmation).
Rhode Island	RI DOH	1988-95	1	117	NK	NK	2,567	NK	NK	Letter from Rhode Island DOH, 18Oct95	2,567 samples includes an unknown number of surface-water samples, but number expected to be small.
Colorado	CO DOH&E	1995	0.2	1	1	NK	5	5	NK	EPA Region VIII, 24Oct95	--

b. Drinking water derived from ground water – private wells

State	Data source	Sampling year(s)	Reporting level (µg/L)	Number of detections	Number of systems with detections	Wells sampled	Samples	Systems sampled	Source of contamination	Reference	Remarks
Missouri	BHMGRP	1992-95	NK	133	4	4	161	NA	Massive failure of UST.	Letter from Missouri DNR, 19Jul95	Private wells located near active remediation site. Table 9 concentrations indicate levels prior to treatment.
Indiana	IN DEM	1991	NK	2	2	NK	NK	NA	NK	Letter from Indiana DEM, 21Jun95	Sampling conducted in response to consumer complaints.

Appendix 4: *Summary of general characteristics and results of State monitoring programs that have analyzed for MTBE in drinking water.—Continued*

[NK, not known; NA, not applicable; µg/L, micrograms per liter]

b. Drinking water derived from ground water – private wells—Continued

State	Data source	Sampling year(s)	Reporting level (µg/L)	Number of detections	Number of systems with detections	Number of			Source of contamination	Reference	Remarks
						Wells sampled	Samples	Systems sampled			
Texas	EPA Region VI	1988-93	NK	9	NK	NK	NK	NA	NK	Note from Texas State Water Program, 28Jul95	The number of samples from private wells in unknown, but thought to be a small subset of the 15,352 samples. Note that samples are not confirmed (i.e., wells with detections were not resampled for confirmation).
Rhode Island	RI DOH	1987-95	1	536	NK	NK	3,155	NA	NK	Letter from Rhode Island DOH, 18Oct95	--

c. Drinking water derived from surface water – public water systems

State	Data source	Sampling year(s)	Reporting level (µg/L)	Number of detects	Number of		Source	Reference	Remarks
					Samples	Systems sampled			
Wisconsin	WI DNR	1995	NK	0	NK	NK	NK	Letter from WI DNR, 14Jun95	Sampling conducted in April 1995 at two systems with surface-water source
Rhode Island	RI DOH	1988-95	1	1	NK	NK	NK	Letter from RI DOH, 180ct95	2,567 samples include an unknown number of surface-water samples, but number expected to be small.

Appendix 5: *Non-occurrence and occurrence of MTBE in ground water for those programs in which there was at least one detection of MTBE*[1].

[RL, reporting level; µg/L, micrograms per liter]

State	Data source	RL in µg/L	Type of well[2]																			
			Monitoring/Observation					Private supply					Public supply					Other/Not known				
			<RL	> = RL to <10 µg/L	> = 10 to <20 µg/L	> = 20 to < = 200 µg/L	>200 µg/L	<RL	> = RL to <10 µg/L	> = 10 to <20 µg/L	> = 20 to < = 200 µg/L	>200 µg/L	<RL	> = RL to <10 µg/L	> = 10 to <20 µg/L	> = 20 to < = 200 µg/L	>200 µg/L	<RL	> = RL to <10 µg/L	> = 10 to <20 µg/L	> = 20 to < = 200 µg/L	>200 µg/L
Colorado	nawqa.spltlusur	0.2	4	13		2	2		1									2	5			
Connecticut	nawqa.connlus31	0.2	5	5																		
Connecticut	nawqa.connlus33	0.2	2	1																		
Connecticut	nawqa.connlus34	0.2	1	1																		
Connecticut	nawqa.connsus	0.2						13	4										1			
Georgia	nawqa.gaflsus	0.2						12	1				13									
Georgia	nawqa.acfblusur1[2]	0.2	5					2										14	2			
Massachusetts	nawqa.conn	0.2																21	2			
Massachusetts	nawqa.connlus33	0.2	5	1																		
Massachusetts	nawqa.connlus34	0.2	3	4																		
New Jersey	nawqa.linj01 (1)	0.2	4	1																		
New Mexico	nawqa.riog	0.2																34	1			
New Mexico	nawqa.rioglus	0.2	23	1																		
Nevada	nawqa.nvbr	0.2																22	4		1	1
Nevada	nawqa.nvbrlusur	0.2	27	3														2		1		
Nevada	nawqa.nvbrsus	0.2						1					2	1				10				
New York	nawqa.hdsnlus1	0.2	12	2									3					3	2			
New York	nawqa.hdsnsus	0.2						41	1									4				
New York	nawqa.linj01	5.0	14	1																		
Pennsylvania	nawqa.lsus	0.2						25	4									1				
Texas	nawqa.trinlus1	0.2	14	3																		
Virginia	nawqa.albesus1	0.2	3	1																		
Vermont	nawqa.connlus32	0.2	6	1																		
Washington	nawqa.ccpt	0.2						1					5	1				28				
Wisconsin	nawqa.umis07	5/10																77	1			

[1] Numbers in this appendix denote either the number of wells in which MTBE was not detected (i.e., analysis was reported as less than the reporting level), or the number of wells in which MTBE was detected, in the specified concentration range.

[2] Some springs were also sampled as part of this study.

Appendix 6: *Concentration of MTBE measured at indicated well, by well type.*

[µg/L, micrograms per liter]

State	Data source	Well ID	Latitude	Longitude	Date of sample (MMDDYYYY)	Concentration of MTBE, in µg/L			
						Well type			
						Monitoring	Domestic supply	Public supply	Other/Not known
Colorado	nawqa.spltlusur	394234104595301	394234	1045953	08051993	800			
Colorado	nawqa.spltlusur	394326105003901	394326	1050039	08051993	0.6			
Colorado	nawqa.spltlusur	394507105004601	394507	1050046	07221993	3.2			
Colorado	nawqa.spltlusur	394830104564001	394830	1045640	08131993	33			
Colorado	nawqa.spltlusur	394833104572201	394833	1045722	07231993	9.6			
Colorado	nawqa.spltlusur	394858104591701	394858	1045917	07301993	0.5			
Colorado	nawqa.spltlusur	393736105004001	393736	1050040	07291993	5.1			
Colorado	nawqa.spltlusur	393843105005201	393843	1050052	08041993	1.2			
Colorado	nawqa.spltlusur	393922105031201	393922	1050312	08111993	0.5			
Colorado	nawqa.spltlusur	393944105000201	393944	1050002	07291993	0.6			
Colorado	nawqa.spltlusur	394044104533901	394044	1045339	08031993	3.5			
Colorado	nawqa.spltlusur	394648105072301	394648	1050723	07141993	23,000			
Colorado	nawqa.spltlusur	394654104584301	394655	1050115	07201993	83			
Colorado	nawqa.spltlusur	394728105045801	394728	1050458	07141993	0.7			
Colorado	nawqa.spltlusur	394811105023201	394811	1050232	07131993				0.3
Colorado	nawqa.spltlusur	393357105020201	393357	1050202	07151993	0.2			
Colorado	nawqa.spltlusur	394056104594801	394056	1045948	08191993				0.5
Colorado	nawqa.spltlusur	394156104550701	394156	1045507	08031993	0.3			
Colorado	nawqa.spltlusur	394314104575001	394314	1045750	08191993				1.3
Colorado	nawqa.spltlusur	394653105053601	394653	1050536	08121993				1.4
Colorado	nawqa.spltlusur	394655105030901	394655	1050309	07201993	0.7			
Colorado	nawqa.spltlusur	394824105065001	394824	1050650	08121993		0.4		
Colorado	nawqa.spltlusur	394835105053301	394835	1050533	09091993				0.2
Connecticut	nawqa.connlus31	415924072304401	415924	723044	06231994	0.7			
Connecticut	nawqa.connlus31	412722072495701	412722	724957	08051994	0.2			

Appendix 6: *Concentration of MTBE measured at indicated well, by well type.—Continued*

[µg/L, micrograms per liter]

State	Data source	Well ID	Latitude	Longitude	Date of sample (MMDDYYYY)	Concentration of MTBE, in µg/L			
						Well type			
						Monitoring	Domestic supply	Public supply	Other/Not known
Connecticut	nawqa.connlus31	413114072495401	413114	724954	07281994	0.2			
Connecticut	nawqa.connlus31	414926072300801	--	--	07261994	0.6			
Connecticut	nawqa.connlus31	415155072284601	415155	722846	07261994	0.5			
Connecticut	nawqa.connlus33	413434073245301	413434	732453	04051994	0.4			
Connecticut	nawqa.connlus34	411314073033501	411314	730335	02071994	0.3			
Connecticut	nawqa.connsus	BU126	414711	725607	06141995		2.2		
Connecticut	nawqa.connsus	ED6	415130	720441	06221995		0.3		
Connecticut	nawqa.connsus	NA46	412846	730119	05311995		1.5		
Connecticut	nawqa.connsus	RX28	413336	731839	06131995				2.1
Connecticut	nawqa.connsus	WHV449	411652	725828	06201995		0.8		
Georgia	nawqa.gaflsus	322513082051401	322513	820514	08171993		0.9		
Georgia	nawqa.acfbsprur1	335519084230001	--	--	10051994				8.7
Georgia	nawqa.acfbsprur1	335734084250101	335734	842501	12071994				0.2
Massachusetts	nawqa.conn	415542072273601	415542	722736	05051994				0.3
Massachusetts	nawqa.conn	415837072305501	415837	723055	05051994				0.2
Massachusetts	nawqa.connlus33	422633073155501	422633	731555	08251994	1.1			
Massachusetts	nawqa.connlus34	420637072451401	420637	724514	06281994	0.3			
Massachusetts	nawqa.connlus34	420744072451001	420744	724510	06281994	0.4			
Massachusetts	nawqa.connlus34	420347071521801	420347	715218	08021994	0.4			
Massachusetts	nawqa.connlus34	420558072185301	420558	721853	08241994	0.5			
New Jersey	nawqa.linj01 (1)	403524074485001	403524	744850	08311994	0.5			
New Mexico	nawqa.riog	373849106074301	373849	1060743	09071993				0.6
New Mexico	nawqa.rioglus	350653106400601	350653	1064006	08151993	7.9			
Nevada	nawqa.nvbr	393022119444301	393022	1194443	08031994				140
Nevada	nawqa.nvbr	393032119473501	393032	1194735	07261994				0.8
Nevada	nawqa.nvbr	393054119445501	393054	1194455	05241994				1.4

