

Occurrence and Potential Human-Health Relevance of Volatile Organic Compounds in
Drinking Water from Domestic Wells in the United States

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List of Abbreviations:

DBCP, Dibromochloropropane

1,1-DCA, 1,1-Dichloroethane

1,1-DCE, 1,1-Dichloroethene

DIPE, Diisopropyl Ether

HBSL, Health-Based Screening Level

LRL, Laboratory Reporting Level

MCL, Maximum Contaminant Level

MRL, Maximum Reporting Level

MTBE, Methyl *tert*-Butyl Ether

NAWQA, National Water-Quality Assessment Program

NWQL, National Water Quality Laboratory

P&T GC/MS, Purge and Trap Gas Chromatography/Mass Spectrometry

PCE, Perchloroethene

RCRA, Resource Conservation and Recovery Act

TAME, *tert*-Amyl Methyl Ether

1,1,1-TCA, 1,1,1-Trichloroethane

TCE, Trichloroethene

THMs, Trihalomethanes

1,2,4-TMB, 1,2,4-Trimethylbenzene

U.S. EPA, United States Environmental Protection Agency

USGS, United States Geological Survey

VOC, Volatile Organic Compound

µg/L, Microgram Per Liter

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Abstract

BACKGROUND: As the population and demand for safe drinking water from domestic wells increase, it is important to examine water quality and contaminant occurrence. A national assessment in 2006 by the U.S. Geological Survey reported findings for 55 volatile organic compounds (VOCs) based on 2,401 domestic wells sampled during 1985–2002.

OJECTIVES: The occurrence of individual and multiple VOCs was examined, and potential human-health relevance of VOC concentrations was assessed. Hydrogeologic and anthropogenic variables that influence the probability of VOC occurrence were identified.

METHODS: The domestic-well samples were collected at the wellhead prior to treatment of water and analyzed for 55 VOCs. Results were used to examine VOC occurrence and identify associations of multiple explanatory variables using logistic regression analyses. A screening-level assessment was used to compare VOC concentrations to U.S. EPA Maximum Contaminant Levels (MCLs) and Health-Based Screening Levels.

RESULTS: VOCs were detected in 65 percent of the samples; about one-half of these samples contained VOC mixtures. Frequently detected VOCs include chloroform, toluene, 1,2,4-trimethylbenzene, and perchloroethene. VOC concentrations generally were less than 1 microgram per liter. One or more VOC concentrations were greater than MCLs in 1.2 percent of samples including dibromochloropropane, 1,2-dichloropropane, ethylene dibromide (fumigants); perchloroethene and trichloroethene (solvents); and 1,1-dichloroethene (organic synthesis compound).

CONCLUSIONS: Drinking water supplied by domestic wells is vulnerable to low-level VOC contamination. About 1 percent of samples had concentrations of potential human-

health concern. Identifying factors associated with VOC occurrence may aid in understanding the sources, transport, and fate of VOCs in ground water.

Introduction

Ground water is used as a drinking-water supply by about one-half of the U.S. population, including almost all people residing in rural areas. As estimated by the U.S. Geological Survey (Hutson et al. 2004), domestic wells provide drinking water to about 43.5 million people representing 15 percent of the total U.S. population (Supplemental Material, Figure 1). Estimated withdrawals from domestic wells increased by 60 percent between 1965 and 2000, with an average withdrawal rate of about 3.6 billion gallons per day in 2000 (Hutson et al. 2004). Between 1995 and 2000, domestic withdrawals increased about 6 percent, and domestic population increased almost 2 percent (Hutson et al. 2004), indicating increased use of self-supplied drinking water. In addition, estimates by the National Ground Water Association indicate that more than 400,000 new domestic wells used for drinking-water supplies are drilled each year in the United States (McCray 2006).

As the population and demand for safe drinking water from domestic wells increase, it is important to examine water quality and identify contaminants that occur in water from domestic wells. One contaminant group of concern is volatile organic compounds (VOCs), which are contained in many products used around households, including solvents, paints, adhesives, deodorizers, refrigerants, fuels, and fumigants. A VOC is an organic chemical that has a high vapor pressure relative to its water solubility. The chemical and physical properties of VOCs allow the compounds to move between the atmosphere, soil, surface water, and ground water. Once in the environment, VOCs can be mobilized, dispersed, diluted, volatilized, adsorbed, and (or) degraded. Although many VOCs have relatively short half-lives in certain media due to abiotic and biotic degradation, other VOCs can be

persistent, degrading little over years or decades. The production of some synthetic organic chemicals (many of which are VOCs) has increased by more than an order of magnitude between 1945 and 1985 (Ashford and Miller 1991). Some VOCs, such as chlorinated solvents, have been used in industry and commerce for almost 100 years (Pankow and Cherry 1996). Once introduced to ground water, VOCs may persist and potentially contaminate drinking-water supplies.

The U.S. Environmental Protection Agency (U.S. EPA) reported that the presence of elevated VOC concentrations in drinking water may be a concern to human health because some VOCs are carcinogens and (or) may adversely affect the liver, kidneys, spleen, and stomach, as well as the nervous, circulatory, reproductive, immune, cardiovascular, and respiratory systems (U.S. EPA 2003, 2007a). Some VOCs may affect cognitive abilities, balance, coordination, and some are eye, skin, and (or) throat irritants (ATSDR 2007a, 2007b; U.S. EPA 2003, 2007a, 2007b).

The U.S. Geological Survey's (USGS) National Water-Quality Assessment (NAWQA) Program recently completed an assessment of 55 VOCs in ground water throughout the United States. A screening-level assessment used in that study compared VOC concentrations to human-health benchmarks for drinking water to aid in understanding the potential human-health relevance of VOC occurrence (Zogorski et al. 2006). VOC concentrations in samples collected prior to treatment or blending during 1985–2002 from 2,401 domestic wells were compared to human-health benchmarks when available, including U.S. EPA Maximum Contaminant Levels (MCLs) for regulated contaminants and Health-Based Screening Levels (HBSLs) for unregulated contaminants (those without U.S. EPA MCLs) (Toccalino et al. 2003). HBSLs, as well as MCLs, are maximum contaminant

concentrations that are not expected to cause adverse health effects over a lifetime of exposure (Toccalino 2007).

MCLs, established under provisions of the Safe Drinking Water Act, are legally enforceable U.S. EPA drinking-water standards (U.S. EPA 2006d) that set the maximum permissible level of a contaminant in water that is delivered to any user of a public water system. MCLs are set as close as feasible to the maximum level of a contaminant at which no known or anticipated adverse effects on human health would occur over a lifetime, taking into account the best available technology, treatment techniques, cost considerations, expert judgment, and public comments (U.S. EPA 2006e).

HBSLs are not legally enforceable drinking-water standards or clean-up levels. Rather, HBSLs are non-enforceable benchmark concentrations in water, when exceeded, may be of potential human-health concern. HBSLs were developed by the USGS in collaboration with U.S. EPA, New Jersey Department of Environmental Protection, and Oregon Health & Science University using standard U.S. EPA Office of Water equations for establishing drinking-water guideline values (Lifetime Health Advisory and Cancer Risk Concentration values) for the protection of human health, and the most current U.S. EPA peer-reviewed, publicly available human-health toxicity information. HBSLs are based on health effects and do not consider cost and technical limitations (Toccalino 2007; Toccalino and Norman 2006; Toccalino et al. 2003) (Supplemental Material, Table 1).

Drinking water from domestic wells is not regulated by Federal standards and typically does not receive the same level of monitoring and treatment as drinking water supplied by public water systems (U.S. EPA 2003). Although regulations vary by State, the quality of water from privately owned domestic wells is the homeowner's responsibility.

This national assessment of 55 VOCs in drinking water from 2,401 domestic well samples has three primary objectives: (1) examine the occurrence of individual VOCs and VOC mixtures; (2) assess the potential human-health relevance of individual VOCs that have established human-health benchmarks; and (3) link VOC occurrence to hydrogeologic and anthropogenic variables that potentially control or influence the occurrence of VOCs in ground water.

Methods

VOC selection. The VOCs in this study were selected on the basis of available information and the feasibility of laboratory analysis of VOCs by purge and trap gas chromatography/mass spectrometry (P&T GC/MS) (Bender et al. 1999). Equipment used for P&T GC/MS included the Tekmar 3000 Concentrator and the Tekmar Velocity Concentrator manufactured by Teledyne Tekmar, Mason, Ohio; Agilent 6890 GC and Agilent 5973 MSD manufactured by Agilent Technologies Inc., Santa Clara, California. Selection of candidate VOCs involved many criteria including potential human-health cancer risks and non-cancer hazards, toxicity to and bioconcentration in freshwater aquatic organisms, physical properties and occurrence statistics, use or potential use as an oxygenate in gasoline, and potential for atmospheric ozone depletion (Bender et al. 1999). Although many VOCs have multiple uses, each compound was placed in a group representing the predominant use (or origin) of the compound, and include fumigants, gasoline hydrocarbons, gasoline oxygenates, organic synthesis compounds (VOCs used in the formation of other organic compounds), refrigerants, solvents, and trihalomethanes (THMs, disinfection by-products).

NAWQA data. Domestic-well data include 2,401 samples collected during 1985–2002 and represent more than 33 of the Nation’s 62 regionally extensive aquifers or aquifer systems (Zogorski et al. 2006). The depth of sampled wells ranged from 6 to 1,500 feet and had a median depth of about 140 feet. The term “sample” represents a distinct geographic site and applies to an environmental domestic-well sample collected at the wellhead prior to household treatment. The characterization of water quality was achieved by sampling 20 to 30 spatially distributed, randomly selected wells throughout network-based, ground-water studies including: (1) large areal and depth dimensions of aquifers considered locally and regionally important (1,621 samples); and (2) shallow, recently recharged ground-water samples (247 samples from agricultural land-use areas and 16 samples from urban land-use areas) (Gilliom et al. 1995).

To supplement NAWQA’s VOC data, existing domestic well data collected by Federal, State, and local agencies (retrospective data) were compiled. Retrospective data that met NAWQA’s design characteristics and data-collection procedures (Lapham and Tadayon 1996) provided information for an additional 517 domestic wells sampled during 1985–1995.

Sampling and analytical methods. A single sample collected at each well represents the water quality discussed in this article. Samples were collected at the wellhead prior to any treatment or holding time in tanks. Most samples were collected by USGS personnel using data-collection protocol and quality-control procedures (Koterba et al. 1995) and analyzed at the USGS National Water Quality Laboratory (NWQL) using P&T GC/MS (Tekmar 3000 Concentrator and Tekmar Velocity Concentrator, Teledyne Tekmar; Agilent 6890 GC and Agilent 5973 MSD, Agilent Technologies Inc.). Information about analytical methods and

quality-control samples used in this study is presented elsewhere (Childress et al. 1999; Connor et al. 1998; Rose and Schroeder 1995).

Prior to April 1996, USGS VOC analytical methodology was similar to U.S. EPA method 524.2, revision 3 (U.S. EPA 1995), using a minimum reporting level (MRL) of 0.2 microgram per liter ($\mu\text{g/L}$). This MRL represents the occurrence of VOCs at a historical reporting value for the USGS and other agencies. An enhanced method for the VOC analysis, implemented in April 1996 by the NWQL, allowed the reporting of VOC concentrations less than the historical MRLs (Connor et al. 1998). Application of this USGS low-level analytical method to domestic-well samples resulted in substantially lower reporting levels for many VOCs. Laboratory reporting levels (LRLs) for most VOCs were different from one another, and LRLs also varied as method changes were implemented or new instrumentation was used (Supplemental Material, Table 2).

