NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

Quality of Water from Domestic Wells in Principal Aquifers of the United States, 1991–2004

Scientific Investigations Report 2008–5227

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

Front cover. Photographs from iStock© Photos (middle photograph) and U.S. Geological Survey.

Quality of Water from Domestic Wells in Principal Aquifers of the United States, 1991–2004

By Leslie A. DeSimone

National Water-Quality Assessment Program

Scientific Investigations Report 2008–5227

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

For product and ordering information:
World Wide Web: http://www.usgs.gov/pubprod
Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: http://www.usgs.gov
Telephone: 1-888-ASK-USGS

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this report is in the public domain, permission must be secured from the individual copyright owners to reproduce any copyrighted materials contained within this report.

Suggested citation:
DeSimone, L.A., 2009, Quality of water from domestic wells in principal aquifers of the United States, 1991–2004: U.S. Geological Survey Scientific Investigations Report 2008–5227, 139 p., available online at http://pubs.usgs.gov/sir/2008/5227.

Foreword

The U.S. Geological Survey (USGS) is committed to providing the Nation with reliable scientific information that helps to enhance and protect the overall quality of life and that facilitates effective management of water, biological, energy, and mineral resources (http://www.usgs.gov). Information on the Nation's water resources is critical to ensuring long-term availability of water that is safe for drinking and recreation and is suitable for industry, irrigation, and fish and wildlife. Population growth and increasing demands for water make the availability of that water, now measured in terms of quantity and quality, even more essential to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to support national, regional, state, and local information needs and decisions related to water-quality management and policy (http://water.usgs.gov/nawqa). The NAWQA Program is designed to answer: What is the quality of our Nation's streams and ground water? How are conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. From 1991–2001, the NAWQA Program completed interdisciplinary assessments and established a baseline understanding of water-quality conditions in 51 of the Nation's river basins and aquifers, referred to as Study Units (http://water.usgs.gov/nawqa/studyu.html).

National and regional assessments are ongoing in the second decade (2001–2012) of the NAWQA Program as 42 of the 51 Study Units are reassessed. These assessments extend the findings in the Study Units by determining status and trends at sites that have been consistently monitored for more than a decade, and filling critical gaps in characterizing the quality of surface water and ground water. For example, increased emphasis has been placed on assessing the quality of source water and finished water associated with many of the Nation's largest community water systems. During the second decade, NAWQA is addressing five national priority topics that build an understanding of how natural features and human activities affect water quality, and establish links between *sources* of contaminants, the *transport* of those contaminants through the hydrologic system, and the potential *effects* of contaminants on humans and aquatic ecosystems. Included are topics on the fate of agricultural chemicals, effects of urbanization on stream ecosystems, bioaccumulation of mercury in stream ecosystems, effects of nutrient enrichment on aquatic ecosystems, and transport of contaminants to public-supply wells. In addition, national syntheses of information on pesticides, volatile organic compounds (VOCs), nutrients, selected trace elements, and aquatic ecology are continuing.

The USGS aims to disseminate credible, timely, and relevant science information to address practical and effective water-resource management and strategies that protect and restore water quality. We hope this NAWQA publication will provide you with insights and information to meet your needs, and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

The USGS recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for cost-effective management, regulation, and conservation of our Nation's water resources. The NAWQA Program, therefore, depends on advice and information from other agencies—Federal, state, regional, interstate, Tribal, and local—as well as nongovernmental organizations, industry, academia, and other stakeholder groups. Your assistance and suggestions are greatly appreciated.