Appendix 6: *Concentration of MTBE measured at indicated well, by well type.—Continued*

[μg/L, micrograms per liter]

State	Data source	Well ID	Latitude	Longitude	Date of sample (MMDDYYYY)	Concentration of MTBE, in μg/L			
						Well type			
						Monitoring	Domestic supply	Public supply	Other/Not known
Nevada	nawqa.nvbr	393132119422801	393132	1194228	06011994				6.2
Nevada	nawqa.nvbr	393132119485801	393132	1194858	08151994				0.3
Nevada	nawqa.nvbr	393139119493401	393139	1194934	06211994				220
Nevada	nawqa.nvbrlusur	360617115063802	360617	1150638	08171993	0.4			
Nevada	nawqa.nvbrlusur	360648115084901	360648	1150849	08231993	0.4			
Nevada	nawqa.nvbrlusur	360821115025001	360821	1150250	08241993	0.7			
Nevada	nawqa.nvbrlusur	360854115060901	--	--	08201993				13
Nevada	nawqa.nvbrsus	360719115095903	360719	1150959	02151995			0.3	
New York	nawqa.hdsnlus1	424418073485601	424418	734856	07131993	0.2			
New York	nawqa.hdsnlus1	424744073592301	424744	735923	07211993	0.6			
New York	nawqa.hdsnlus1	424942073474401	--	--	08231994				0.4
New York	nawqa.hdsnlus1	425048073472501	--	--	08231994				0.3
New York	nawqa.hdsnsus	411938073595201	411938	735952	11301994		0.2		
New York	nawqa.linj01	404631073543901	404631	735439	09161992	7.9			
Pennsylvania	nawqa.lsus	395346076502901	395346	765029	07121993		1.3		
Pennsylvania	nawqa.lsus	400229076020301	400229	760203	07151993		0.5		
Pennsylvania	nawqa.lsus	400629076365201	400629	763652	07201993		0.5		
Pennsylvania	nawqa.lsus	400724075593201	400724	755932	07191993		0.3		
Texas	nawqa.trinlusur1	324243097105001	324243	971050	09021993	1.4			
Texas	nawqa.trinlusur1	325144097040201	325144	970402	07281993	0.2			
Texas	nawqa.trinlusur1	325225097045901	325225	970459	08201993	0.7			
Virginia	nawqa.albesus1	364101076544803	364101	765448	08171994	1			
Vermont	nawqa.connlus32	430746072263701	430746	722637	08121994	2.4			
Washington	nawqa.ccptsus	470904119190401	470858	1191905	08011994			1.8	
Wisconsin	nawqa.umis07	BG392	450006	923849	06091994				0.8

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
New Jersey	cert labs	61223	distribution	01251994		1.4
New Jersey	cert labs	61223	distribution	03221994		3.3
New Jersey	cert labs	61223	distribution	04261994		33.6
New Jersey	cert labs	61223	distribution	08091994		9.5
New Jersey	cert labs	61223	distribution	11091994		3.9
New Jersey	cert labs	13001	distribution	06151994		0.7
New Jersey	cert labs	13001	distribution	06151994		2.2
New Jersey	cert labs	13001	distribution	09071994		2.3
New Jersey	cert labs	13001	distribution	09281994		0.7
New Jersey	cert labs	18202	distribution	03281994		0.7
New Jersey	cert labs	18202	distribution	04041994		0.5
New Jersey	cert labs	18202	distribution	04041994		0.8
New Jersey	cert labs	18202	distribution	04041994		1.8
New Jersey	cert labs	18202	distribution	04041994		0.8
New Jersey	cert labs	18202	distribution	04041994		0.5
New Jersey	cert labs	18202	distribution	09121994		3.1
New Jersey	cert labs	18202	distribution	12191994		0.6
New Jersey	cert labs	18202	distribution	12271994		1.1
New Jersey	cert labs	26733	distribution	05181994		0.34
New Jersey	cert labs	26733	distribution	05181994		0.39
New Jersey	cert labs	20011	distribution	03211994		1.2
New Jersey	cert labs	13026	distribution	01061994		0.8
New Jersey	cert labs	51597	distribution	01211994		0.5
New Jersey	cert labs	22908	distribution	12211994		0.8
New Jersey	cert labs	26113	distribution	02091994		3.4
New Jersey	cert labs	26113	distribution	05231994		3.8
New Jersey	cert labs	26113	distribution	08191994		4.1
New Jersey	cert labs	26113	distribution	11181994		1.9
New Jersey	cert labs	42800	distribution	08171994		1.3
New Jersey	cert labs	58008	distribution	02011994		2.8
New Jersey	cert labs	58008	distribution	03011994		3
New Jersey	cert labs	58008	distribution	04051994		3.6
New Jersey	cert labs	58008	distribution	07051994		4.2
New Jersey	cert labs	58008	distribution	08021994		0.8
New Jersey	cert labs	58008	distribution	08021994		4.8
New Jersey	cert labs	58008	distribution	08171994		1.3
New Jersey	cert labs	58008	distribution	09061994		7
New Jersey	cert labs	58008	distribution	10041994		6.8
New Jersey	cert labs	58008	distribution	10041994		5.5
New Jersey	cert labs	58008	distribution	11011994		6.9

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
New Jersey	cert labs	15205	distribution	06131994		1.34
New Jersey	cert labs	13293	distribution	05261994		1.9
New Jersey	cert labs	13293	distribution	07201994		4.3
New Jersey	cert labs	13293	distribution	12281994		1.5
New Jersey	cert labs	13293	distribution	12311994		1.5
New Jersey	cert labs	13293	distribution	02011995		0.8
New Jersey	cert labs	13293	distribution	02011995		1.5
New Jersey	cert labs	14144	distribution	03071994		11
New Jersey	cert labs	14144	distribution	06071994		4.8
New Jersey	cert labs	14144	distribution	09011994		6.1
New Jersey	cert labs	16616	distribution	12271994		1.1
New Jersey	cert labs	18293	distribution	03251994		0.58
New Jersey	cert labs	18293	distribution	03251994		16.4
New Jersey	cert labs	16121	distribution	01101994		0.9
New Jersey	cert labs	16121	distribution	04051994		0.5
New Jersey	cert labs	16121	distribution	06071994		0.7
New Jersey	cert labs	16121	distribution	07071994		0.6
New Jersey	cert labs	16121	distribution	10041994		0.8
New Jersey	cert labs	31160	distribution	06071994		2.4
New Jersey	cert labs	19203	distribution	03281994		0.8
New Jersey	cert labs	19203	distribution	07121994		0.7
New Jersey	cert labs	19203	distribution	07121994		1.5
New Jersey	cert labs	19319	distribution	03151994		0.8
New Jersey	New Jersey DOH	32159	distribution	12071992		0.7
New Jersey	New Jersey DOH	77000	distribution	12221992		1
New Jersey	New Jersey DOH	60011	distribution	08171994		0.4
New Jersey	New Jersey DOH	60011	distribution	08171995		0.4
New Jersey	New Jersey DOH	80865	distribution	05061992		0.2
New Jersey	New Jersey DOH	38904	distribution	05051992		0.1
New Jersey	New Jersey DOH	42800	distribution	01201994		0.6
New Jersey	New Jersey DOH	45480	distribution	02071994		0.4
New Jersey	New Jersey DOH	58008	distribution	02021994		2
New Jersey	New Jersey DOH	13126	distribution	01281993		2
New Jersey	New Jersey DOH	86452	distribution	05121992		0.8
New Jersey	New Jersey DOH	16678	distribution	02081993		0.4
New Jersey	New Jersey DOH	33226	distribution	05111992		0.5
New Jersey	New Jersey DOH	66270	distribution	02231992		0.9
New Jersey	New Jersey DOH	16121	distribution	09281994		0.5
New Jersey	New Jersey DOH	13227	distribution	09221994		1