Reporting of VOC data. The VOC data set was examined in two ways to address the objectives of this study. Analytical results from the total 2,401 domestic wells sampled (1985–2002), including 1,193 samples analyzed at an MRL of 0.2 $\mu\text{g/L}$ and 1,208 samples analyzed with the low-level method, were used to gain a broad perspective on VOC concentrations relative to human-health benchmarks. Using data from all 2,401 domestic well samples maximized the number of VOC concentrations that could be compared to human-health benchmarks, thereby providing a basis for a more comprehensive evaluation of VOC occurrence data in the context of human health.

VOC occurrence findings, including detection frequencies, concentrations, and spatial distributions, are reported in this article using data from a subset of the samples—that is the 1,208 samples collected and analyzed (1996–2002) with the low-level method. This data

provide a relevant assessment of low-level VOC concentrations that are present in ambient ground water (untreated water characteristic of the aquifer resources) and best describe VOC concentrations that may be present in drinking water supplied by domestic wells. The low-level analytical method also provides the highest analytical resolution data for multivariate statistical analyses of individual compounds to determine explanatory factors associated with VOC occurrence. Furthermore, as precision of analytical methodologies improves, the USGS low-level VOC data in this study can effectively be used in future comparative analyses for assessment of long-term VOC occurrence trends. Based on these collective objectives, low-level analytical results for VOC occurrence from 1,208 samples are reported with no censoring of data.

Statistical analyses. Nonparametric statistical tests were used to analyze VOC occurrence data. Multivariate logistic regression analyses were used to determine relations between probability of VOC occurrence relative to hydrogeologic and anthropogenic variables. Information on this statistical approach and variables (Moran et al. 2006) is available in Supplemental Material, Appendix 1. The significance of logistic regression analyses was tested using various statistical criteria (Helsel and Hirsch 1992). Standardized coefficients were computed to compare slope coefficients directly between one another (Menard 2002).

Screening-level assessment. Thirty-five of the 42 VOCs detected in domestic-well samples have established human-health benchmarks. VOC concentrations for 27 regulated compounds were compared to their MCLs, and concentrations for 8 unregulated VOCs were compared to their HBSLs. VOC concentrations of potential human-health concern in domestic-well samples were defined as those concentrations greater than MCLs or HBSLs.

VOC concentrations within one order of magnitude of MCLs or HBSLs were identified as compounds that may warrant additional monitoring to analyze trends in occurrence and to provide an early indication of concentrations approaching human-health benchmarks (Toccalino and Norman 2006). State and Federal agencies use a variety of thresholds (typically one-tenth or one-half of a human-health benchmark) to identify contaminants that may warrant additional monitoring (U.S. EPA 2000, 2002), or for related purposes, such as ranking the susceptibility of wells to contamination (New Jersey Department of Environmental Protection 2003, 2004) and identifying contaminants of potential human-health concern (U.S. EPA 1993). Using concentrations within one order of magnitude of a human-health benchmark to identify compounds that may warrant additional monitoring is therefore consistent with various State and Federal practices.

Results

VOC occurrence. One or more VOCs were detected in 65 percent of the domestic-well samples. Of the 55 VOCs monitored, 42 compounds were detected. Detection frequencies were greater than 10 percent for chloroform (25.6 percent), toluene (17.9 percent), 1,2,4-trimethylbenzene (1,2,4-TMB) (15.2 percent), and perchloroethene (PCE) (11 percent) (Table 1). Nineteen VOCs had detection frequencies between 1 and 10 percent, and 18 VOCs had detection frequencies greater than 0.1 and less than 1 percent (Table 1). The 15 frequently detected compounds represent all VOC groups except fumigants. These VOCs have widespread applications and multiple uses, and most compounds were detected throughout the conterminous United States and in Alaska. VOC concentrations generally

were low; of the sampled wells, 91 percent had total VOC concentrations equal to or less than 1 µg/L and about one percent had total VOC concentrations greater than 10 µg/L.

Of the well samples, 31 percent had a single VOC detection and 34 percent had VOC mixtures, which in this study are defined as two or more VOCs that are present in a domestic-well sample. The 10 most frequently detected VOCs each occurred more frequently in samples with mixtures than as single VOCs in samples (Supplemental Material, Table 3). The median concentrations for these VOCs generally were greater when detected in a mixture than alone. Of the 10 frequently detected VOCs, methyl *tert*-butyl ether (MTBE) had the greatest median concentration both alone and in mixtures. Median concentrations generally were greatest for gasoline oxygenates and refrigerants, and median concentrations were lowest for fumigants and gasoline hydrocarbons.

As many as 24 individual VOCs were detected in one sample; however, the most frequently occurring mixtures were composed of two to three unique compounds. Chloroform was a common constituent in the four most frequently detected mixtures, co-occurring in two-compound mixtures with, in decreasing order of detection frequency, 1,1,1-trichloroethane (1,1,1-TCA), PCE, toluene, and MTBE (Supplemental Material, Table 4). The co-occurrence of chloroform with a VOC from another group, for example PCE, may result from wide distribution of these compounds that spatially overlap. VOC mixtures, such as PCE and 1,1,1-TCA, may co-occur because the physical and chemical properties of these compounds could result in similar environmental behavior. Mixtures may also result from VOCs sharing the same source, such as toluene and 1,2,4-TMB in gasoline products. Mixtures such as PCE and trichloroethene (TCE) may result from the degradation of the parent compound, PCE, to the by-product, TCE.

Relational analyses. Results of logistic regression analyses for frequently detected VOCs and associated variables are summarized in Table 2. VOCs that had a variable with a standardized coefficient equal to or greater than zero indicate that as the variable increases, the probability of detecting that compound increases; conversely, VOCs that had a variable with a standardized coefficient less than zero indicate that as the variable increases, the probability of detecting that compound decreases. If a standardized coefficient of a variable for a VOC was equal to or greater than 0.1 (absolute value), the variable was considered to be strongly associated with the probability of a compound's occurrence; if a standardized coefficient of a variable for a VOC was less than 0.1 (absolute value) the variable was considered to be weakly associated with the probability of the compound's occurrence. Based on the strength of variable associations and the frequency of VOC detections, the five variables in order of decreasing importance were (1) dissolved oxygen, (2) precipitation, (3) the number of Resource Conservation and Recovery Act (RCRA) sites (that generate, transport, store, or dispose of hazardous waste materials) within a 1-kilometer (km) radius of the well, (4) aquifer type, and (5) water temperature.

The hydrogeologic variable most strongly and frequently associated with VOC occurrence in domestic-well water was dissolved-oxygen content, which is a key factor in biodegradation. The probability of detecting chloroform, MTBE, 1,1,1-TCA, and toluene increased with increasing dissolved-oxygen content (Table 2), whereas the probability of detecting chloromethane decreased with increasing dissolved-oxygen content. The probability of detecting MTBE increased with increasing precipitation as expected. Precipitation is the driving force for recharge and the transport of VOCs from land surface to the water table. The probability of detecting MTBE decreased with increasing depth to the

top of the well's screened interval. Depth to the top of the screened interval is believed to be roughly equivalent to the depth to the top of the aquifer (Moran et al. 2006). Increased depth to the screened interval allows more traveltime from the MTBE source to the aquifer which may allow for increased attenuation of MTBE concentrations through natural loss processes such as biodegradation, sorption, dispersion, and volatilization. Furthermore, the probability of detecting MTBE decreased with increasing water temperature, which is believed to be related to the biologic activity necessary for transformation of the compound (Moran et al. 2006).

The anthropogenic variable most strongly and frequently associated with probability of VOC occurrence was the number of RCRA sites within a 1-km radius of the well. The probability of detecting three solvents, PCE, TCE, and 1,1,1-TCA, increased with increasing number of sites near the wells. The probability of detecting the oxygenate MTBE increased with increasing number of leaking underground storage tank (LUST) sites within a 1-km radius of the well.

Comparison of VOC concentrations to human-health benchmarks. One or more VOC concentrations were greater than a human-health benchmark in 1.2 percent of the domestic-well samples. Six VOCs had concentrations greater than MCLs: dibromochloropropane (DBCP), 1,2-dichloropropane, ethylene dibromide (fumigants); PCE and TCE (solvents); and 1,1-dichloroethene (organic synthesis compound) (Table 3 and Figure 1). With the exception of ethylene dibromide, these VOCs also had concentrations less than but within one order of magnitude of their MCL in samples. One or more VOCs were detected within one order of magnitude of their MCL in 2.1 percent of the samples and include nine regulated VOCs: benzene (gasoline hydrocarbon); vinyl chloride (organic

synthesis compound); carbon tetrachloride, 1,2-dichloroethane, methylene chloride, and 1,1,1-TCA (solvents); and bromoform, chloroform, and dibromochloromethane (THMs) (Figure 1 and Supplemental Material, Table 5). No VOC concentrations were greater than or within one order of magnitude of HBSLs. Seven VOCs detected in samples but without established MCLs or HBSLs were, in order of decreasing detection frequency, MTBE, 1,1-dichloroethane (1,1-DCA), 1,2,4-TMB, chloroethane, *tert*-amyl methyl ether (TAME), diisopropyl ether (DIPE), and *n*-propylbenzene.

VOCs with concentrations of potential human-health concern commonly occurred in mixtures. Twenty-three of the 32 VOC concentrations greater than MCLs were in samples containing VOC mixtures. Thirty-five of the 67 VOC concentrations within one order of magnitude of MCLs were in samples containing VOC mixtures.

Sampling locations and spatial distributions of VOC concentrations in the United States relative to human-health benchmarks are shown in Figure 2. Samples with VOC concentrations greater than MCLs generally were localized within regions or States (Supplemental Material, Table 6) and generally were detected in highly populated areas, such as New Jersey, or were potentially associated with a particular VOC use, such as the historical application of DBCP on crops in the Central Valley of California (Burow et al. 1999). Samples with one or more VOC concentrations within one order of magnitude of an MCL were distributed throughout the conterminous United States, and samples with VOC concentrations less than one order of an MCL or HBSL were distributed throughout the conterminous United States and in Alaska (Figure 2).

The 15 VOCs that had concentrations greater than and (or) within one order of magnitude of MCLs in the 2,401 domestic-well samples also were examined relative to their

overall detection frequencies. The solvents methylene chloride, PCE, and TCE were among the most frequently detected compounds, and compared to other VOCs, had a large percent of samples with concentrations greater than or within one order of magnitude of an MCL (Supplemental Material, Figure 2). These solvents are important VOCs to consider for source control and monitoring programs at local, State, and national levels.

Discussion

Scope of NAWQA study and relevance of findings. Several ground-water studies have been completed that focused on select VOCs or VOC groups. A study by the State of Maine focused on MTBE, benzene, toluene, ethylbenzene, and xylenes in domestic wells (State of Maine 1998). A study in the 1980s by the Wisconsin Department of Natural Resources (2007) tested for VOCs in water from domestic wells that were known or suspected to be vulnerable to VOC contamination. A NAWQA study by Moran et al. (2002) reported preliminary VOC occurrence information on 55 VOCs based on 1,926 domestic-well samples using a reporting level of 0.2 µg/L. The NAWQA study described in this article is the first national investigation to report the occurrence of a large number of VOCs in ambient ground water from domestic-well samples analyzed using low-level analytical methods and to assess the potential human-health relevance of individual VOC concentrations that have established human-health benchmarks.