Matthew C. Larsen
Associate Director for Water

THIS PAGE INTENTIONALLY LEFT BLANK

Contents

Foreword iii
Abstract 1
Introduction 2
Methods 6
Well Selection 6
Sample Collection and Analysis 7
Quality Assurance and Quality Control 7
Data Sources and Treatment 7
Statistical Methods and Data Presentation 8
Water-Quality Benchmarks for Human Health 8
Domestic Wells Sampled for the NAWQA Program, 1991–2004 9
Quality of Water from Domestic Wells 17
Physical Properties and Dissolved Solids 17
Major Ions 23
Trace Elements 27
Nutrients and Dissolved Organic Carbon 34
Radon and Other Radionuclides 37
Organic Compounds 42
Fecal Indicator Bacteria 53
Summary Comparison of Contaminant Concentrations to Human-Health Benchmarks 55
Co-occurrence of Contaminants as Mixtures 57
Approach for Assessment of Mixtures 57
Occurrence and Distribution of Mixtures 58
Composition of Mixtures 58
Assessing the Potential Significance of Mixtures to Human Health 63
Comparison with Previous Studies of Domestic Well-Water Quality 64
Summary and Conclusions 66
Acknowledgments 69
References 69
APPENDIXES IN BACK OF REPORT:
Appendix 1. Summary of selected studies of domestic well water quality in the United States 83
Appendix 2. Characteristics, principal aquifers, study units, and assessment studies of domestic wells sampled for the NAWQA Program, 1991–2004, by aquifer type 93
Appendix 3. Sampling and analytical methods and summary of field quality-control data for chemical contaminants measured in domestic wells sampled for the NAWQA Program, 1991–2004 101
Appendix 4. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water 111

APPENDIXES ON CD-ROM IN BACK OF REPORT:

Appendix 5. Summary statistics for physical properties and concentrations of major ions, trace elements, nutrients, radionuclides, and fecal indicator bacteria in samples collected from domestic wells for the NAWQA Program, 1991–2004 .....[on CD-ROM]

Appendix 6. Percentages of wells in principal aquifers with values of physical properties or concentrations of major ions, trace elements, nutrients, radionuclides, or organic compounds greater than human-health benchmarks or guidelines for drinking water in samples collected from domestic wells for the NAWQA Program, 1991–2004.....[on CD-ROM]

Appendix 7. Detection frequencies of organic compounds at any concentration and at several common reporting levels in samples collected from domestic wells for the NAWQA Program, 1991–2004 .....[on CD-ROM]

Figures

1. Map showing NAWQA study units and assessment studies in which domestic wells were sampled, 1991–2004 5
2. Maps showing *(A)* principal aquifers of the United States and *(B)* domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004.....10
3. Boxplots showing *(A)* well depth, *(B)* depth to top of open interval, and *(C)* depth to water in domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004 14
4. Maps showing population supplied by domestic wells by county in the United States in 1995 by *(A)* population density and *(B)* population as percent of total county population 15
5. Bar graphs showing water withdrawals for public supply in the United States in 2000 and numbers of domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, by principal aquifer 16
6. Map showing geographic distribution of dissolved solids concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 18
7. Boxplots showing *(A)* dissolved solids, *(B)* pH, *(C)* alkalinity, and *(D)* dissolved oxygen in samples collected from domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, by aquifer rock type 20
8. Map showing geographic distribution of pH in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 21
9. Map showing geographic distribution of alkalinity in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004.....22
10. Boxplot showing dissolved oxygen concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, by aquifer condition.....23
11. Trilinear diagrams of ionic composition of water in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, by principal aquifer rock type in *(A)* basin-fill and other non-glacial sand and gravel aquifers, *(B)* glacial sand and gravel aquifers, *(C)* coastal plain aquifers in semi-consolidated sand, *(D)* sandstone aquifers, *(E)* sandstone and carbonate-rock aquifers, *(F)* carbonate-rock aquifers, *(G)* basaltic-rock aquifers, and *(H)* crystalline-rock aquifers.....24

12. Map showing geographic distribution of hardness of water in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 26
13. Map showing geographic distribution of fluoride concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 27
14. Boxplots showing concentrations of *(A)* arsenic, *(B)* boron, *(C)* manganese, *(D)* strontium, and *(E)* uranium in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2001, by aquifer rock type.....31
15. Map showing geographic distribution of arsenic concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 32
16. Map showing geographic distribution of manganese concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 33
17. Map showing geographic distribution of uranium concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 34
18. Map showing geographic distribution of nitrate concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 37
19. Boxplots showing nitrate concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, by *(A)* aquifer rock type and *(B)* land use.....38
20. Map showing geographic distribution of radon concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1994–2004 40
21. Boxplot showing radon concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, by aquifer rock type.....41
22. Scatterplot showing concentrations of frequently detected organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 43
23. Bar graph showing detection frequency for frequently occurring organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 44
24. Bar graph showing percentage of samples in which one or more organic compounds were detected, at any concentration and at common reporting levels of 0.02 and 0.2 micrograms per liter, for domestic wells sampled for the NAWQA Program, 1991–2004, in aquifer studies.....45
25A–C. Maps showing geographic distribution of organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, at *(A)* detections above a common reporting level of 0.2 microgram per liter (µg/L), *(B)* detections above a common reporting level of 0.02 µg/L, and *(C)* concentrations greater than human-health benchmarks.....46
26. Boxplot showing concentrations of nitrate and organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 50
27. Map showing geographic distribution of atrazine and deethylatrazine in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 50
28. Map showing geographic distribution of chloroform in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004.....51