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
New Jersey	New Jersey DOH	26434	distribution	06111992		0.3
New Jersey	New Jersey DOH	52856	distribution	03181992		0.7
New Jersey	New Jersey DOH	10566	distribution	05061992		0.8
Iowa	Alvord PWS	21130	well	01121994		63
Iowa	Alvord PWS	21130	well	08031994		15
Iowa	Alvord PWS	21130	well	10171994		17
Missouri	BHMGRP	private well #1	well prior to filters	09021992	3,300	
Missouri	BHMGRP	private well #1	well prior to filters	09221992	4,700	
Missouri	BHMGRP	private well #1	well prior to filters	09301992	7,000	
Missouri	BHMGRP	private well #1	well prior to filters	10061992	3,100	
Missouri	BHMGRP	private well #1	well prior to filters	10201992	4,400	
Missouri	BHMGRP	private well #1	well prior to filters	12291992	2,900	
Missouri	BHMGRP	private well #1	well prior to filters	11031992	6,000	
Missouri	BHMGRP	private well #1	well prior to filters	11171992	1,200	
Missouri	BHMGRP	private well #1	well prior to filters	12031992	3,000	
Missouri	BHMGRP	private well #1	well prior to filters	12181992	1,300	
Missouri	BHMGRP	private well #1	well prior to filters	01141993	4,500	
Missouri	BHMGRP	private well #1	well prior to filters	01291993	3,000	
Missouri	BHMGRP	private well #1	well prior to filters	02091993	2,800	
Missouri	BHMGRP	private well #1	well prior to filters	02231993	6,900	
Missouri	BHMGRP	private well #1	well prior to filters	03181993	9,000	
Missouri	BHMGRP	private well #1	well prior to filters	03301993	9,300	
Missouri	BHMGRP	private well #1	well prior to filters	04131993	11,000	
Missouri	BHMGRP	private well #1	well prior to filters	04271993	4,500	
Missouri	BHMGRP	private well #1	well prior to filters	05261993	14,000	
Missouri	BHMGRP	private well #1	well prior to filters	06081993	11,000	
Missouri	BHMGRP	private well #1	well prior to filters	06231993	3,400	
Missouri	BHMGRP	private well #1	well prior to filters	07191993	4,000	
Missouri	BHMGRP	private well #1	well prior to filters	09161993	1,800	
Missouri	BHMGRP	private well #1	well prior to filters	10071993	880	
Missouri	BHMGRP	private well #1	well prior to filters	10221993	4,400	
Missouri	BHMGRP	private well #1	well prior to filters	11051993	1,800	
Missouri	BHMGRP	private well #1	well prior to filters	11231993	1,400	
Missouri	BHMGRP	private well #1	well prior to filters	12081993	1,500	
Missouri	BHMGRP	private well #1	well prior to filters	12211993	2,000	
Missouri	BHMGRP	private well #1	well prior to filters	01061994	2,000	
Missouri	BHMGRP	private well #1	well prior to filters	02021994	3,300	
Missouri	BHMGRP	private well #1	well prior to filters	02161994	4,040	
Missouri	BHMGRP	private well #1	well prior to filters	03171994	3,902	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Missouri	BHMGRP	private well #1	well prior to filters	04271994	2,400	
Missouri	BHMGRP	private well #1	well prior to filters	07071994	1,200	
Missouri	BHMGRP	private well #1	well prior to filters	07211994	1,200	
Missouri	BHMGRP	private well #1	well prior to filters	08041994	1,900	
Missouri	BHMGRP	private well #1	well prior to filters	08181994	1,300	
Missouri	BHMGRP	private well #1	well prior to filters	08311994	700	
Missouri	BHMGRP	private well #1	well prior to filters	09121994	780	
Missouri	BHMGRP	private well #1	well prior to filters	09261994	920	
Missouri	BHMGRP	private well #1	well prior to filters	10131994	2,600	
Missouri	BHMGRP	private well #1	well prior to filters	10271994	1,400	
Missouri	BHMGRP	private well #1	well prior to filters	11031994	1,400	
Missouri	BHMGRP	private well #1	well prior to filters	11091994	1,600	
Missouri	BHMGRP	private well #1	well prior to filters	01111995	1,900	
Missouri	BHMGRP	private well #2	well prior to filters	09021992	3,000	
Missouri	BHMGRP	private well #2	well prior to filters	09151992	2,100	
Missouri	BHMGRP	private well #2	well prior to filters	09221992	3,400	
Missouri	BHMGRP	private well #2	well prior to filters	09301992	3,600	
Missouri	BHMGRP	private well #2	well prior to filters	10061992	1,700	
Missouri	BHMGRP	private well #2	well prior to filters	04131993	7,100	
Missouri	BHMGRP	private well #2	well prior to filters	04271993	1,800	
Missouri	BHMGRP	private well #2	well prior to filters	05141993	3,800	
Missouri	BHMGRP	private well #2	well prior to filters	05261993	17,000	
Missouri	BHMGRP	private well #2	well prior to filters	06081993	14,000	
Missouri	BHMGRP	private well #2	well prior to filters	06231993	5,000	
Missouri	BHMGRP	private well #2	well prior to filters	07191993	8,200	
Missouri	BHMGRP	private well #2	well prior to filters	09161993	2,300	
Missouri	BHMGRP	private well #2	well prior to filters	10071993	1,500	
Missouri	BHMGRP	private well #2	well prior to filters	10221993	4,100	
Missouri	BHMGRP	private well #2	well prior to filters	11051993	5,900	
Missouri	BHMGRP	private well #2	well prior to filters	11231993	2,200	
Missouri	BHMGRP	private well #2	well prior to filters	12211993	2,600	
Missouri	BHMGRP	private well #2	well prior to filters	03031994	3,060	
Missouri	BHMGRP	private well #2	well prior to filters	03171994	2,903	
Missouri	BHMGRP	private well #2	well prior to filters	04191994	3,600	
Missouri	BHMGRP	private well #2	well prior to filters	04271994	2,300	
Missouri	BHMGRP	private well #2	well prior to filters	07071994	1,700	
Missouri	BHMGRP	private well #2	well prior to filters	07211994	2,200	
Missouri	BHMGRP	private well #2	well prior to filters	08041994	2,200	
Missouri	BHMGRP	private well #2	well prior to filters	08181994	1,600	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Missouri	BHMGRP	private well #2	well prior to filters	08311994	850	
Missouri	BHMGRP	private well #2	well prior to filters	09121994	670	
Missouri	BHMGRP	private well #2	well prior to filters	09261994	940	
Missouri	BHMGRP	private well #2	well prior to filters	10131994	1,300	
Missouri	BHMGRP	private well #2	well prior to filters	11091994	510	
Missouri	BHMGRP	private well #2	well prior to filters	01111995	1,100	
Missouri	BHMGRP	private well #3	well prior to filters	09021992	690	
Missouri	BHMGRP	private well #3	well prior to filters	09081992	990	
Missouri	BHMGRP	private well #3	well prior to filters	09151992	790	
Missouri	BHMGRP	private well #3	well prior to filters	09221992	160	
Missouri	BHMGRP	private well #3	well prior to filters	09301992	2,200	
Missouri	BHMGRP	private well #3	well prior to filters	10061992	1,100	
Missouri	BHMGRP	private well #3	well prior to filters	10201992	1,700	
Missouri	BHMGRP	private well #3	well prior to filters	11031992	1,100	
Missouri	BHMGRP	private well #3	well prior to filters	12031992	1,100	
Missouri	BHMGRP	private well #3	well prior to filters	12181992	610	
Missouri	BHMGRP	private well #3	well prior to filters	01141993	910	
Missouri	BHMGRP	private well #3	well prior to filters	01291993	530	
Missouri	BHMGRP	private well #3	well prior to filters	02091993	1,300	
Missouri	BHMGRP	private well #3	well prior to filters	02231993	250	
Missouri	BHMGRP	private well #3	well prior to filters	03181993	720	
Missouri	BHMGRP	private well #3	well prior to filters	03301993	450	
Missouri	BHMGRP	private well #3	well prior to filters	04131993	1,300	
Missouri	BHMGRP	private well #3	well prior to filters	04271993	2,600	
Missouri	BHMGRP	private well #3	well prior to filters	05141993	540	
Missouri	BHMGRP	private well #3	well prior to filters	05261993	1,000	
Missouri	BHMGRP	private well #3	well prior to filters	06081993	1,600	
Missouri	BHMGRP	private well #3	well prior to filters	06231993	140	
Missouri	BHMGRP	private well #3	well prior to filters	07191993	1,400	
Missouri	BHMGRP	private well #3	well prior to filters	09161993	210	
Missouri	BHMGRP	private well #3	well prior to filters	10071993	230	
Missouri	BHMGRP	private well #3	well prior to filters	10221993	740	
Missouri	BHMGRP	private well #3	well prior to filters	11101993	72	
Missouri	BHMGRP	private well #3	well prior to filters	11231993	620	
Missouri	BHMGRP	private well #3	well prior to filters	12081993	1,100	
Missouri	BHMGRP	private well #3	well prior to filters	12211993	960	
Missouri	BHMGRP	private well #3	well prior to filters	01061994	730	
Missouri	BHMGRP	private well #3	well prior to filters	02021994	1,500	
Missouri	BHMGRP	private well #3	well prior to filters	02161994	738	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Missouri	BHMGRP	private well #3	well prior to filters	03031994	525	
Missouri	BHMGRP	private well #3	well prior to filters	03171994	981	
Missouri	BHMGRP	private well #3	well prior to filters	03291994	794	
Missouri	BHMGRP	private well #3	well prior to filters	04141994	100	
Missouri	BHMGRP	private well #3	well prior to filters	04191994	340	
Missouri	BHMGRP	private well #3	well prior to filters	04271994	110	
Missouri	BHMGRP	private well #3	well prior to filters	05121994	76	
Missouri	BHMGRP	private well #3	well prior to filters	05251994	400	
Missouri	BHMGRP	private well #3	well prior to filters	06011994	46	
Missouri	BHMGRP	private well #3	well prior to filters	07071994	280	
Missouri	BHMGRP	private well #3	well prior to filters	07211994	490	
Missouri	BHMGRP	private well #3	well prior to filters	08041994	50	
Missouri	BHMGRP	private well #3	well prior to filters	08181994	99	
Missouri	BHMGRP	private well #3	well prior to filters	08311994	14	
Missouri	BHMGRP	private well #3	well prior to filters	09121994	13	
Missouri	BHMGRP	private well #3	well prior to filters	10131994	380	
Missouri	BHMGRP	private well #3	well prior to filters	10271994	340	
Missouri	BHMGRP	private well #3	well prior to filters	11031994	430	
Missouri	BHMGRP	private well #3	well prior to filters	11091994	370	
Missouri	BHMGRP	private well #3	well prior to filters	01111995	780	
Missouri	BHMGRP	private well #4	well prior to filters	09161993	8.8	
Missouri	BHMGRP	private well #4	well prior to filters	07071994	1,500	
Illinois	IL EPA	73081	distribution	08041993		770
Illinois	IL EPA	73081	distribution	09291993		270
Illinois	IL EPA	73081	distribution	12281993		620
Illinois	IL EPA	73081	distribution	02151994		400
Illinois	IL EPA	73081	distribution	02151994		400
Illinois	IL EPA	73081	well	02241994		580
Illinois	IL EPA	73081	well	02241994		350
Illinois	IL EPA	32018	distribution	12091993		50
Illinois	IL EPA	32018	distribution	01261994		37
Illinois	IL EPA	32018	distribution	02151994		50
Illinois	IL EPA	32018	distribution	05251994		20
Illinois	IL EPA	47420	distribution	03061995		4
Illinois	IL EPA	76547	distribution	03211994		24
Illinois	IL EPA	76547	distribution	06081994		11
Illinois	IL EPA	76547	distribution	08211994		24