About two-thirds of the NAWQA wells sampled throughout the United States since 1996 contained low-level VOC concentrations, indicating that VOC contamination of drinking water supplied by domestic wells may be more prevalent than previously reported

by monitoring programs that used analytical methods with higher reporting levels, such as those described by Squillace et al. (1999) and the State of Maine (1998). As analytical reporting levels decrease, the detection frequency of VOCs increases; however, this does not necessarily indicate differences in water quality from a human-health perspective, but may reflect the greater resolving power of analytical instruments

Mixtures were a common mode of VOC occurrence in domestic-well samples; however, chemical regulation and toxicological research have historically focused on individual chemicals rather than on mixtures (Monosson 2005). Furthermore, few data are available on the potential human-health effects resulting from long-term exposure to multiple compounds at low concentrations. This study identified frequently detected VOC mixtures, and in addition, a current NAWQA study is assessing multi-contaminant occurrence of nitrate, radon, pesticides, VOCs, and trace elements (including arsenic and uranium) from domestic-well samples throughout the United States. Identification of commonly occurring mixtures may aid U.S. EPA and others in prioritizing future toxicological and risk-assessment research.

Results of the relational analyses of VOCs in samples with variables reinforce the importance of identifying VOC sources and assessing the vulnerability of drinking-water supplies to VOCs. Identification of hydrogeologic and anthropogenic variables associated with the occurrence of an individual VOC, when coupled with the knowledge of the behavior and fate of the compound, can aid in understanding the vulnerability of aquifers to VOC contamination.

VOC concentrations generally were less than human-health benchmarks; concentrations of six VOCs in 1.2 percent of the samples were of potential human-health

concern because their concentrations were greater than MCLs. With the exception of 1,1-DCE, all of these compounds are regulated as carcinogens in drinking water (U.S. EPA 2006b). The potential health effects of these six VOCs with concentrations greater than MCLs are summarized in Table 3. Ingestion of water containing VOC concentrations greater than MCLs or HBSLs does not necessarily indicate that adverse human-health effects will occur. Human-health benchmarks are conservative (protective) because they incorporate safety factors to account for uncertainty in toxicity information and are based on lifetime exposure. Additionally, all samples in this study were collected at the wellhead before treatment. Treatment of water from domestic wells may reduce VOC concentrations at the tap (Toccalino et al. 2006).

Nine additional VOCs had concentrations less than but within one order of magnitude of MCLs (Supplemental Material, Table 5). These findings indicate that 15 VOCs may warrant inclusion in regional and national low-concentration, trends-monitoring programs. The potential human-health relevance for the seven VOCs that were detected in samples but do not have established MCLs or HBSLs cannot be evaluated at this time. However, 1,2,4-TMB, MTBE, and 1,1,-DCA are presently included on U.S. EPA's Contaminant Candidate List and are prioritized for monitoring and data collection for public water systems (U.S. EPA 2006a).

Potential human exposure to VOCs by ingestion of drinking water from domestic wells. The effective protection and management of the quality of drinking water supplied by domestic wells are shared responsibilities among well owners, governmental agencies, research organizations, and academic institutions. Proactive domestic-well owners can properly maintain wells, routinely test drinking water, and implement management practices

around the home to reduce VOC contamination. Although drinking water from domestic wells is not regulated by Federal standards, some homeowners are improving their drinking-water quality by utilizing granular activated-carbon filtering systems and filters mounted on taps and refrigerator dispensers. Reverse osmosis also is used to treat drinking-water.

Domestic well owners may rely on water supplied by jugs with filters or on bottled water for consumption. At the Federal level, bottled water is regulated as a packaged food product and is governed by the U.S. Food and Drug Administration by Standards of Quality (U.S. EPA 2004).

A survey of 373 households was conducted to characterize drinking water consumed by domestic-well users in the United States (Probe Research Inc. 2005). An estimated 52 percent of the surveyed households indicated that drinking water was used straight from the tap with no treatment. If the statistics from the Probe Research Inc. drinking-water survey are representative of drinking-water ingested by members of households throughout the United States, more than 22 million people are drinking untreated domestic-well water straight from the tap. Furthermore, 65 percent of the domestic-well samples analyzed with NAWQA's low-level method contained one or more VOCs. Applying this VOC detection frequency to the statistics provided by the Probe Research Survey Inc. (2005) indicates that more than 14 million people throughout the conterminous United States and Alaska may be exposed to low VOC concentrations in their drinking water. In addition, 1.2 percent of the domestic wells sampled in the NAWQA assessment contained at least one VOC concentration greater than its MCL indicating that as many as 300,000 domestic-well users may be potentially ingesting drinking water that contains one or more VOCs at concentrations greater than MCLs.

The number of domestic-well users exposed to VOCs may be underestimated using data from the Probe Research Survey Inc. (2005). Calculations based on the Probe Research Survey Inc. (2005) indicate that nearly 9 million additional domestic well users rely on household-water treatment systems for removal of VOCs from drinking water; however, the effectiveness of VOC removal by in-house water-treatment systems is undetermined. Evaluating the effective removal of VOCs by in-house treatment methods from water supplied by domestic wells would necessitate routine monitoring, which presently is not required.

Most States and some local agencies provide guidance to well owners through Web sites and printed materials. Guidance varies by State; however, information provided may include guidelines for well construction, proper well maintenance, preventative measures for contaminants, recommendations for water-quality testing, and certified treatment devices (U.S. EPA 2006c). Some States have initiated measures to assess water quality to aid in the protection of human health. For example, New Jersey passed a law in 2002 that requires private domestic well owners to test “raw” or untreated water for contaminants, including regulated VOCs, and to disclose results before selling or leasing properties (New Jersey Department of Environmental Protection 2006). Furthermore, some lawmakers have introduced bills in Congress that would mandate testing of private wells throughout the United States.

Future direction and challenges. Science-based strategies are needed for identification of contaminants that are not regulated but may be present in drinking water from domestic wells. In addition, assessing the occurrence of contaminants from products that may be of current and future concern, such as personal care products, food additives, detergents, and

pharmaceuticals, is warranted. Providing information on the occurrence of contaminants in drinking water from domestic wells is important for local, State, and Federal water-resource managers and others charged with protecting and managing drinking-water resources. In addition, because many organic contaminants do not have human-health benchmarks, continued research is needed to provide the toxicological data necessary to develop these benchmarks, which in turn provide tools for evaluating water-quality data in the context of human health.

Previously sampled wells, such as those included in this study, could be re-sampled to further assess water-quality conditions and to determine variability and trends in contaminant occurrence and concentrations. Data collected systematically over a period of time could aid in determining if a correlation exists between an identified contaminant source and VOC occurrence in a drinking-water supply. In addition, domestic wells that are located near areas that are known to be associated with contaminant sources could be targeted for monitoring.

At domestic-well sampling sites, well characteristics and pumping information may be available; however, a challenge for future studies is to obtain ancillary information relevant to human health for domestic-well users. For example, standard questionnaires could accompany sampling activities. If used, the type of household water-treatment systems could be identified, such as granulated activated-carbon for removal of VOCs, and supplementary drinking-water sources, including bottled water, could be determined. Additional pertinent information could include the number and age of household members, amount of water ingested, length of time using the water supply, and upgrades or changes in the household-water system since the initial installation at the time of the home construction.

As population, urbanization, and the demand for drinking water from domestic wells increase, continued evaluation of water quality is important. Research, including design, analysis, compilation of data, and comparison of measured contaminant concentrations to human-health benchmarks, can be used to assess the drinking-water quality from domestic wells and to prioritize investigations in a systematic effort at and among local, State, and national levels.

List of References

Ashford NA, Miller CS. 1991. Chemical Exposures—Low Levels and High Stakes. New York, NY:Van Nostrand Reinhold.

ATSDR. 2007a. Toxfaqs. U.S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry. Available: <http://www.atsdr.cdc.gov/toxfaq.html> [accessed 25 June 2007].

ASTDR. 2007b. Toxicological Profile Information Sheet. U.S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry Available: <http://www.atsdr.cdc.gov/toxpro2.html> [accessed 25 June 2007].

Bender DA, Zogorski JS, Halde MJ, Rowe BL. 1999. Selection procedure and salient information for volatile organic compounds emphasized in the National Water-Quality Assessment Program. OFR 99-182. Rapid City, SD:U.S. Geological Survey. Available: http://onlinepubs.er.usgs.gov/djvu/OFR/1999/ofr_99_182.djvu [accessed 25 June 2007].

Burow KR, Panshin SY, Dubrovsky NM, VanBrocklin D, Fogg GE. 1999. Evaluation of processes affecting 1,2-dibromo-3-chloropropane (DBCP) concentrations in ground water in the eastern San Joaquin Valley, California—Analysis of chemical data and ground-water flow and transport simulations. WRIR 99-4059. Reston, VA:U.S. Geological Survey. Available:

<http://ca.water.usgs.gov/sanj/pub/usgs/wrir99-4059/wrir99-4059.pdf> [accessed 25 June 2007].

Childress CJO, Foreman WT, Connor BF, Maloney TJ. 1999. New reporting procedures based on long-term method detection levels and some considerations for interpretations of water-quality data provided by the U.S. Geological Survey National Water Quality Laboratory. OFR 99-193. Reston, VA:U.S. Geological Survey. Available: http://water.usgs.gov/owq/OFR_99-193/index.html [accessed 25 June 2007].

Connor BF, Rose DL, Noriega MC, Murtagh LK, Abney SR. 1998. Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of 86 volatile organic compounds in water by gas chromatography/mass spectrometry, including detections less than the reporting limits. OFR 97-829. Denver, CO:U.S. Geological Survey. Available: <http://nwql.usgs.gov/Public/pubs/OFR97-829/OFR97-829.pdf> [accessed 25 June 2007].

Gilliom RJ, Alley WM, Gurtz ME. 1995. Design of the National Water-Quality Assessment Program—Occurrence and distribution of water-quality conditions. Circular 1112. Sacramento, CA:U.S. Geological Survey. Available: <http://pubs.usgs.gov/circ/circ1112/> [accessed 25 June 2007].

Helsel DR, Hirsch RM. 1992. Statistical Methods in Water Resources. New York, NY:Elsevier.

Hutson SS, Barber NL, Kenny JF, Linsey KS, Lumia DS, Maupin MA. 2004. Estimated use of water in the United States in 2000. Circular 1268. Reston, VA:U.S. Geological Survey. Available: <http://pubs.usgs.gov/circ/2004/circ1268/> [accessed 25 June 2007].

Koterba MT, Wilde FD, Lapham WW. 1995. Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program—Collection and documentation of water-quality samples and related data. OFR 95-399. Reston, VA:U.S. Geological Survey. Available: http://onlinepubs.er.usgs.gov/djvu/OFR/1995/ofr_95_399.djvu [accessed 25 June 2007].

Lapham WW, Tadayon S. 1996. Plan for assessment of the occurrence, status, and distribution of volatile organic compounds in aquifers of the United States. OFR 96-199. Rapid City, SD:U.S. Geological Survey. Available: http://onlinepubs.er.usgs.gov/djvu/OFR/1996/ofr_96_199.djvu [accessed 25 June 2007].

McCray KB. 2006. personal communication. National Ground Water Association. Westerville, OH.