29. Map showing geographic distribution of methyl *tert*-butyl ether (MTBE) in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 52
30. Map showing geographic distribution of fecal indicator bacteria detected in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 54
31. Bar graph showing fecal indicator bacteria detected in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, by aquifer rock type 54
32. Map showing geographic distribution of wells with at least one contaminant at concentrations greater than or greater than one-tenth of human-health benchmarks in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 56
33. Graph showing frequency of occurrence of contaminants in mixtures in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 58
34A–B. Maps showing geographic distribution of wells with multiple contaminants *(A)* at concentrations greater than human-health benchmarks and *(B)* at concentrations greater than one-tenth of human-health benchmarks in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 59
35. Boxplots showing dissolved solids concentrations in relation to the numbers of contaminants present at *(A)* concentrations greater than human-health benchmarks and *(B)* concentrations greater than one-tenth of human-health benchmarks in samples collected from domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004 61

Tables

1. Characteristics of domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, by principal aquifer 12
2. Summary statistics for physical properties of, and major ions in, samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 17
3. Comparison of physical properties and concentrations of major ions in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, with human-health benchmarks and non-health guidelines for drinking water.....19
4. Summary statistics for trace elements in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004.....28
5. Comparison of concentrations of trace elements in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, with human-health benchmarks and non-health guidelines for drinking water 30
6. Summary statistics for nutrients, dissolved organic carbon, radionuclides, and fecal indicator bacteria in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004.....36
7. Comparison of concentrations of nitrate and radionuclides in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, with human-health benchmarks and non-health guidelines for drinking water 39
8. Land-use classification used to categorize domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004.....39
9. Comparison of concentrations of organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, with human-health benchmarks for drinking water.....49
10. Number and percentage of domestic wells, in a subset of 1,389 domestic wells from the NAWQA Program in aquifer studies, 1991–2004, containing one or more contaminants at concentrations greater than a human-health benchmark or greater than one-tenth of a benchmark.....55
11. Composition and frequency of occurrence of unique mixtures of contaminants individually at concentrations of potential concern for human health in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 62
12. Composition and frequency of occurrence of unique mixtures of contaminants individually at concentrations of potential concern for human health and any detectable concentration for organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004 63

Conversion Factors and Abbreviations

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.00378	milliliter (mL)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)

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

$$°F=(1.8\times°C)+32$$

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

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Concentrations of fecal indicator bacteria in water are given in colony forming units per 100 milliliters (CFU/100mL).

Concentrations of radioisotopes in water are given in picocuries per liter (pCi/L).

ABBREVIATIONS USED IN REPORT

α	acceptable statistical significance level
AA	atomic absorption spectrometry
BTEX	benzene, toluene, ethylbenzene, and xylenes
$CaCO_3$	calcium carbonate
CDC	U.S. Centers for Disease Control and Prevention
DBCP	dibromochloropropane
E. coli	*Escherichia coli*
EDB	ethylene dibromide
GCMS	gas chromatography/mass spectrometry
HBSL	Health-Based Screening Level
HPLC	high performance liquid chromatography
ICP	inductively-coupled plasma

ICP-AES	inductively-coupled plasma–atomic emission spectroscopy
ICP-MS	inductively-coupled plasma–mass spectrometry
LRL	laboratory reporting level
LT-MDL	long-term method-detection level
MTBE	methyl *tert*-butyl ether
MCL	Maximum Contaminant Level
MDL	method-detection level
MRL	minimum reporting level
n	number of samples
NAWQA	National Water-Quality Assessment
NPS	National Survey of Pesticides in Drinking-Water Wells
NSA	National Statistical Assessment of Rural Water Conditions
NWIS	National Water Information System
NWQL	National Water-Quality Laboratory
p	attained statistical significance level
QC	quality control
PCE	perchloroethene
R^2	coefficient of determination, or fraction of variance explained by regression
RPD	relative percent difference
RSD	relative standard deviation
SD	standard deviation
SDWA	Safe Drinking Water Act
SMCL	Secondary Maximum Contaminant Level
SSMDC	sample-specific minimum detectable concentration
TCE	trichloroethene
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VOC	volatile organic compound