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Illinois	IL EPA	76547	distribution	04111995		15
Illinois	IL EPA	76547	distribution	04111995		15
Illinois	IL EPA	76547	distribution	04111995		15
Illinois	IL EPA	76547	distribution	09141994		10
Illinois	IL EPA	76547	distribution	11281994		19
Illinois	IL EPA	36973	well	07091990		1.8
Illinois	IL EPA	36973	well	07091990		1.2
Illinois	IL EPA	42786	well	07091990		0.9
Illinois	IL EPA	42786	well	07091990		1.1
Illinois	IL EPA	42786	well	07231990		0.8
Illinois	IL EPA	42786	distribution	07231990		0.4
Illinois	IL EPA	66369	distribution	06291993		85
Illinois	IL EPA	66369	distribution	08301993		14
Illinois	IL EPA	66369	distribution	11221993		24
Indiana	IN DEM	private well 1	well	00001991	5,400	
Indiana	IN DEM	private well 2	well	00001991	40	
Texas	EPA Region VI	2020013	distribution	03181993		6.3
Texas	EPA Region VI	2050011	distribution	06071993		4.3
Texas	EPA Region VI	1011467	distribution	06151993		8
Texas	EPA Region VI	0840063	distribution	06151993		10.4
Texas	EPA Region VI	1011033	distribution	06151993		8.2
Texas	EPA Region VI	1012202	distribution	06151993		4.7
Texas	EPA Region VI	1012722	distribution	06151993		3.6
Texas	EPA Region VI	2020013	distribution	06231993		42
Texas	EPA Region VI	private well	well	02061990	5	
Texas	EPA Region VI	private well	well	04201990	2	
Texas	EPA Region VI	private well	well	11281990	12	
Texas	EPA Region VI	private well	well	04221991	2	
Texas	EPA Region VI	private well	well	05201991	3,360	
Texas	EPA Region VI	private well	well	09101991	20	
Texas	EPA Region VI	private well	well	12041991	2	
Texas	EPA Region VI	private well	well	03181992	8	
Texas	EPA Region VI	private well	well	12041992	2.8	
Rhode Island	RI DOH	public water system	distribution	01261988		2
Rhode Island	RI DOH	public water system	distribution	10181988		53
Rhode Island	RI DOH	public water system	distribution	09261988		61
Rhode Island	RI DOH	public water system	distribution	11211988		1
Rhode Island	RI DOH	public water system	distribution	02161989		33
Rhode Island	RI DOH	public water system	distribution	06081989		48

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	public water system	distribution	07121989		3
Rhode Island	RI DOH	public water system	distribution	09061989		32
Rhode Island	RI DOH	public water system	distribution	09261989		17
Rhode Island	RI DOH	public water system	distribution	10121989		28
Rhode Island	RI DOH	public water system	distribution	11091989		21
Rhode Island	RI DOH	public water system	distribution	11101989		9
Rhode Island	RI DOH	public water system	distribution	11271989		4
Rhode Island	RI DOH	public water system	well	01101990		5
Rhode Island	RI DOH	public water system	distribution	01241990		8
Rhode Island	RI DOH	public water system	well	03081990		10
Rhode Island	RI DOH	public water system	distribution	03121990		1
Rhode Island	RI DOH	public water system	distribution	03161990		5
Rhode Island	RI DOH	public water system	distribution	04131990		5
Rhode Island	RI DOH	public water system	distribution	05091990		3
Rhode Island	RI DOH	public water system	distribution	05101990		4
Rhode Island	RI DOH	public water system	distribution	05101990		9
Rhode Island	RI DOH	public water system	distribution	05161990		12
Rhode Island	RI DOH	public water system	distribution	06061990		5
Rhode Island	RI DOH	public water system	well	06191990		5
Rhode Island	RI DOH	public water system	distribution	06201990		5
Rhode Island	RI DOH	public water system	distribution	07061990		3
Rhode Island	RI DOH	public water system	distribution	07241990		1
Rhode Island	RI DOH	public water system	distribution	07311990		5
Rhode Island	RI DOH	public water system	distribution	08161990		4
Rhode Island	RI DOH	public water system	distribution	08171990		39
Rhode Island	RI DOH	public water system	well	08171990		4
Rhode Island	RI DOH	public water system	distribution	08171990		4
Rhode Island	RI DOH	public water system	distribution	09171990		1
Rhode Island	RI DOH	public water system	distribution	09171990		2
Rhode Island	RI DOH	public water system	distribution	09171990		9
Rhode Island	RI DOH	public water system	well	01051990		17,800
Rhode Island	RI DOH	public water system	distribution	10251990		2
Rhode Island	RI DOH	public water system	well	10251990		9
Rhode Island	RI DOH	public water system	distribution	10291990		1
Rhode Island	RI DOH	public water system	well	11071990		1
Rhode Island	RI DOH	public water system	well	11191990		5
Rhode Island	RI DOH	public water system	well	11201990		8
Rhode Island	RI DOH	public water system	well	12051990		7
Rhode Island	RI DOH	public water system	well	12191990		4

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	public water system	well	01161991		2
Rhode Island	RI DOH	public water system	well	02121991		2
Rhode Island	RI DOH	public water system	well	02131991		2
Rhode Island	RI DOH	public water system	distribution	02131991		1
Rhode Island	RI DOH	public water system	well	02211991		8
Rhode Island	RI DOH	public water system	distribution	03121991		4
Rhode Island	RI DOH	public water system	distribution	03121991		5
Rhode Island	RI DOH	public water system	well	04121991		1
Rhode Island	RI DOH	public water system	well	04181991		2
Rhode Island	RI DOH	public water system	well	04181991		6
Rhode Island	RI DOH	public water system	well	05091991		1
Rhode Island	RI DOH	public water system	distribution	05151991		2
Rhode Island	RI DOH	public water system	well	05171991		1
Rhode Island	RI DOH	public water system	well	05171991		2
Rhode Island	RI DOH	public water system	well	05171991		3
Rhode Island	RI DOH	public water system	well	05171991		4
Rhode Island	RI DOH	public water system	well	06041991		1
Rhode Island	RI DOH	public water system	well	06051991		2
Rhode Island	RI DOH	public water system	distribution	07251991		1
Rhode Island	RI DOH	public water system	well	07251991		1
Rhode Island	RI DOH	public water system	well	07291991		2
Rhode Island	RI DOH	public water system	well	08141991		1
Rhode Island	RI DOH	public water system	well	09171991		5
Rhode Island	RI DOH	public water system	well	09251991		2
Rhode Island	RI DOH	public water system	distribution	10071991		1
Rhode Island	RI DOH	public water system	distribution	10071991		1
Rhode Island	RI DOH	public water system	well	10151991		2
Rhode Island	RI DOH	public water system	distribution	10301991		1
Rhode Island	RI DOH	public water system	well	10301991		1
Rhode Island	RI DOH	public water system	well	11141991		2
Rhode Island	RI DOH	public water system	distribution	11181991		1
Rhode Island	RI DOH	public water system	well	11191991		3
Rhode Island	RI DOH	public water system	well	11221991		3
Rhode Island	RI DOH	public water system	well	11221991		3
Rhode Island	RI DOH	public water system	well	11221991		3
Rhode Island	RI DOH	public water system	well	01071992		1
Rhode Island	RI DOH	public water system	well	01281992		1
Rhode Island	RI DOH	public water system	distribution	03051992		7
Rhode Island	RI DOH	public water system	distribution	08191992		1