Menard S. 2002. Applied Logistic Regression Analysis. Thousand Oaks, CA:Sage Publications, Inc.

Monosson E. 2005. Chemical mixtures—Considering the evolution of toxicology and chemical assessment. Environ Health Perspect 113:383-390.

Moran MJ, Lapham WW, Rowe BL, Zogorski JS. 2002. Occurrence and status of volatile organic compounds in ground water from rural, untreated, self-supplied domestic wells in the United States, 1986-99. WRIR 02-4085. Rapid City, SD:U.S. Geological Survey. Available: http://sd.water.usgs.gov/nawqa/pubs/wrir/wrir02_4085.pdf [accessed 25 June 2007].

Moran MJ, Zogorski JS, Rowe BL. 2006. Approach to an assessment of volatile organic compounds in the Nation's ground water and drinking-water supply wells. OFR 2005-1452. Reston, VA:U.S. Geological Survey. Available: <http://pubs.usgs.gov/of/2005/1452/pdf/ofr2005-1452.pdf> [accessed 25 June 2007].

New Jersey Department of Environmental Protection. 2003. Susceptibility of source water to community water-supply wells in New Jersey to contamination by volatile organic compounds. Trenton, NJ:New Jersey Department of Environmental Protection, Source Water Assessment Program. Available: http://www.state.nj.us/dep/swap/reports/gw_voc.pdf [accessed 10 July 2007].

New Jersey Department of Environmental Protection. 2004. New Jersey source water assessment program statewide summary. Trenton, NJ:New Jersey Department of Environmental Protection, Source Water Assessment Program. Available: http://state.nj.us/dep/swap/reports/swap_sum200412.pdf [accessed 10 July 2007].

New Jersey Department of Environmental Protection. 2006. Private well testing act.
Available: <http://www.state.nj.us/dep/pwta> [accessed 02 November 2006].

Pankow JF, Cherry JA. 1996. Dense Chlorinated Solvents and Other NDAPLS in
Groundwater. Portland, OR:Waterloo Press.

Probe Research Inc. 2005. A clear perspective—USA 2005 National Drinking Water Survey,
Winnipeg, MN:Probe Research, Inc.

Rose DL, Schroeder MP. 1995. Methods of analysis by the U.S. Geological Survey National
Water Quality Laboratory—Determination of volatile organic compounds in water by purge
and trap capillary gas chromatography/mass spectrometry. OFR 94-708-W. Denver, CO:U.S.
Geological Survey. Available:
http://onlinepubs.er.usgs.gov/djvu/OFR/1994/ofr_94_708W.djvu [accessed 25 June 2007].

Squillace PJ, Moran MJ, Lapham WW, Price CV, Clawges RM, Zogorski JS. 1999. Volatile
organic compounds in untreated ambient ground water of the United States, 1985-1995.
Environ Sci & Techn 33:4176-4187.

State of Maine. 1998. The presence of MTBE and other gasoline compounds in Maine's
drinking water—A preliminary report, October 13, 1998. Augusta, ME:Bureau of Health,
Department of Human Services. Available:
<http://www.maine.gov/dhhs/eohp/wells/documents/MTBE.PDF> [accessed 25 June 2007].

Toccalino PL. 2007. Development and application of Health-Based Screening Levels for use in water-quality assessments. SIR 2007-5106. Reston, VA:U.S. Geological Survey.

Available: <http://pubs.usgs.gov/sir/2007/5106/pdf/sir20075106.pdf> [accessed 25 June 2007].

Toccalino PL, Norman JE. 2006. Health-Based Screening Levels to evaluate U.S. Geological Survey ground-water quality data. Risk Analyses 26:1339-1348.

Toccalino P, Nowell L, Wilber W, Zogorski J, Donahue J, Eiden C, Kriegman S, et al. 2003. Development of Health-Based Screening Levels for use in State- or local-scale water-quality assessments. WRIR 03-4054. Rapid City, SD:U.S. Geological Survey. Available:

<http://pubs.usgs.gov/wri/wri034054/wri034054.pdf> [accessed 25 June 2007].

Toccalino PL, Rowe BL, Norman JE. 2006. Volatile organic compounds in the Nation's drinking-water supply wells—What findings may mean to human health. FS 2006-3043.

Reston, VA:U.S. Geological Survey. Available:

<http://pubs.usgs.gov/fs/2006/3043/pdf/fs2006-3043.pdf> [accessed 25 June 2007].

U.S. EPA. 1993. Risk assessment—Technical guidance manual selecting exposure routes and contaminants of concern by risk-based screening. EPA/903/R-93-001. Washington, DC:U.S.

Environmental Protection Agency, Region 3, Hazardous Waste Management Division.

Available: <http://www.epa.gov/reg3hwmd/risk/human/info/guide2.htm> [accessed July 2007].

U.S.EPA. 1995. Method 524.2—Measurement of purgeable organic compounds in water by capillary column gas chromatography/mass spectrometry, Revision 4.1. Washington, DC: U.S. Environmental Protection Agency, Office of Research and Development. Available: <http://www.ultrasci.com/docs/analyticalmethod/method11.pdf> [accessed 02 February 2007].

U.S. EPA. 2000. Sets of scientific issues being considered by the Environmental Protection Agency regarding: Session I - Consultation—National drinking water survey design for assessing chronic exposure. In: Proceedings from Scientific Advisory Panel Meeting: FIFRA 6-7 June, Arlington, VA:SAP Report No. 2000-03, 15 September 2000. Washington, D.C:U.S. Environmental Protection Agency. Available: <http://www.epa.gov/oscpmont/sap/meetings/2000/june/finwateronly.pdf> [accessed 10 July 2007].

U.S. EPA. 2002. Code of Federal Regulations, 40CFR159, Subpart D—Reporting requirements for risk/benefit information. Available: http://a257.g.akamaitech.net/7/257/2422/14mar20010800/edocket.access.gpo.gov/cfr_2002/julqtr/40cfr159.184.htm and <http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=f97df7c20da63eb13856ea52cd2be5c6&rgn=div5&view=text&node=40:23.0.1.1.10&idno=40> [accessed 11 July 2007].

U.S. EPA. 2003 Water on tap—What you need to know. Washington, DC:U.S. Environmental Protection Agency, Office of Water. Available:

http://www.epa.gov/safewater/wot/pdfs/book_waterontap_full.pdf [accessed 27 September 2006].

U.S. EPA. 2004. Code of Federal Regulations 21CFR165.110, Subpart B—Requirements for specific standardized beverages—Bottled water. Available:

http://a257.g.akamaitech.net/7/257/2422/12feb20041500/edocket.access.gpo.gov/cfr_2004/a/prqtr/pdf/21cfr165.110.pdf [accessed 13 July 2007].

U.S. EPA. 2006a. Drinking water Contaminant Candidate List and regulatory determinations—CCL List 2. Washington, DC:U.S. Environmental Protection Agency, Office of Water. Available: <http://www.epa.gov/safewater/ccl/ccl2.html> [accessed 19 October 2006].

U.S. EPA. 2006b. 2006 Edition of the Drinking Water Standards and Health Advisories. EPA/822/R-06/013, August 2006. Washington, DC:U.S. Environmental Protection Agency, Office of Water. Available: <http://www.epa.gov/waterscience/criteria/drinking/dwstandards.pdf> [accessed 08 February 2007].

U.S. EPA. 2006c. Private drinking water wells. Washington, DC:U.S. Environmental Protection Agency, Office of Ground Water and Drinking Water. Available: http://www.epa.gov/safewater/privatewells/wherelive_state.html [accessed 31 October 2006].

U.S. EPA. 2006d. Safe Drinking Water Act. Washington, DC:U.S. Environmental Protection Agency, Office of Ground Water and Drinking Water. Available: <http://www.epa.gov/safewater/sdwa/index.html> [accessed 20 October 2006].

U.S. EPA. 2006e. Setting standards for safe drinking water. Washington, DC:U.S. Environmental Protection Agency, Office of Ground Water and Drinking Water. Available: <http://www.epa.gov/safewater/standard/setting.html> [accessed 09 July 2007].

U.S. EPA. 2007a. Drinking water contaminants. Washington, DC:U.S. Environmental Protection Agency, Office of Ground and Drinking Water. Available: <http://www.epa.gov/safewater/contaminants/index.html> [accessed 08 August 2007].

U.S. EPA. 2007b. Integrated Risk Information System. Washington, DC:U.S. Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment. Available: <http://www.epa.gov/iris/> [accessed 25 June 2007].

Wisconsin Department of Natural Resources. 2007. Volatile organic chemicals in drinking water. Available: <http://www.dnr.state.wi.us/org/water/dwg/voc.htm> [accessed 22 January 2007].

Zogorski JS, Carter JM, Ivahnenko T, Lapham WW, Moran MJ, Rowe BL, et al. 2006. The quality of our Nation's waters—Volatile organic compounds in the Nation's

ground water and drinking-water supply wells. Circular 1292. Reston, VA:U.S. Geological Survey. Available: <http://pubs.usgs.gov/circ/circ1292/pdf/circular1292.pdf> [accessed 25 June 2007].

Table 1. Detection frequencies of volatile organic compounds (VOCs)^a in 1,208 domestic-well samples analyzed with the U.S. Geological Survey's low-level analytical method and reported with no censoring of data. VOCs are listed in order of decreasing detection frequency.

Compound (abbreviation)	VOC group	Number of well samples	Number of detections	Detection frequency, in percent
Chloroform	THM	1,207	309	25.6
Toluene	Gasoline hydrocarbon	1,203	215	17.9
1,2,4-Trimethylbenzene (1,2,4-TMB)	Gasoline hydrocarbon	1,190	181	15.2
Perchloroethene (PCE)	Solvent	1,179	130	11.0
Chloromethane	Solvent	1,207	117	9.7
1,1,1-Trichloroethane (1,1,1-TCA)	Solvent	1,208	103	8.5
Methylene chloride	Solvent	1,207	74	6.1
Methyl <i>tert</i> -butyl ether (MTBE)	Gasoline oxygenate	1,208	67	5.5
Dichlorodifluoromethane	Refrigerant	1,208	43	3.6
Trichloroethene (TCE)	Solvent	1,207	41	3.4
Benzene	Gasoline hydrocarbon	1,208	37	3.1
Bromodichloromethane	THM	1,207	34	2.8
<i>m</i> - and <i>p</i> -Xylene ^b	Gasoline hydrocarbon	1,206	28	2.3
1,1-Dichloroethane (1,1-DCA)	Solvent	1,207	27	2.2
Styrene	Gasoline hydrocarbon	1,202	26	2.2
1,4-Dichlorobenzene	Fumigant	1,208	23	1.9
Trichlorofluoromethane	Refrigerant	1,208	23	1.9
Bromoform	THM	1,206	22	1.8
1,1-Dichloroethene (1,1-DCE)	Organic synthesis	1,207	19	1.6
Chlorobenzene	Solvent	1,208	16	1.3
Carbon tetrachloride	Solvent	1,207	13	1.1
Dibromochloromethane	THM	1,207	13	1.1
<i>cis</i> -1,2-Dichloroethene	Solvent	1,207	11	.91
1,2-Dichloropropane	Fumigant	1,207	9	.75
Isopropylbenzene	Gasoline hydrocarbon	1,208	9	.75
<i>o</i> -Xylene	Gasoline hydrocarbon	1,205	8	.66
Ethylbenzene	Gasoline hydrocarbon	1,208	7	.58
<i>tert</i> -Amyl methyl ether (TAME)	Gasoline oxygenate	1,206	6	.50
1,3-Dichlorobenzene	Solvent	1,208	6	.50
Trichlorotrifluoroethane	Refrigerant	1,207	6	.50
Chloroethane	Solvent	1,207	4	.33
1,2-Dichlorobenzene	Solvent	1,208	4	.33
Diisopropyl ether (DIPE)	Gasoline oxygenate	1,096	4	.36
Dibromochloropropane (DBCP)	Fumigant	1,208	3	.25
Naphthalene	Gasoline hydrocarbon	1,208	3	.25
<i>n</i> -Propylbenzene	Solvent	1,208	3	.25
<i>n</i> -Butylbenzene	Gasoline hydrocarbon	1,208	2	.17
1,2-Dichloroethane	Solvent	1,208	2	.17
1,2,3-Trichloropropane	Fumigant	1,208	2	.17
1,1,2-Trichloroethane	Solvent	1,208	1	.083
Vinyl chloride	Organic synthesis	1,208	1	.083

[THM, trihalomethane; Organic synthesis, organic synthesis compound]

^aVOCs not detected: acrolein, acrylonitrile, bromomethane, *trans*-1,2-dichloroethene, *cis*-1,3-dichloropropene, *trans*-1,3-dichloropropene, ethyl *tert*-butyl ether (ETBE), ethylene dibromide (EDB), hexachlorobutadiene, hexachloroethane, 1,2,3-trichlorobenzene, 1,2,4-trichlorobenzene, and vinyl bromide.

^bConsidered as two of the 55 compounds included in this assessment.

Table 2. Alphabetized listing of frequently detected volatile organic compounds (VOCs) and statistical summary of hydrogeologic and anthropogenic variables associated with the probability of occurrence of the compound in domestic-well samples^a.

Compound (abbreviation)	Number of samples in analyses	Associated variables ^b	Type of variable	Coefficient in logistic regression equation	Standardized coefficient
Chloroform	842	dissolved-oxygen content	fate	1.142	0.20
		depth to water level	transport	-0.005	-0.18
Chloromethane	1,182	dissolved-oxygen content	fate	-0.990	-0.15
		recharge	transport	-0.002	-0.07
Dichlorodifluoromethane Methylene chloride	1,184	water temperature	fate	-0.087	-0.06
	1,168	dissolved-oxygen content	fate	-0.536	-0.08
Methyl <i>tert</i> -butyl ether (MTBE)	969	depth of well	transport	-0.003	-0.13
		permeability of soil	transport	0.104	0.09
		aquifer type	transport	-0.943	-0.07
		dissolved-oxygen content	fate	1.291	0.10
		depth to top of screened interval	transport	-0.008	-0.15
		LUST sites within 1 km of well ^c	source	1.907	0.10
		precipitation	transport	0.073	0.17
Perchloroethene (PCE)	1,155	water temperature	fate	-0.184	-0.13
		dissolved-oxygen content	fate	0.384	0.09
1,1,1-Trichloroethane(1,1,1-TCA)	1,184	RCRA sites within 1 km of well ^c	source	0.158	0.16
		dissolved-oxygen content	fate	2.592	0.30
Trichloroethene (TCE)	1,183	RCRA sites within 1 km of well ^c	source	0.307	0.15
	1,165	precipitation	transport	0.026	0.09
1,2,4-Trimethylbenzene (1,2,4-TMB)	1,178	RCRA sites within 1 km of well ^c	source	0.196	0.10
		agricultural land use	source	0.004	0.05
Toluene	1,178	precipitation	transport	-0.046	-0.05
		aquifer type	transport	-0.600	-0.09
		dissolved-oxygen content	fate	0.657	0.11

[LUST, leaking underground storage tank; km, kilometer; RCRA, Resource Conservation and Recovery Act]

^aMoran et al. (2006) provides a thorough discussion of logistic regression analysis used in this study, including the statistical approach, ancillary variables, and sources of data.

^bVariables strongly associated with the occurrence of VOCs are those with absolute values of standardized coefficients of 0.1 or greater.

^cNumber of sites within a 1 km-radius of well.

Table 3. Six regulated volatile organic compounds (VOCs) were detected at concentrations greater than U.S. EPA Maximum Contaminant Levels (MCLs) in domestic-well samples. Five of the six VOCs are regulated carcinogens in drinking water, and most may adversely affect the liver.

Compound (abbreviation)	VOC group	MCL, in $\mu\text{g/L}$	No. of sampled wells	No. of samples with concentrations greater than MCL	Carcinogen ^a	Potential health effects from exposure to concentrations greater than the MCL ^b
Dibromochloropropane (DBCP)	Fumigant	0.2	1,962	14	yes	reproductive problems; increased risk of cancer
1,1-Dichloroethene (1,1-DCE)	Org. syn.	7	2,400	1	no	liver problems
1,2-Dichloropropane	Fumigant	5	2,400	3	yes	increased risk of cancer
Ethylene dibromide (EDB)	Fumigant	0.05	2,085	3	yes	problems with liver, stomach, reproductive system or kidneys; increased risk of cancer
Perchloroethene (PCE)	Solvent	5	2,371	5	yes	liver problems; increased risk of cancer
Trichloroethene (TCE)	Solvent	5	2,400	6	yes	liver problems; increased risk of cancer

[$\mu\text{g/L}$, microgram per liter; No., number; Org. syn., organic synthesis compound]

^aConsidered a probable or likely human carcinogen by U.S. EPA (2006b).

^bData from U.S. EPA (2003).

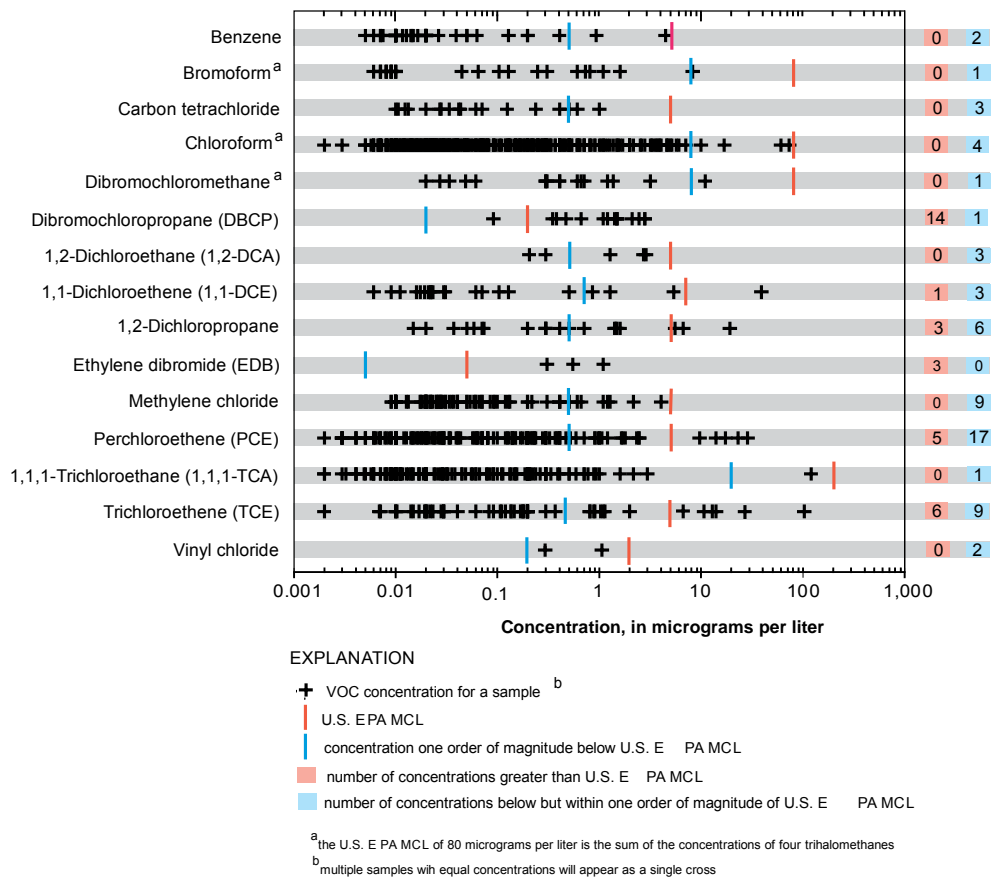


Figure 1. Distribution of 15 volatile organic compounds (VOCs) with concentrations greater than and (or) within one order of magnitude of U.S. EPA Maximum Contaminant Levels (MCLs) in 2,401 domestic well-samples.

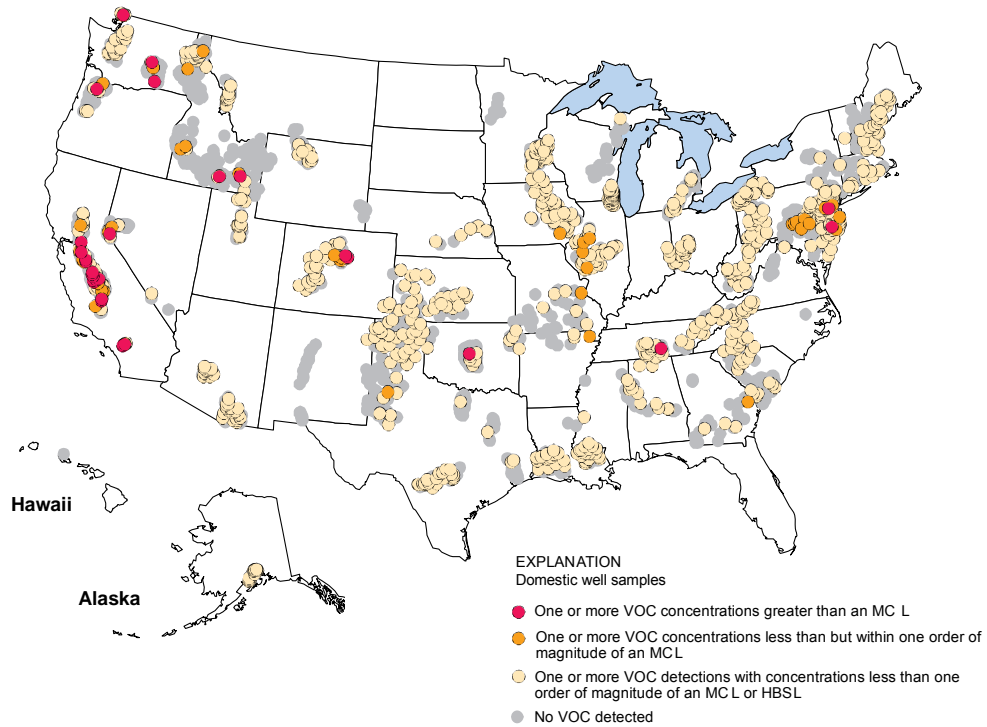


Figure 2. Locations of domestic wells sampled for volatile organic compounds (VOCs) and locations of measured VOC concentrations relative to human-health benchmarks, including U.S. Environmental Protection Agency Maximum Contaminant Levels (MCLs) for regulated VOCs and to Health-Based Screening Levels (HBSLs) for unregulated VOCs.