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	public water system	well	01051993		2
Rhode Island	RI DOH	public water system	well	01111990		7
Rhode Island	RI DOH	public water system	distribution	02021993		2
Rhode Island	RI DOH	public water system	well	11181993		6
Rhode Island	RI DOH	public water system	well	12231993		1
Rhode Island	RI DOH	public water system	well	12231993		5
Rhode Island	RI DOH	public water system	well	12231993		4
Rhode Island	RI DOH	public water system	surface water	01251994		1
Rhode Island	RI DOH	public water system	distribution	02031994		8
Rhode Island	RI DOH	public water system	distribution	03091994		5
Rhode Island	RI DOH	public water system	well	03291994		1
Rhode Island	RI DOH	public water system	well	04141994		6
Rhode Island	RI DOH	public water system	distribution	04291994		6
Rhode Island	RI DOH	public water system	distribution	05191994		7
Rhode Island	RI DOH	public water system	distribution	06071994		6
Rhode Island	RI DOH	public water system	well	06291994		5
Rhode Island	RI DOH	public water system	distribution	07061994		6
Rhode Island	RI DOH	public water system	distribution	08111994		7
Rhode Island	RI DOH	public water system	distribution	08251994		6
Rhode Island	RI DOH	public water system	well	09061994		1
Rhode Island	RI DOH	public water system	well	09061994		3
Rhode Island	RI DOH	public water system	distribution	09261994		5
Rhode Island	RI DOH	public water system	distribution	10211994		6
Rhode Island	RI DOH	public water system	distribution	12291994		12
Rhode Island	RI DOH	public water system	well	02231995		14
Rhode Island	RI DOH	public water system	well	04051995		10
Rhode Island	RI DOH	public water system	well	05251995		22
Rhode Island	RI DOH	public water system	distribution	07101995		10
Rhode Island	RI DOH	public water system	well	07101995		3
Rhode Island	RI DOH	public water system	distribution	04181995		9.6
Rhode Island	RI DOH	public water system	well	06301995		2.2
Rhode Island	RI DOH	public water system	distribution	05241995		9
Rhode Island	RI DOH	public water system	distribution	07171995		15
Rhode Island	RI DOH	public water system	distribution	06291995		10
Rhode Island	RI DOH	private well	well	10201987	5	
Rhode Island	RI DOH	private well	well	10271987	213	
Rhode Island	RI DOH	private well	well	10301987	25	
Rhode Island	RI DOH	private well	well	11041987	130	
Rhode Island	RI DOH	private well	well	11041987	150	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	11091987	4	
Rhode Island	RI DOH	private well	well	11161987	1	
Rhode Island	RI DOH	private well	well	11231987	1	
Rhode Island	RI DOH	private well	well	12101987	16	
Rhode Island	RI DOH	private well	well	12141987	35	
Rhode Island	RI DOH	private well	well	12171987	80	
Rhode Island	RI DOH	private well	well	01071988	40	
Rhode Island	RI DOH	private well	well	01201988	290	
Rhode Island	RI DOH	private well	well	01191988	47	
Rhode Island	RI DOH	private well	well	01211988	27	
Rhode Island	RI DOH	private well	well	02011988	35	
Rhode Island	RI DOH	private well	well	02011988	170	
Rhode Island	RI DOH	private well	well	03281988	73	
Rhode Island	RI DOH	private well	well	03291988	12	
Rhode Island	RI DOH	private well	well	04041988	300	
Rhode Island	RI DOH	private well	well	04111988	90	
Rhode Island	RI DOH	private well	well	04111988	100	
Rhode Island	RI DOH	private well	well	04111988	120	
Rhode Island	RI DOH	private well	well	04251988	20	
Rhode Island	RI DOH	private well	well	05231988	13	
Rhode Island	RI DOH	private well	well	05231988	2	
Rhode Island	RI DOH	private well	well	05231988	170	
Rhode Island	RI DOH	private well	well	05231988	1,300	
Rhode Island	RI DOH	private well	well	05231988	4	
Rhode Island	RI DOH	private well	well	05231988	1,000	
Rhode Island	RI DOH	private well	well	05251988	60	
Rhode Island	RI DOH	private well	well	05251988	4	
Rhode Island	RI DOH	private well	well	05311988	85	
Rhode Island	RI DOH	private well	well	06061988	43	
Rhode Island	RI DOH	private well	well	06061988	1	
Rhode Island	RI DOH	private well	well	06071988	1,800	
Rhode Island	RI DOH	private well	well	06071988	11	
Rhode Island	RI DOH	private well	well	06241988	53	
Rhode Island	RI DOH	private well	well	06301988	2	
Rhode Island	RI DOH	private well	well	07121988	2	
Rhode Island	RI DOH	private well	well	07121988	10	
Rhode Island	RI DOH	private well	well	07121988	3	
Rhode Island	RI DOH	private well	well	07121988	7	
Rhode Island	RI DOH	private well	well	07121988	2	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	07121988	250	
Rhode Island	RI DOH	private well	well	07121988	40	
Rhode Island	RI DOH	private well	well	07181988	2	
Rhode Island	RI DOH	private well	well	07151988	22	
Rhode Island	RI DOH	private well	well	08221988	3	
Rhode Island	RI DOH	private well	well	09011988	26	
Rhode Island	RI DOH	private well	well	08221988	2	
Rhode Island	RI DOH	private well	well	09201988	2	
Rhode Island	RI DOH	private well	well	09191988	5	
Rhode Island	RI DOH	private well	well	10191988	11	
Rhode Island	RI DOH	private well	well	05031989	1	
Rhode Island	RI DOH	private well	well	09191988	9	
Rhode Island	RI DOH	private well	well	11141988	3	
Rhode Island	RI DOH	private well	well	12121988	35	
Rhode Island	RI DOH	private well	well	01051989	12	
Rhode Island	RI DOH	private well	well	01231989	120	
Rhode Island	RI DOH	private well	well	01241989	35	
Rhode Island	RI DOH	private well	well	01311989	30	
Rhode Island	RI DOH	private well	well	01311989	40	
Rhode Island	RI DOH	private well	well	01301989	140	
Rhode Island	RI DOH	private well	well	02011989	35	
Rhode Island	RI DOH	private well	well	03071989	4	
Rhode Island	RI DOH	private well	well	04041989	36	
Rhode Island	RI DOH	private well	well	04041989	5	
Rhode Island	RI DOH	private well	well	04251989	1	
Rhode Island	RI DOH	private well	well	05221989	230	
Rhode Island	RI DOH	private well	well	06191989	8	
Rhode Island	RI DOH	private well	well	06191989	120	
Rhode Island	RI DOH	private well	well	07131989	9	
Rhode Island	RI DOH	private well	well	04281989	150	
Rhode Island	RI DOH	private well	well	05021989	125	
Rhode Island	RI DOH	private well	well	08201989	50	
Rhode Island	RI DOH	private well	well	08101989	13	
Rhode Island	RI DOH	private well	well	08101989	8	
Rhode Island	RI DOH	private well	well	08101989	12	
Rhode Island	RI DOH	private well	well	07261989	94	
Rhode Island	RI DOH	private well	well	09191989	25	
Rhode Island	RI DOH	private well	well	09191989	37	
Rhode Island	RI DOH	private well	well	09191989	6	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	09201989	56	
Rhode Island	RI DOH	private well	well	10051989	2	
Rhode Island	RI DOH	private well	well	10021989	1	
Rhode Island	RI DOH	private well	well	10171989	28	
Rhode Island	RI DOH	private well	well	10171989	45	
Rhode Island	RI DOH	private well	well	10211989	12	
Rhode Island	RI DOH	private well	well	10211989	139	
Rhode Island	RI DOH	private well	well	10251989	2	
Rhode Island	RI DOH	private well	well	11111989	30	
Rhode Island	RI DOH	private well	well	11111989	7	
Rhode Island	RI DOH	private well	well	11031989	23	
Rhode Island	RI DOH	private well	well	11071989	33	
Rhode Island	RI DOH	private well	well	11071989	49	
Rhode Island	RI DOH	private well	well	11071989	41	
Rhode Island	RI DOH	private well	well	11071989	18	
Rhode Island	RI DOH	private well	well	11171989	4	
Rhode Island	RI DOH	private well	well	11201989	79	
Rhode Island	RI DOH	private well	well	11241989	5	
Rhode Island	RI DOH	private well	well	12061989	34	
Rhode Island	RI DOH	private well	well	12051989	70	
Rhode Island	RI DOH	private well	well	12141989	10	
Rhode Island	RI DOH	private well	well	12191989	5	
Rhode Island	RI DOH	private well	well	01111990	31	
Rhode Island	RI DOH	private well	well	01111990	1	
Rhode Island	RI DOH	private well	well	01051990	90	
Rhode Island	RI DOH	private well	well	01161990	4	
Rhode Island	RI DOH	private well	well	01251990	6	
Rhode Island	RI DOH	private well	well	01221990	92	
Rhode Island	RI DOH	private well	well	01221990	27	
Rhode Island	RI DOH	private well	well	01221990	85	
Rhode Island	RI DOH	private well	well	01221990	147	
Rhode Island	RI DOH	private well	well	01221990	716	
Rhode Island	RI DOH	private well	well	02011990	116	
Rhode Island	RI DOH	private well	well	02011990	27	
Rhode Island	RI DOH	private well	well	01191990	320	
Rhode Island	RI DOH	private well	well	01191990	35	
Rhode Island	RI DOH	private well	well	01191990	2	
Rhode Island	RI DOH	private well	well	01221990	46	
Rhode Island	RI DOH	private well	well	01221990	59	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	01221990	77	
Rhode Island	RI DOH	private well	well	01191990	5	
Rhode Island	RI DOH	private well	well	01191990	3	
Rhode Island	RI DOH	private well	well	02121990	39	
Rhode Island	RI DOH	private well	well	02121990	20	
Rhode Island	RI DOH	private well	well	02121990	3	
Rhode Island	RI DOH	private well	well	02121990	33	
Rhode Island	RI DOH	private well	well	02051990	5	
Rhode Island	RI DOH	private well	well	02051990	6	
Rhode Island	RI DOH	private well	well	02151990	53	
Rhode Island	RI DOH	private well	well	02051990	177	
Rhode Island	RI DOH	private well	well	02151990	30	
Rhode Island	RI DOH	private well	well	11211989	3	
Rhode Island	RI DOH	private well	well	02021990	100	
Rhode Island	RI DOH	private well	well	02191990	1	
Rhode Island	RI DOH	private well	well	02211990	1	
Rhode Island	RI DOH	private well	well	02231990	29	
Rhode Island	RI DOH	private well	well	02261990	4	
Rhode Island	RI DOH	private well	well	02011990	274	
Rhode Island	RI DOH	private well	well	02011990	1	