Supplemental Material, Table 1. Three U.S. Environmental Protection Agency (U.S. EPA) Office of Water (OW) equations are used to calculate Health-Based Screening Levels (HBSLs) for unregulated contaminants as determined by the U.S. EPA cancer classification for each chemical. The relation between the U.S. EPA Weight-of-Evidence cancer classifications and the corresponding OW equations used to calculate HBSLs are shown in tables 1a and 1b (Toccalino 2007).

Table 1a. Relations between the alpha-numeric U.S. EPA Weight-of-Evidence cancer classifications (U.S. EPA 1986) and three equations used to calculate HBSLs.

1986 U.S. EPA Weight-of-Evidence Descriptors	OW equation used to calculate HBSL
A – Known human carcinogen	Cancer Risk Concentration (eq. 1)
B1, B2 – Probable human carcinogen	Cancer Risk Concentration (eq. 1)
C – Possible human carcinogen carcinogens (eq. 2)	Lifetime Health Advisory (Lifetime HA) for Group C
D – Unclassifiable	Lifetime HA (eq. 3)
E – Evidence of non-carcinogenicity for humans	Lifetime HA (eq. 3)
No Weight-of-Evidence descriptor, but reference dose is available	Lifetime HA (eq. 3)

[U.S. EPA, U.S. Environmental Protection Agency; HA, Health Advisory; HBSL, Health-Based Screening Level; OW, U.S. EPA Office of Water; eq., equation]

$$\text{HBSL } (\mu\text{g/L}) = \frac{(70 \text{ kg body wt}) \times (\text{risk level})}{(2 \text{ L water consumed/day}) \times (\text{SF} [\text{mg/kg/day}]^{-1}) \times (\text{mg}/1,000 \mu\text{g})} \quad (1)$$

Where $\mu\text{g/L}$ = micrograms per liter; kg body wt = kilograms of body weight; risk level is 10^{-6} to 10^{-4} cancer risk range; SF = cancer slope factor; $(\text{mg/kg/day})^{-1}$ = inverse of milligrams of chemical per kilogram of body weight per day; mg = milligrams; and μg = micrograms.

$$\text{HBSL } (\mu\text{g/L}) = \left[\frac{(\text{RfD} [\text{mg/kg/day}]) \times (70 \text{ kg body wt}) \times (1,000 \mu\text{g/mg}) \times \text{RSC}}{(2 \text{ L water consumed/day})} \right] \div \text{RMF} \quad (2)$$

$$\text{HBSL } (\mu\text{g/L}) = \frac{(\text{RfD} [\text{mg/kg/day}]) \times (70 \text{ kg body wt}) \times (1,000 \mu\text{g/mg}) \times \text{RSC}}{(2 \text{ L water consumed/day})} \quad (3)$$

Where RfD = reference dose; mg/kg/day = milligrams of chemical per kilogram of body weight per day; RSC = Relative Source Contribution (defaults to 20 percent in the absence of other data); and RMF = Risk Management Factor (defaults to 10 in the absence of other data).

Table 1b. Relation between the descriptive 1996, 1999, and 2005 U.S. EPA Weight-of-Evidence cancer classifications and the three equations used to calculate HBSLs.

U.S. EPA Weight-of-Evidence Descriptors			OW equation used to calculate HBSL
1996 (U.S. EPA 1996)	1999 (U.S. EPA 1999)	2005 (U.S. EPA 2005)	
Known/likely	Carcinogenic to humans	Carcinogenic to humans	Cancer Risk Concentration (eq. 1)
--	Likely to be carcinogenic to humans	Likely to be carcinogenic to humans	Cancer Risk Concentration (eq. 1)
--	Suggestive evidence of carcinogenicity but not sufficient to assess human carcinogenic potential	Suggestive evidence of carcinogenic potential	Lifetime Health Advisory (Lifetime HA) for Group C carcinogens (eq. 2)
Cannot be determined	Data are inadequate for an assessment of human carcinogenic potential	Inadequate information to assess carcinogenic potential	Lifetime HA (eq. 3)
Not likely	Not likely to be carcinogenic to humans	Not likely to be carcinogenic to humans	Lifetime HA (eq. 3)
Multiple narrative descriptors such as: "Likely to be carcinogenic to humans under high-dose conditions but not likely to be carcinogenic to humans under low-dose conditions"			Lifetime HA (eq. 3) ¹
No Weight-of-Evidence descriptor, but reference dose is available			Lifetime HA (eq. 3)

[U.S. EPA, U.S. Environmental Protection Agency; HA, Health Advisory; HBSL, Health-Based Screening Level; OW, U.S. EPA Office of Water; --no cancer classification]

¹Equation 3 for Lifetime HA values is used with these types of multiple narrative Weight-of-Evidence descriptors because concentrations detected in the environment typically are low.

Supplemental Material, Table 2. Listing of the range of laboratory reporting levels for 55 volatile organic compounds (VOCs) analyzed in a subset (1,208 samples) of 2,401 domestic well samples. The low-level analytical method for the 1,208 domestic well samples was initiated in April 1996. For samples collected prior to April 1996, 54 VOCs were analyzed at a minimum reporting level (MRL) of 0.2 microgram per liter ($\mu\text{g/L}$) with the exception of dibromochloropropane which had an MRL of 0.1 $\mu\text{g/L}$.

Compound (abbreviation)	Range of laboratory reporting levels, in $\mu\text{g/L}$
Acrolein	1.43
Acrylonitrile	0.4 - 1.23
<i>tert</i> -Amyl methyl ether	0.04-0.11
Benzene	0.016 - 0.1
Bromodichloromethane	0.028 - 0.048
Bromoform	0.06 - 0.104
Bromomethane	0.148 - 0.4
Butylbenzene	0.12 - 0.19
Carbon tetrachloride	0.06 - 0.088
Chlorobenzene	0.02 - 0.028
Chloroethane	0.1 - 0.12
Chloroform	0.024 - 0.052
Chloromethane	0.1 - 0.5
Dibromochloromethane	0.1 - 0.182
Dibromochloropropane (DBCP)	0.21 - 0.51
1,2-Dichlorobenzene	0.04 - 0.048
1,3-Dichlorobenzene	0.03 - 0.054
1,4-Dichlorobenzene	0.034 - 0.05
Dichlorodifluoromethane	0.096 - 0.27
1,1-Dichloroethane (1,1-DCA)	0.035 - 0.066
1,2-Dichloroethane (1,2-DCA)	0.1 - 0.134
1,1-Dichloroethene (1,1-DCE)	0.02 - 0.044
<i>cis</i> -1,2-Dichloroethene	0.02 - 0.038
<i>trans</i> -1,2-Dichloroethene	0.018 - 0.032
1,2-Dichloropropane	0.02 - 0.068
<i>cis</i> -1,3-Dichloropropene	0.05 - 0.092
<i>trans</i> -1,3-Dichloropropene	0.09 - 0.134
Diisopropyl ether (DIPE)	0.06 - 0.1
Ethyl <i>tert</i> -butyl ether (ETBE)	0.03 - 0.054
Ethylbenzene	0.02 - 0.03
Ethylene dibromide (EDB)	0.036 - 0.04
Hexachlorobutadiene	0.1 - 0.142
Hexachloroethane	0.14 - 0.362
Isopropylbenzene	0.032 - 0.06
Methyl <i>tert</i> -butyl ether (MTBE)	0.1 - 0.17
Methylene chloride	0.04 - 0.382
Naphthalene	0.25 - 0.52
Perchloroethene (PCE)	0.027 - 0.1
<i>n</i> -Propylbenzene	0.04 - 0.042
Styrene	0.04 - 0.042
Toluene	0.018 - 0.05
1,2,3-Trichlorobenzene	0.12 - 0.27
1,2,4-Trichlorobenzene	0.07 - 0.19
1,1,1-Trichloroethane (1,1,1-TCA)	0.032 - 0.04
1,1,2-Trichloroethane (1,1,2-TCA)	0.04 - 0.064
Trichloroethene (TCE)	0.02 - 0.038
Trichlorofluoromethane	0.08 - 0.16
1,2,3-Trichloropropane	0.07 - 0.18
Trichlorotrifluoroethane	0.032 - 0.092
1,2,4-Trimethylbenzene (1,2,4-TMB)	0.04 - 0.056
Vinyl bromide	0.1 - 0.12
Vinyl chloride	0.06 - 0.112
<i>m</i> - and <i>p</i> -Xylene	0.06 - 0.08
<i>o</i> -Xylene	0.038 - 0.07

Supplemental Material, Table 3. Occurrence data for frequently detected volatile organic compounds (VOCs) alone and in mixtures in 1,208 domestic well samples. Samples were analyzed using the U.S. Geological Survey's low-level analytical method and results are reported with no censoring of data. Compounds are listed in order of decreasing number of detections for individual VOCs.

Compound (abbreviation)	number of detections		Concentration, in micrograms per liter					
			minimum		median		maximum	
	alone	mixture	alone	mixture	alone	mixture	alone	mixture
Chloroform	99	210	0.006	0.002	0.030	0.040	3.33	16.8
Toluene	74	141	.006	.004	.023	.025	4.40	1.05
1,2,4-Trimethylbenzene (1,2,4-TMB)	57	124	.006	.004	.025	.019	.330	.240
Chloromethane	34	83	.007	.009	.030	.030	.090	.080
Methylene chloride	19	55	.010	.009	.026	.028	1.20	2.20
Perchloroethene (PCE)	19	111	.007	.002	.021	.029	1.64	17.8
1,1,1-Trichloroethane (1,1,1-TCA)	12	91	.007	.002	.047	.017	.950	.883
Methyl <i>tert</i> -butyl ether (MTBE)	8	59	.035	.010	.127	.220	.985	30.2
Trichloroethene (TCE)	5	36	.010	.002	.020	.087	14.3	104
<i>m</i> - and <i>p</i> -Xylene	4	24	.009	.008	.011	.020	.014	.170

Supplemental Material, Table 4. Mixtures of volatile organic compounds (VOCs) most commonly occurring in 1,208 domestic well samples analyzed with the U.S. Geological Survey's low-level method and reported with no censoring of data^a. VOC mixtures are listed in order of decreasing detection frequency.