Rhode Island	RI DOH	private well	well	02221990	4	
Rhode Island	RI DOH	private well	well	02221990	16	
Rhode Island	RI DOH	private well	well	03071990	40	
Rhode Island	RI DOH	private well	well	03071990	15	
Rhode Island	RI DOH	private well	well	03081990	39	
Rhode Island	RI DOH	private well	well	03081990	5	
Rhode Island	RI DOH	private well	well	03021990	15	
Rhode Island	RI DOH	private well	well	03021990	1,439	
Rhode Island	RI DOH	private well	well	03111990	5	
Rhode Island	RI DOH	private well	well	03111990	28	
Rhode Island	RI DOH	private well	well	03201990	478	
Rhode Island	RI DOH	private well	well	03201990	77	
Rhode Island	RI DOH	private well	well	03201990	6	
Rhode Island	RI DOH	private well	well	03201990	102	
Rhode Island	RI DOH	private well	well	03201990	18	
Rhode Island	RI DOH	private well	well	03201990	24	
Rhode Island	RI DOH	private well	well	03201990	40	
Rhode Island	RI DOH	private well	well	03201990	49	
Rhode Island	RI DOH	private well	well	03201990	22	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	03201990	9	
Rhode Island	RI DOH	private well	well	03151990	41	
Rhode Island	RI DOH	private well	well	03151990	164	
Rhode Island	RI DOH	private well	well	03091990	4	
Rhode Island	RI DOH	private well	well	03091990	5	
Rhode Island	RI DOH	private well	well	03091990	18	
Rhode Island	RI DOH	private well	well	03091990	65	
Rhode Island	RI DOH	private well	well	02221990	15	
Rhode Island	RI DOH	private well	well	02221990	19	
Rhode Island	RI DOH	private well	well	03281990	4	
Rhode Island	RI DOH	private well	well	03211990	19	
Rhode Island	RI DOH	private well	well	04051990	37	
Rhode Island	RI DOH	private well	well	04051990	9	
Rhode Island	RI DOH	private well	well	04051990	3	
Rhode Island	RI DOH	private well	well	04031990	12	
Rhode Island	RI DOH	private well	well	04031990	1,500	
Rhode Island	RI DOH	private well	well	04251990	9	
Rhode Island	RI DOH	private well	well	04251990	38	
Rhode Island	RI DOH	private well	well	04251990	29	
Rhode Island	RI DOH	private well	well	04241990	9	
Rhode Island	RI DOH	private well	well	04251990	4	
Rhode Island	RI DOH	private well	well	04261990	4	
Rhode Island	RI DOH	private well	well	04301990	3	
Rhode Island	RI DOH	private well	well	04301990	2	
Rhode Island	RI DOH	private well	well	05011990	34	
Rhode Island	RI DOH	private well	well	05011990	32	
Rhode Island	RI DOH	private well	well	05011990	16	
Rhode Island	RI DOH	private well	well	05011990	28	
Rhode Island	RI DOH	private well	well	05021990	19	
Rhode Island	RI DOH	private well	well	05021990	9	
Rhode Island	RI DOH	private well	well	05021990	98	
Rhode Island	RI DOH	private well	well	05021990	14	
Rhode Island	RI DOH	private well	well	05021990	61	
Rhode Island	RI DOH	private well	well	05021990	8	
Rhode Island	RI DOH	private well	well	05021990	28	
Rhode Island	RI DOH	private well	well	05071990	140	
Rhode Island	RI DOH	private well	well	05031990	1	
Rhode Island	RI DOH	private well	well	05101990	4	
Rhode Island	RI DOH	private well	well	05101990	32	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	05101990	4	
Rhode Island	RI DOH	private well	well	05101990	2	
Rhode Island	RI DOH	private well	well	05171990	35	
Rhode Island	RI DOH	private well	well	05171990	3	
Rhode Island	RI DOH	private well	well	05161990	41	
Rhode Island	RI DOH	private well	well	05161990	157	
Rhode Island	RI DOH	private well	well	05161990	4	
Rhode Island	RI DOH	private well	well	05161990	28	
Rhode Island	RI DOH	private well	well	05231990	1,353	
Rhode Island	RI DOH	private well	well	05231990	9	
Rhode Island	RI DOH	private well	well	05241990	23	
Rhode Island	RI DOH	private well	well	05241990	127	
Rhode Island	RI DOH	private well	well	05241990	94	
Rhode Island	RI DOH	private well	well	05241990	5	
Rhode Island	RI DOH	private well	well	05241990	6	
Rhode Island	RI DOH	private well	well	05171990	2	
Rhode Island	RI DOH	private well	well	05241990	52	
Rhode Island	RI DOH	private well	well	05241990	748	
Rhode Island	RI DOH	private well	well	05241990	28	
Rhode Island	RI DOH	private well	well	05241990	38	
Rhode Island	RI DOH	private well	well	06041990	40	
Rhode Island	RI DOH	private well	well	05311990	17	
Rhode Island	RI DOH	private well	well	06041990	4	
Rhode Island	RI DOH	private well	well	06141990	24	
Rhode Island	RI DOH	private well	well	06241990	5	
Rhode Island	RI DOH	private well	well	06241990	97	
Rhode Island	RI DOH	private well	well	06211990	31	
Rhode Island	RI DOH	private well	well	06271990	2	
Rhode Island	RI DOH	private well	well	06271990	9	
Rhode Island	RI DOH	private well	well	07021990	11	
Rhode Island	RI DOH	private well	well	07021990	23	
Rhode Island	RI DOH	private well	well	07051990	3	
Rhode Island	RI DOH	private well	well	07051990	2	
Rhode Island	RI DOH	private well	well	07051990	33	
Rhode Island	RI DOH	private well	well	07051990	5	
Rhode Island	RI DOH	private well	well	07061990	1	
Rhode Island	RI DOH	private well	well	07181990	2	
Rhode Island	RI DOH	private well	well	07171990	20	
Rhode Island	RI DOH	private well	well	07171990	15	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	07251990	4	
Rhode Island	RI DOH	private well	well	07251990	1	
Rhode Island	RI DOH	private well	well	07261990	23	
Rhode Island	RI DOH	private well	well	07251990	74	
Rhode Island	RI DOH	private well	well	07251990	8	
Rhode Island	RI DOH	private well	well	07251990	6	
Rhode Island	RI DOH	private well	well	07251990	6	
Rhode Island	RI DOH	private well	well	07251990	6	
Rhode Island	RI DOH	private well	well	07261990	3	
Rhode Island	RI DOH	private well	well	07261990	157	
Rhode Island	RI DOH	private well	well	07261990	86	
Rhode Island	RI DOH	private well	well	07261990	15	
Rhode Island	RI DOH	private well	well	07261990	24	
Rhode Island	RI DOH	private well	well	07261990	33	
Rhode Island	RI DOH	private well	well	07271990	1	
Rhode Island	RI DOH	private well	well	08091990	1,040	
Rhode Island	RI DOH	private well	well	08091990	16	
Rhode Island	RI DOH	private well	well	08201990	24	
Rhode Island	RI DOH	private well	well	08221990	14	
Rhode Island	RI DOH	private well	well	08271990	2	
Rhode Island	RI DOH	private well	well	08271990	29	
Rhode Island	RI DOH	private well	well	08271990	23	
Rhode Island	RI DOH	private well	well	08271990	29	
Rhode Island	RI DOH	private well	well	08271990	123	
Rhode Island	RI DOH	private well	well	08271990	64	
Rhode Island	RI DOH	private well	well	08271990	13	
Rhode Island	RI DOH	private well	well	08271990	17	
Rhode Island	RI DOH	private well	well	08301990	63	
Rhode Island	RI DOH	private well	well	08301990	8	
Rhode Island	RI DOH	private well	well	08301990	46	
Rhode Island	RI DOH	private well	well	08301990	18	
Rhode Island	RI DOH	private well	well	08301990	6	
Rhode Island	RI DOH	private well	well	08301990	800	
Rhode Island	RI DOH	private well	well	08301990	9	
Rhode Island	RI DOH	private well	well	08301990	21	
Rhode Island	RI DOH	private well	well	09051990	2	
Rhode Island	RI DOH	private well	well	09051990	11	
Rhode Island	RI DOH	private well	well	09121990	2	
Rhode Island	RI DOH	private well	well	09101990	11	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	09101990	3	
Rhode Island	RI DOH	private well	well	09101990	30	
Rhode Island	RI DOH	private well	well	09101990	45	
Rhode Island	RI DOH	private well	well	09101990	8	
Rhode Island	RI DOH	private well	well	09101990	20	
Rhode Island	RI DOH	private well	well	09101990	50	
Rhode Island	RI DOH	private well	well	09181990	86	
Rhode Island	RI DOH	private well	well	09201990	6	
Rhode Island	RI DOH	private well	well	09171990	1,484	
Rhode Island	RI DOH	private well	well	09171990	28	
Rhode Island	RI DOH	private well	well	09171990	22	
Rhode Island	RI DOH	private well	well	09171990	98	
Rhode Island	RI DOH	private well	well	09171990	23	
Rhode Island	RI DOH	private well	well	09171990	17	
Rhode Island	RI DOH	private well	well	09171990	103	
Rhode Island	RI DOH	private well	well	09171990	47	
Rhode Island	RI DOH	private well	well	09171990	16	
Rhode Island	RI DOH	private well	well	10021990	104	
Rhode Island	RI DOH	private well	well	10101990	31	
Rhode Island	RI DOH	private well	well	10151990	2	
Rhode Island	RI DOH	private well	well	10111990	1	
Rhode Island	RI DOH	private well	well	10111990	3	
Rhode Island	RI DOH	private well	well	10161990	2	
Rhode Island	RI DOH	private well	well	10221990	60	
Rhode Island	RI DOH	private well	well	10221990	83	
Rhode Island	RI DOH	private well	well	10221990	78	
Rhode Island	RI DOH	private well	well	10221990	97	
Rhode Island	RI DOH	private well	well	10221990	37	
Rhode Island	RI DOH	private well	well	10221990	25	
Rhode Island	RI DOH	private well	well	10221990	11	
Rhode Island	RI DOH	private well	well	10251990	2	
Rhode Island	RI DOH	private well	well	10311990	9	
Rhode Island	RI DOH	private well	well	10311990	11	
Rhode Island	RI DOH	private well	well	10311990	47	
Rhode Island	RI DOH	private well	well	10311990	31	
Rhode Island	RI DOH	private well	well	10311990	24	
Rhode Island	RI DOH	private well	well	10311990	21	
Rhode Island	RI DOH	private well	well	10301990	12	
Rhode Island	RI DOH	private well	well	10301990	5	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	11141990	3	
Rhode Island	RI DOH	private well	well	11271990	17	
Rhode Island	RI DOH	private well	well	11271990	80	
Rhode Island	RI DOH	private well	well	11271990	15	
Rhode Island	RI DOH	private well	well	11271990	17	
Rhode Island	RI DOH	private well	well	11271990	5	
Rhode Island	RI DOH	private well	well	11271990	22	
Rhode Island	RI DOH	private well	well	11281990	37	
Rhode Island	RI DOH	private well	well	11281990	22	
Rhode Island	RI DOH	private well	well	11281990	80	
Rhode Island	RI DOH	private well	well	11281990	2	
Rhode Island	RI DOH	private well	well	11271990	45	
Rhode Island	RI DOH	private well	well	12061990	2	
Rhode Island	RI DOH	private well	well	12061990	29	
Rhode Island	RI DOH	private well	well	12191990	210	
Rhode Island	RI DOH	private well	well	12191990	9	
Rhode Island	RI DOH	private well	well	12191990	27	
Rhode Island	RI DOH	private well	well	12191990	67	
Rhode Island	RI DOH	private well	well	12191990	7	
Rhode Island	RI DOH	private well	well	12191990	49	
Rhode Island	RI DOH	private well	well	12191990	18	
Rhode Island	RI DOH	private well	well	12191990	26	
Rhode Island	RI DOH	private well	well	12201990	29	
Rhode Island	RI DOH	private well	well	12201990	11	
Rhode Island	RI DOH	private well	well	12201990	14	
Rhode Island	RI DOH	private well	well	12201990	3	
Rhode Island	RI DOH	private well	well	12201990	4	
Rhode Island	RI DOH	private well	well	12201990	17	
Rhode Island	RI DOH	private well	well	12201990	3	
Rhode Island	RI DOH	private well	well	12201990	16	
Rhode Island	RI DOH	private well	well	01171991	2	
Rhode Island	RI DOH	private well	well	01221991	1	
Rhode Island	RI DOH	private well	well	02111991	3,000	
Rhode Island	RI DOH	private well	well	02141991	52	
Rhode Island	RI DOH	private well	well	02251991	2	
Rhode Island	RI DOH	private well	well	02251991	5	
Rhode Island	RI DOH	private well	well	02271991	5	
Rhode Island	RI DOH	private well	well	01281991	1	
Rhode Island	RI DOH	private well	well	02261991	3	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	03051991	2	
Rhode Island	RI DOH	private well	well	03051991	2	
Rhode Island	RI DOH	private well	well	03061991	14	
Rhode Island	RI DOH	private well	well	03211991	305	
Rhode Island	RI DOH	private well	well	03211991	5	
Rhode Island	RI DOH	private well	well	03211991	2	
Rhode Island	RI DOH	private well	well	03071991	2	
Rhode Island	RI DOH	private well	well	04021991	1	
Rhode Island	RI DOH	private well	well	03261991	3	
Rhode Island	RI DOH	private well	well	04021991	3	
Rhode Island	RI DOH	private well	well	04101991	1	
Rhode Island	RI DOH	private well	well	04101991	5	
Rhode Island	RI DOH	private well	well	04051991	7	
Rhode Island	RI DOH	private well	well	04051991	8	
Rhode Island	RI DOH	private well	well	05071991	21	
Rhode Island	RI DOH	private well	well	05071991	22	
Rhode Island	RI DOH	private well	well	05071991	190	
Rhode Island	RI DOH	private well	well	05071991	1	
Rhode Island	RI DOH	private well	well	05131991	277	
Rhode Island	RI DOH	private well	well	05131991	21	
Rhode Island	RI DOH	private well	well	05161991	5	
Rhode Island	RI DOH	private well	well	05221991	1	
Rhode Island	RI DOH	private well	well	06021991	7	
Rhode Island	RI DOH	private well	well	06131991	59	
Rhode Island	RI DOH	private well	well	06131991	6	
Rhode Island	RI DOH	private well	well	06181991	155	
Rhode Island	RI DOH	private well	well	07031991	2	
Rhode Island	RI DOH	private well	well	07171991	2	
Rhode Island	RI DOH	private well	well	06211991	209	
Rhode Island	RI DOH	private well	well	08211991	1	
Rhode Island	RI DOH	private well	well	08131991	9	
Rhode Island	RI DOH	private well	well	08261991	87	
Rhode Island	RI DOH	private well	well	08271991	7	
Rhode Island	RI DOH	private well	well	08271991	31	
Rhode Island	RI DOH	private well	well	08271991	18	
Rhode Island	RI DOH	private well	well	09051991	4	
Rhode Island	RI DOH	private well	well	09111991	14	
Rhode Island	RI DOH	private well	well	10031991	2	
Rhode Island	RI DOH	private well	well	10041991	2	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	10041991	103	
Rhode Island	RI DOH	private well	well	10041991	73	
Rhode Island	RI DOH	private well	well	10081991	55	
Rhode Island	RI DOH	private well	well	10081991	1	
Rhode Island	RI DOH	private well	well	10081991	5	
Rhode Island	RI DOH	private well	well	10081991	12	
Rhode Island	RI DOH	private well	well	10171991	2	
Rhode Island	RI DOH	private well	well	10231991	6	
Rhode Island	RI DOH	private well	well	10231991	7	
Rhode Island	RI DOH	private well	well	10231991	2	
Rhode Island	RI DOH	private well	well	10291991	2	
Rhode Island	RI DOH	private well	well	10311991	1	
Rhode Island	RI DOH	private well	well	11081991	5	
Rhode Island	RI DOH	private well	well	11121991	8	
Rhode Island	RI DOH	private well	well	12031991	2	
Rhode Island	RI DOH	private well	well	12171991	3	
Rhode Island	RI DOH	private well	well	11131991	2	
Rhode Island	RI DOH	private well	well	09101991	1	
Rhode Island	RI DOH	private well	well	09101991	1	
Rhode Island	RI DOH	private well	well	07171991	1	
Rhode Island	RI DOH	private well	well	07171991	4	
Rhode Island	RI DOH	private well	well	08191992	30	
Rhode Island	RI DOH	private well	well	08201992	130	
Rhode Island	RI DOH	private well	well	08201992	3	
Rhode Island	RI DOH	private well	well	08201992	2	
Rhode Island	RI DOH	private well	well	09281992	2	
Rhode Island	RI DOH	private well	well	11051992	1.5	
Rhode Island	RI DOH	private well	well	11061992	2	
Rhode Island	RI DOH	private well	well	12021992	3	
Rhode Island	RI DOH	private well	well	12021992	2	
Rhode Island	RI DOH	private well	well	12021992	45	
Rhode Island	RI DOH	private well	well	12181992	2	
Rhode Island	RI DOH	private well	well	01281993	2	
Rhode Island	RI DOH	private well	well	03091993	1	
Rhode Island	RI DOH	private well	well	03161993	11	
Rhode Island	RI DOH	private well	well	04061993	3	
Rhode Island	RI DOH	private well	well	04061993	2	
Rhode Island	RI DOH	private well	well	03251993	1	
Rhode Island	RI DOH	private well	well	04151993	7	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	04201993	7	
Rhode Island	RI DOH	private well	well	04221993	1	
Rhode Island	RI DOH	private well	well	04221993	3	
Rhode Island	RI DOH	private well	well	04221993	4	
Rhode Island	RI DOH	private well	well	04221993	23	
Rhode Island	RI DOH	private well	well	04151993	111	
Rhode Island	RI DOH	private well	well	04151993	65	
Rhode Island	RI DOH	private well	well	04151993	35	
Rhode Island	RI DOH	private well	well	04221993	2	
Rhode Island	RI DOH	private well	well	04221993	3	
Rhode Island	RI DOH	private well	well	06101993	1	
Rhode Island	RI DOH	private well	well	06221993	3	
Rhode Island	RI DOH	private well	well	06301993	25	
Rhode Island	RI DOH	private well	well	06301993	9	
Rhode Island	RI DOH	private well	well	07271993	2	
Rhode Island	RI DOH	private well	well	07301993	17	
Rhode Island	RI DOH	private well	well	07301993	3	
Rhode Island	RI DOH	private well	well	07301993	3	
Rhode Island	RI DOH	private well	well	07271993	2	
Rhode Island	RI DOH	private well	well	07301993	13	
Rhode Island	RI DOH	private well	well	08261993	8	
Rhode Island	RI DOH	private well	well	08251993	1	
Rhode Island	RI DOH	private well	well	08261993	17	
Rhode Island	RI DOH	private well	well	09021993	4	
Rhode Island	RI DOH	private well	well	09021993	31	
Rhode Island	RI DOH	private well	well	09171993	55	
Rhode Island	RI DOH	private well	well	09171993	885	
Rhode Island	RI DOH	private well	well	09171993	280	
Rhode Island	RI DOH	private well	well	09171993	5	
Rhode Island	RI DOH	private well	well	09171993	65	
Rhode Island	RI DOH	private well	well	09171993	185	
Rhode Island	RI DOH	private well	well	09171993	15	
Rhode Island	RI DOH	private well	well	09231993	1	
Rhode Island	RI DOH	private well	well	09231993	1	
Rhode Island	RI DOH	private well	well	09211993	3	
Rhode Island	RI DOH	private well	well	09211993	1	
Rhode Island	RI DOH	private well	well	09211993	5	
Rhode Island	RI DOH	private well	well	09241993	77	
Rhode Island	RI DOH	private well	well	09241993	2	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	09241993	1	
Rhode Island	RI DOH	private well	well	09241993	2	
Rhode Island	RI DOH	private well	well	09241993	2	
Rhode Island	RI DOH	private well	well	09241993	2	
Rhode Island	RI DOH	private well	well	09291993	1	
Rhode Island	RI DOH	private well	well	09291993	1	
Rhode Island	RI DOH	private well	well	09291993	2	
Rhode Island	RI DOH	private well	well	10081993	14	
Rhode Island	RI DOH	private well	well	10071993	3	
Rhode Island	RI DOH	private well	well	10071993	87	
Rhode Island	RI DOH	private well	well	10071993	237	
Rhode Island	RI DOH	private well	well	11091993	2	
Rhode Island	RI DOH	private well	well	11301993	6	
Rhode Island	RI DOH	private well	well	12011993	44	
Rhode Island	RI DOH	private well	well	12091993	5	
Rhode Island	RI DOH	private well	well	01061994	1	
Rhode Island	RI DOH	private well	well	01111994	2,500	
Rhode Island	RI DOH	private well	well	01211994	42	
Rhode Island	RI DOH	private well	well	01211994	40	
Rhode Island	RI DOH	private well	well	01211994	115	
Rhode Island	RI DOH	private well	well	01211994	20	
Rhode Island	RI DOH	private well	well	02011994	35	
Rhode Island	RI DOH	private well	well	02011994	67	
Rhode Island	RI DOH	private well	well	02011994	27	
Rhode Island	RI DOH	private well	well	02031994	10	
Rhode Island	RI DOH	private well	well	02101994	126	
Rhode Island	RI DOH	private well	well	02101994	235	
Rhode Island	RI DOH	private well	well	02221994	54	
Rhode Island	RI DOH	private well	well	02221994	120	
Rhode Island	RI DOH	private well	well	02221994	21	
Rhode Island	RI DOH	private well	well	02221994	23	
Rhode Island	RI DOH	private well	well	02221994	23	
Rhode Island	RI DOH	private well	well	02221994	16	
Rhode Island	RI DOH	private well	well	02221994	10	
Rhode Island	RI DOH	private well	well	02241994	11	
Rhode Island	RI DOH	private well	well	02241994	1	
Rhode Island	RI DOH	private well	well	03291994	1,150	
Rhode Island	RI DOH	private well	well	07221994	70	
Rhode Island	RI DOH	private well	well	07221994	170	