Rank	Compound 1		Compound 2		Compound 3		Compound 4		detection	Percent of samples with mixture
	VOC	use	VOC	use	VOC	use	VOC	use		
1	Chloroform	THM	1,1,1-TCA	solvent	NA	NA	NA	NA	64	5.3
2	Chloroform	THM	PCE	solvent	NA	NA	NA	NA	62	5.1
3	Chloroform	THM	Toluene	gas. hydro.	NA	NA	NA	NA	51	4.2
4	Chloroform	THM	MTBE	gas. oxy.	NA	NA	NA	NA	43	3.6
5	PCE	solvent	1,1,1-TCA	solvent	NA	NA	NA	NA	41	3.5
6	Toluene	gas. hydro.	1,2,4-TMB	gas. hydro.	NA	NA	NA	NA	36	3.0
7	Chloroform	THM	PCE	solvent	1,1,1-TCA	solvent	NA	NA	35	2.9
7	Toluene	gas. hydro.	PCE	solvent	NA	NA	NA	NA	35	2.9
9	Chloroform	THM	1,2,4-TMB	gas. hydro.	NA	NA	NA	NA	33	2.7
10	Chloroform	THM	Chloromethane	solvent	NA	NA	NA	NA	31	2.6
11	Chloromethane	solvent	1,2,4-TMB	gas. hydro.	NA	NA	NA	NA	30	2.5
12	Chloroform	THM	Methylene chloride	solvent	NA	NA	NA	NA	26	2.2
13	Chloroform	THM	TCE	solvent	NA	NA	NA	NA	24	2.0
13	PCE	solvent	TCE	solvent	NA	NA	NA	NA	24	2.0
15	1,1,1-TCA	solvent	MTBE	gas. oxy.	NA	NA	NA	NA	22	1.8
16	Chloroform	THM	1,1,1-TCA	solvent	MTBE	gas. oxy.	NA	NA	21	1.7
16	1,1,1-TCA	solvent	TCE	solvent	NA	NA	NA	NA	21	1.7
18	Chloroform	THM	PCE	solvent	TCE	solvent	NA	NA	20	1.7
18	PCE	solvent	MTBE	gas. oxy.	NA	NA	NA	NA	20	1.7
20	PCE	solvent	1,1-DCE	org. syn.	NA	NA	NA	NA	19	1.6
20	PCE	solvent	1,1,1-TCA	solvent	TCE	solvent	NA	NA	19	1.6
20	Toluene	gas. hydro.	1,1,1-TCA	solvent	NA	NA	NA	NA	19	1.6
23	Chloroform	THM	1,1-DCA	solvent	NA	NA	NA	NA	18	1.5
23	Chloroform	THM	1,1-DCE	org. syn.	NA	NA	NA	NA	18	1.5
23	Chloroform	THM	PCE	solvent	1,1-DCE	org. syn.	NA	NA	18	1.5
23	Chloroform	THM	PCE	solvent	MTBE	gas. oxy.	NA	NA	18	1.5
23	Chloroform	THM	PCE	solvent	1,1,1-TCA	solvent	TCE	solvent	18	1.5
23	Chloroform	THM	1,1,1-TCA	solvent	TCE	solvent	NA	NA	18	1.5
23	Toluene	gas. hydro.	Methylene chloride	solvent	NA	NA	NA	NA	18	1.5
30	1,1-DCE	org. syn.	1,1,1-TCA	solvent	NA	NA	NA	NA	17	1.4
30	PCE	solvent	1,1-DCA	solvent	NA	NA	NA	NA	17	1.4
30	PCE	solvent	1,1-DCE	org. syn.	1,1,1-TCA	solvent	NA	NA	17	1.4
33	Chloroform	THM	1,1-DCE	org. syn.	1,1,1-TCA	solvent	NA	NA	16	1.3
33	Chloroform	THM	PCE	solvent	1,1-DCE	org. syn.	1,1,1-TCA	solvent	16	1.3
33	1,1-DCA	solvent	1,1,1-TCA	solvent	NA	NA	NA	NA	16	1.3
36	Chloroform	THM	PCE	solvent	1,1-DCA	solvent	NA	NA	15	1.2
36	Chloromethane	solvent	Methylene chloride	solvent	NA	NA	NA	NA	15	1.2
36	Methylene chloride	solvent	1,2,4-TMB	gas. hydro.	NA	NA	NA	NA	15	1.2
36	Toluene	gas. hydro.	MTBE	gas. oxy.	NA	NA	NA	NA	15	1.2
36	Toluene	gas. hydro.	<i>m</i> - and <i>p</i> -Xylene	gas. hydro.	NA	NA	NA	NA	15	1.2
41	Benzene	gas. hydro.	1,2,4-TMB	gas. hydro.	NA	NA	NA	NA	14	1.2
41	Chloromethane	solvent	PCE	solvent	NA	NA	NA	NA	14	1.2
41	Chloroform	THM	1,1-DCA	solvent	1,1,1-TCA	solvent	NA	NA	14	1.2
41	Chloroform	THM	1,1-DCE	org. syn.	TCE	solvent	NA	NA	14	1.2
41	Chloroform	THM	PCE	solvent	1,1-DCE	org. syn.	TCE	solvent	14	1.2
41	1,1-DCE	org. syn.	TCE	solvent	NA	NA	NA	NA	14	1.2
41	PCE	solvent	1,1-DCA	solvent	1,1,1-TCA	solvent	NA	NA	14	1.2
41	PCE	solvent	1,1-DCE	org. syn.	TCE	solvent	NA	NA	14	1.2
41	1,1,1-TCA	solvent	1,2,4-TMB	gas. hydro.	NA	NA	NA	NA	14	1.2
50	1,1-DCE	org. syn.	1,1,1-TCA	solvent	TCE	solvent	NA	NA	13	1.1

[No., number; NA, not applicable; THM, trihalomethane; 1,1,1-TCA, 1,1,1-trichloroethane; PCE, perchloroethene; gas. hydro., gasoline hydrocarbon; MTBE, methyl *tert*-butyl ether; gas. oxy., gasoline oxygenate; 1,2,4-TMB, 1,2,4-trimethylbenzene; TCE, trichloroethene; 1,1-DCE, 1,1-dichloroethene; org. syn., organic synthesis compound; 1,1-DCA, 1,1-dichloroethane]

^aThe occurrence of mixtures, as reported in these results, is defined as two or more VOCs that are present in a domestic well sample.

^bVOCs are listed in decreasing order of the concentration for each compound within the mixture.

Supplemental Material, Table 5. Alphabetical listing of volatile organic compounds (VOCs) in 2,401 domestic well samples with concentrations less than but within one order of magnitude of U.S. Environmental Protection Agency's Maximum Contaminant Levels (MCLs).

Compound (abbreviation)	VOC group	MCL, in micrograms per liter	Number of well samples	Number of samples with concentrations within one order of magnitude of the MCL
Benzene	Gasoline hydrocarbon	5	2,401	2
Bromoform	THM	^a 80	2,399	1
Carbon tetrachloride	Solvent	5	2,400	3
Chloroform	THM	^a 80	2,400	4
Dibromochloromethane	THM	^a 80	2,400	1
^b Dibromochloropropane (DBCP)	Fumigant	0.2	1,962	1
1,2-Dichloroethane (1,2-DCA)	Solvent	5	2,383	3
^b 1,1-Dichloroethene (1,1-DCE)	Organic synthesis compound	7	2,400	3
^b 1,2-Dichloropropane	Fumigant	5	2,400	6
Methylene chloride	Solvent	6	2,398	9
^b Perchloroethene (PCE)	Solvent	5	2,371	17
1,1,1-Trichloroethane (1,1,1-TCA)	Solvent	200	2,401	1
^b Trichloroethene (TCE)	Solvent	5	2,400	9
Total trihalomethanes	THM	^a 80	2,400	5
Vinyl chloride	Organic synthesis compound	2	2,401	2

[THM, trihalomethane]

^a The MCL is for total trihalomethanes.

^b Compound also had concentrations greater than MCL

Supplemental Material, Table 6. Summary of concentrations of volatile organic compounds (VOCs) in 2,401 domestic well samples by State in comparison to human-health benchmarks, including U.S. Environmental Protection Agency Maximum Contaminant Levels (MCLs) for regulated VOCs and to Health-Based Screening Levels (HBSLs) for unregulated VOCs^a.

State	VOCs in domestic well samples									
	Total number of wells	^b One or more VOC concentrations greater than MCL		^b One or more VOC concentrations less than but within one order of magnitude of MCL		One or more VOCs detected, but concentrations less than one order of magnitude of MCL or HBSL ^c		Contained no VOCs		
		number	percent	number	percent	number	percent	number	percent	
Alaska	21	0	0.0	0	0.0	16	76.2	5	23.8	
Alabama	21	0	0	0	0	11	52.4	10	47.6	
Arkansas	12	0	0	1	8.3	3	25.0	8	66.7	
Arizona	56	0	0	0	0	33	58.9	23	41.1	
California	144	16	11.1	9	6.3	36	25.0	83	57.6	
Colorado	60	2	3.3	3	5.0	27	45.0	28	46.7	
Connecticut	13	0	0	0	0	5	38.5	8	61.5	
Delaware	5	0	0	0	0	2	40.0	3	60.0	
Georgia	23	0	0	1	4.4	3	13.0	19	82.6	
Hawaii	1	0	0	0	0	0	0	1	100	
Iowa	58	0	0	1	1.7	41	70.7	16	27.6	
Idaho	366	2	.5	4	1.1	15	4.1	345	94.3	
Illinois	61	0	0	4	6.5	40	65.6	17	27.9	
Indiana	3	0	0	0	0	3	100	0	0	
Kansas	46	0	0	0	0	29	63.0	17	37.0	
Louisiana	51	0	0	0	0	32	62.7	19	37.3	
Massachusetts	9	0	0	0	0	3	33.3	6	66.7	
Maryland	9	0	0	0	0	2	22.2	7	77.8	
Maine	36	0	0	0	0	20	55.6	16	44.4	
Michigan	29	0	0	0	0	8	27.6	21	72.4	
Minnesota	47	0	0	0	0	25	53.2	22	46.8	
Missouri	30	0	0	1	3.3	6	20.0	23	76.7	
Mississippi	9	0	0	0	0	5	55.6	4	44.4	
Montana	31	0	0	0	0	9	29.0	22	71.0	
North Carolina	18	0	0	0	0	13	72.2	5	27.8	
Nebraska	9	0	0	0	0	5	55.6	4	44.4	
New Hampshire	20	0	0	0	0	8	40.0	12	60.0	
New Jersey	115	2	1.7	4	3.5	72	62.6	37	32.2	
New Mexico	31	0	0	0	0	1	3.2	30	96.8	
Nevada	79	1	1.3	2	2.5	4	5.1	72	91.1	
New York	55	0	0	0	0	15	27.3	40	72.7	
Ohio	32	0	0	0	0	22	68.8	10	31.2	
Oklahoma	111	1	.9	0	0	16	14.4	94	84.7	
Oregon	64	1	1.6	1	1.6	4	6.2	58	90.6	
Pennsylvania	186	0	0	7	3.8	63	33.9	116	62.3	
Rhode Island	3	0	0	0	0	2	66.7	1	33.3	
South Carolina	49	0	0	0	0	17	34.7	32	65.3	
Tennessee	44	1	2.3	0	0	28	63.6	15	34.1	
Texas	166	0	0	1	.6	52	31.3	113	68.1	
Utah	30	0	0	0	0	15	50.0	15	50.0	
Virginia	26	0	0	0	0	9	34.6	17	65.4	
Vermont	3	0	0	0	0	1	33.3	2	66.7	
Washington	105	3	2.9	3	2.9	24	22.8	75	71.4	
Wisconsin	48	0	0	0	0	29	60.4	19	39.6	
West Virginia	30	0	0	0	0	18	60.0	12	40.0	
Wyoming	36	0	0	0	0	9	25.0	27	75.0	

^a Sampling was not evenly distributed throughout the States. See Figure 3 for sampling locations within individual States.

^b No VOC concentrations were greater than or within one order of magnitude of an HBSL.

^c HBSLs were developed by the U.S. Geological Survey in collaboration with the U.S. EPA, New Jersey Department of Environmental Protection, and the Oregon Health & Science University.

Supplemental Material, Appendix 1. To determine associations between multiple explanatory variables and the probability of VOC occurrence in drinking water supplied by domestic wells, multivariate logistic regression analyses were used. The following discussion is based on the statistical approach described by Moran (2006) and Moran et al. (2006).