Appendix 7: *Concentration of MTBE measured at indicated sampling point, by type of drinking-water supply.—Continued*

[µg/L, micrograms per liter]

State	Data source	System number	Sampling point description[1]	Date of sample	Private (µg/L)	Public (µg/L)
Rhode Island	RI DOH	private well	well	07221994	530	
Rhode Island	RI DOH	private well	well	07221994	780	
Rhode Island	RI DOH	private well	well	07221994	1,050	
Rhode Island	RI DOH	private well	well	07221994	490	
Rhode Island	RI DOH	private well	well	08041994	1	
Rhode Island	RI DOH	private well	well	08171994	12	
Rhode Island	RI DOH	private well	well	08171994	21	
Rhode Island	RI DOH	private well	well	09161994	55	
Rhode Island	RI DOH	private well	well	09161994	91	
Rhode Island	RI DOH	private well	well	09161994	375	
Rhode Island	RI DOH	private well	well	09161994	1,390	
Rhode Island	RI DOH	private well	well	09161994	730	
Rhode Island	RI DOH	private well	well	09161994	235	
Rhode Island	RI DOH	private well	well	10261994	4	
Rhode Island	RI DOH	private well	well	12081994	31	
Rhode Island	RI DOH	private well	well	06201995	15	
Rhode Island	RI DOH	private well	well	06201995	170	
Rhode Island	RI DOH	private well	well	06151995	8	
Rhode Island	RI DOH	private well	well	06151995	37	
Rhode Island	RI DOH	private well	well	06151995	49	
Rhode Island	RI DOH	private well	well	06151995	17	
Rhode Island	RI DOH	private well	well	06281995	2	
Rhode Island	RI DOH	private well	well	06281995	110	
Rhode Island	RI DOH	private well	well	06281995	3	
Colorado	CO DOH&E	13419	distribution	09271995		0.29

[1] Refers to samples collected from the public water distribution network. Samples may be of treated or untreated water. Well refers to samples of untreated water collected at a well or wellhead.

Appendix 8: *Brief description of the modelling done to simulate the transport of atmospheric MTBE to shallow ground water.*

MTBE transport was simulated using a numerical two-phase flow and transport model. This model allows tracking of a single component in either phase in three spatial dimensions. Both fluid components were considered active, hence capillary, gravitational, and viscous forces were all allowed to act on both phases. Transport in the gaseous or aqueous phases included the processes of: advection, diffusion, dispersion, equilibrium gas/water transfer, and equilibrium sorption.

A control volume numerical formulation approach was used to approximate the governing equations. A sequential approach was used to simulate the flow and transport components within the model. The resulting set of highly non-linear equations were solved using a full Jacobian iterative approach in conjunction with pre-conditioned orthomim solver at each time step.

All of the MTBE simulations used a one-dimensional model domain. The boundary conditions for water flow at the lower boundary was prescribed at 2 meters below the initial equilibrium water-table location. The upper boundary flow condition was a prescribed flux during infiltration events. When there was no precipitation, the boundary was either "no flow" or a specified evapotranspiration rate. The gas-phase boundary condition at the upper boundary was constant atmospheric pressure.

The initial conditions for transport were zero for MTBE concentrations throughout the subsurface domain. The transport boundary condition for the upper boundary for the gas phase was either a constant concentration condition (during periods when MTBE was present in the atmosphere) or diffusion through a stagnant boundary layer when the atmospheric MTBE concentration was zero. For the aqueous phase, the MTBE flux at the upper boundary was controlled by rainfall when MTBE was present in the atmosphere. At the lower boundary, mass was allowed to leave the model domain by advective transport only.