In logistic regression, the response or dependent variable is the occurrence (coded as 1), or non-occurrence (coded as 0), of one or more VOCs. The explanatory variables are then related to the probability of occurrence of the response variable in a manner similar to linear regression. The magnitude and sign of the estimated slope coefficients determine the strength and direction of the association of explanatory variables with the probability of detecting VOCs in water according to the following equation:

$$P = \frac{e^{(\beta_0 + \beta_1 X_1 + \dots + \beta_i X_i)}}{1 + e^{(\beta_0 + \beta_1 X_1 + \dots + \beta_i X_i)}}$$

where

P = probability of detecting a VOC;
 β_0 = the y-intercept;
 β_i = slope coefficient of X_i , explanatory variables; and
 X_i = 1 to i explanatory variables.

Uncorrected estimated slope coefficients do not give an accurate assessment of the strength of an association because the units of each variable, especially continuous variables, have large differences in magnitude and variance. Therefore, standardized coefficients were computed in order to compare the slope coefficients directly between one another. The standardized coefficients indicate how many standard deviations of change in the dependent variable are associated with one standard deviation of change in the explanatory variable, and were computed following Menard (2002).

Explanatory variables were entered into logistic regression manually in a step-wise manner, and the regression was analyzed for significance at each step. For the overall regression, if the likelihood ratio of the model produced a p -value of ≤ 0.05 , all explanatory variables were considered significantly associated with the probability of occurrence of a VOC. The significance of nested logistic regression models was tested using the partial likelihood ratio test. For cases where one additional coefficient was added, the Wald statistic of the coefficient was used to determine significance. If the Wald statistic p -value of the slope coefficient was < 0.05 , and the upper and lower bound of the odds ratio did not include 1, the additional variable was considered significantly associated with the probability of occurrence of a VOC. The Hosmer-Lemeshow test was used to assess how well the observed binary responses were predicted by the model equation (Hosmer and Lemeshow, 1989). The null hypothesis for this test is that the predicted responses are identical to the observed responses. Therefore, a higher p -value for this test indicates a better correspondence between the observed and predicted responses.

A variety of explanatory data were used in the logistic regression analyses. These data represented 24 hydrogeologic factors and 24 anthropogenic factors that could control or influence the sources, transport, or fate of VOCs in ground water. A complete listing of these variables is available in Moran et al. (2006).

Supplemental Material, List of References

Hosmer DW, Lemeshow S. 1989. Applied Logistic Regression. New York, NY:Wiley and Sons.

Hutson SS, Barber NL, Kenny JF, Linsey KS, Lumia DS, Maupin MA. 2004. Estimated use of water in the United States in 2000. Circular 1268. Reston, VA:U.S. Geological Survey. Available: <http://pubs.usgs.gov/circ/2004/circ1268/> [accessed 25 June 2007].

Menard S. 2002. Applied Logistic Regression Analysis. Thousand Oaks, CA:Sage Publications, Inc.

Moran MJ. 2006. Occurrence and implication of selected chlorinated solvents in ground water and source water in the United States and in drinking water in 12 Northeast and Mid-Atlantic States, 1993-2002. SIR 2005-5268. Reston, VA:U.S. Geological Survey. Available: <http://pubs.usgs.gov/sir/2005/5268/sir20055268.pdf> [accessed 25 June 2007].

Moran MJ, Zogorski JS, Rowe BL. 2006. Approach to an assessment of volatile organic compounds in the Nation's ground water and drinking-water supply wells. OFR 2005-1452. Reston, VA:U.S. Geological Survey. Available: <http://pubs.usgs.gov/of/2005/1452/pdf/ofr2005-1452.pdf> [accessed 25 June 2007].

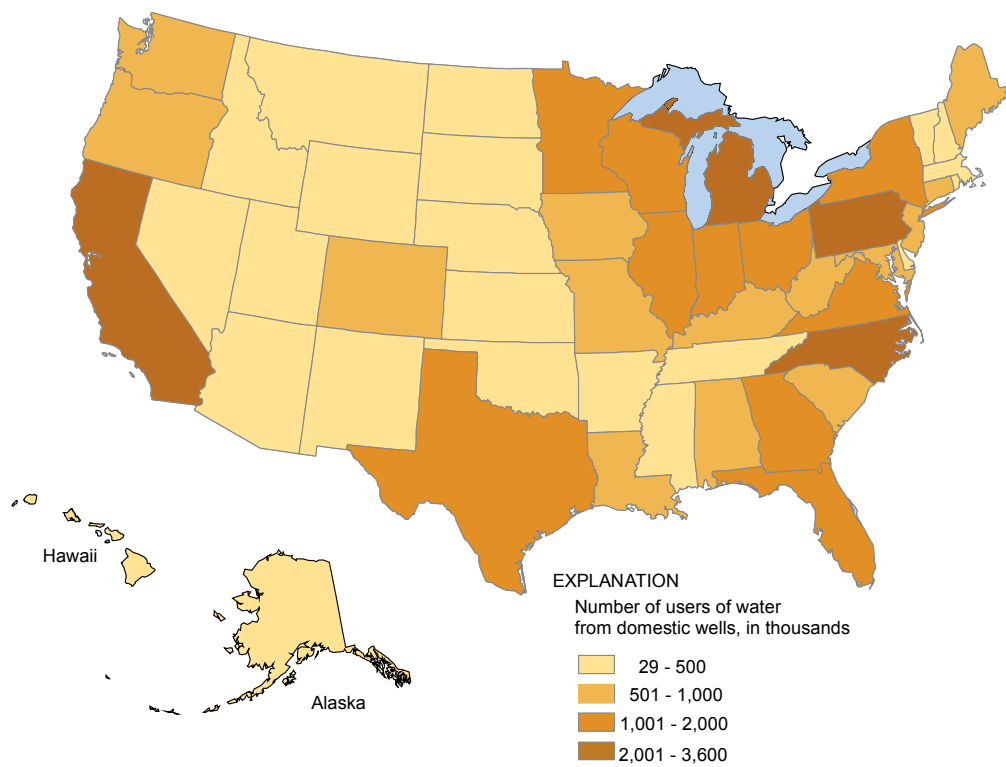
Toccalino PL. 2007. Development and application of Health-Based Screening Levels for use in water-quality assessments. SIR 2007-5106. Reston, VA:U.S. Geological Survey. Available: <http://pubs.usgs.gov/sir/2007/5106/pdf/sir20075106.pdf> [accessed 25 June 2007].

U.S. EPA. 1986. Guidelines for carcinogen risk assessment. EPA/630/R-00/004, September 24 1986. Washington, DC:U.S. Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment Federal Register.

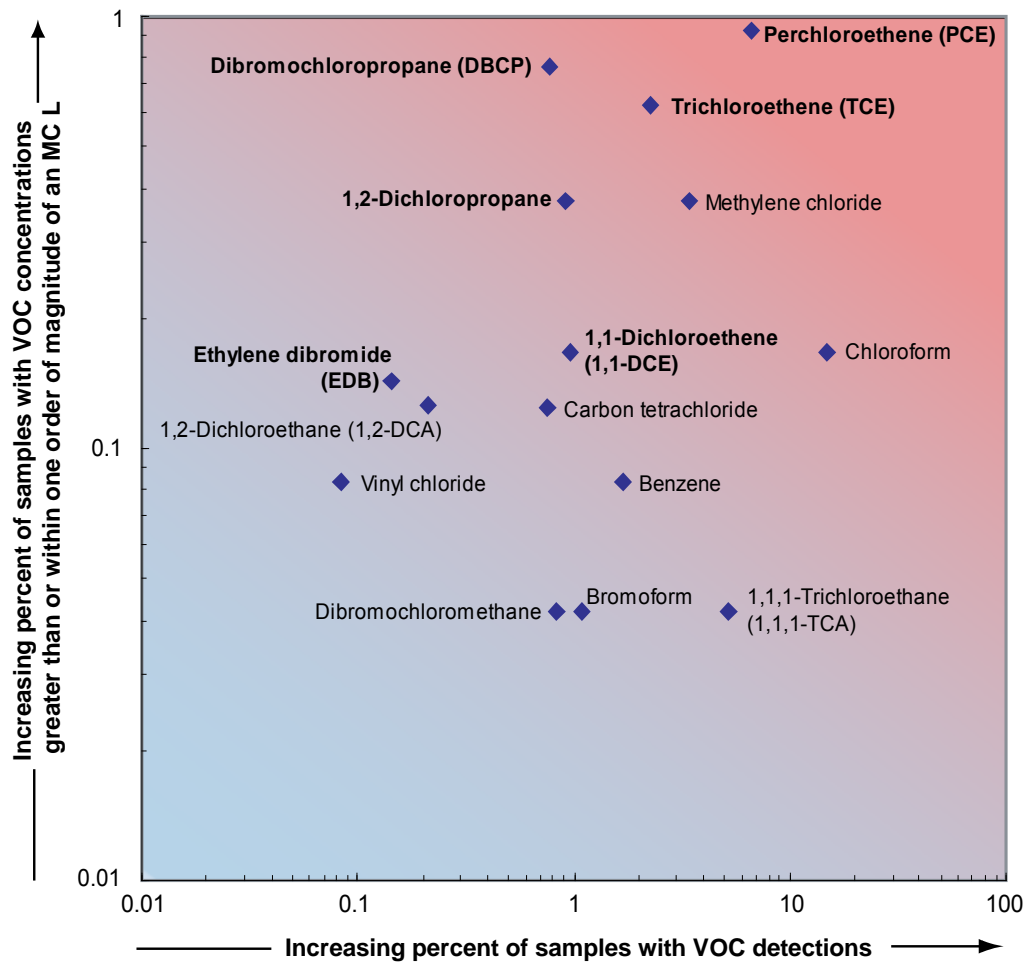
U.S. EPA. 1996. Proposed guidelines for carcinogen risk assessment. EPA/600/P-92/003C, April 1996. Washington, DC:U.S. Environmental Protection Agency, Office of Research and Development. Available: http://www.epa.gov/ncea/raf/pdfs/propcra_1996.pdf [accessed 06 July 2007].

U.S. EPA. 1999. Guidelines for carcinogen risk assessment NCEA-F-0644, July 1999. Washington, DC:U.S. Environmental Protection Agency, Office of Research and Development. Available: <http://www.epa.gov/ncea/raf/car2sab/preamble.pdf> [accessed 25 June 2007].

U.S. EPA. 2005. Guidelines for carcinogen risk assessment. EPA/630/P-03/001B, March 2005. Washington, DC:U.S. Environmental Protection Agency, Office of Research and Development, Risk Assessment Forum. Available: <http://cfpub.epa.gov/ncea/raf/recordisplay.cfm?deid=116283> [accessed June 25 2007].



Supplemental Material, Figure 1. Geographic distribution by State of the estimated number of people dependent on domestic wells for their drinking-water supply. The largest self-supplied populations and domestic well withdrawals were in California and Michigan. These two States represent 15 percent of the total domestic well users and 15 percent of the total domestic well withdrawals (Hutson et al. 2004). In addition, North Carolina and Pennsylvania each have more than 2 million people dependent on domestic wells for their drinking-water supply.



Supplemental Material, Figure 2. Occurrence patterns in domestic well samples for 15 volatile organic compounds (VOCs) with concentrations that are: (1) greater than U.S. EPA Maximum Contaminant Levels (MCLs) represented by bolded text; and (2) within one order of magnitude of MCLs. VOCs within the red portion of the graph may be of greater concern because these VOCs had the highest concentrations relative to MCLs and were more frequently detected than compounds within the blue portion of the graph. A complete listing of VOC concentrations compared to human-health benchmarks is included in Table S6 of the Supporting Information.