THIS PAGE INTENTIONALLY LEFT BLANK

Quality of Water from Domestic Wells in Principal Aquifers of the United States, 1991–2004

By Leslie A. DeSimone

Abstract

As part of the National Water-Quality Assessment Program of the U.S. Geological Survey (USGS), water samples were collected during 1991–2004 from domestic wells (private wells used for household drinking water) for analysis of drinking-water contaminants, where contaminants are considered, as defined by the Safe Drinking Water Act, to be all substances in water. Physical properties and the concentrations of major ions, trace elements, nutrients, radon, and organic compounds (pesticides and volatile organic compounds) were measured in as many as 2,167 wells; fecal indicator bacteria and radionuclides also were measured in some wells. The wells were located within major hydrogeologic settings of 30 regionally extensive aquifers used for water supply in the United States. One sample was collected from each well prior to any in-home treatment. Concentrations were compared to water-quality benchmarks for human health, either U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Levels (MCLs) for public water supplies or USGS Health-Based Screening Levels (HBSLs).

No individual contaminant was present in concentrations greater than available health benchmarks in more than 8 percent of the sampled wells. Collectively, however, about 23 percent of wells had at least 1 contaminant present at concentrations greater than an MCL or HBSL, based on analysis of samples from 1,389 wells in which most contaminants were measured. Radon, nitrate, several trace elements, fluoride, gross alpha- and beta-particle radioactivity, and fecal indicator bacteria were found most frequently (in one or more percent of wells) at concentrations greater than benchmarks and, thus, are of potential concern for human health. Radon concentrations were greater than the lower of two proposed MCLs (300 picocuries per liter or pCi/L) in about 65 percent of the wells and greater than the higher proposed MCL (4,000 pCi/L) in about 4 percent of wells. Nitrate, arsenic, manganese, strontium, and gross alpha-particle radioactivity (uncorrected) each were present at levels greater than MCLs or HBSLs in samples from about 5 to 7 percent of the wells; boron, fluoride, uranium, and gross beta-particle radioactivity were present at levels greater than MCLs or HBSLs in about 1 to 2 percent of the wells. Total coliform and *Escherichia coli* bacteria were detected in about 34 and 8 percent, respectively, of sampled wells. Thus, with the exception of nitrate and fecal indicator bacteria, the contaminants that were present in the sampled wells most frequently at concentrations greater than human-health benchmarks were naturally occurring.

Anthropogenic organic compounds were frequently detected at low concentrations, using typical analytical detection limits of 0.001 to 0.1 micrograms per liter, but were seldom present at concentrations greater than MCLs or HBSLs. The most frequently detected compounds included the pesticide atrazine, its degradate deethylatrazine, and the volatile organic compounds chloroform, methyl *tert*-butyl ether, perchloroethene, and dichlorofluoromethane. Only 7 of 168 organic compounds were present in samples at concentrations greater than MCLs or HBSLs, each in less than 1 percent of wells. These were diazinon, dibromochloroprane, dinoseb, dieldrin, ethylene dibromide, perchloroethene, and trichloroethene. Overall, concentrations of any organic compound greater than MCLs or HBSLs were present in 0.8 percent of wells, and concentrations of any organic compound greater than one-tenth of MCLs or HBSLs were present in about 3 percent of wells.

Several other properties and contaminants were measured at values or concentrations outside of recommended ranges for drinking water for aesthetic quality (for example, taste or odor) or other non-health reasons. About 16 percent of the sampled wells had pH values less than (14.4 percent) or greater than (1.9 percent) the USEPA recommended range of 6.5 to 8.5. Total dissolved solids were greater than the USEPA Secondary Maximum Contaminant Level (SMCL) of 500 milligrams per liter in about 15 percent of wells. Iron and manganese concentrations were greater than SMCLs in about 19 and 21 percent of wells, respectively. Concentrations of fluoride, which can be harmful at high levels but prevents tooth decay at lower levels, were less than those recommended by the U.S. Centers for Disease Control and Prevention in about 90 percent of the sampled wells.

Geographic patterns of occurrence among principal aquifers showed that several contaminants and properties may be of greater potential concern in certain locations or regions than nationally. For example, radon concentrations were greater than the proposed MCLs in 30 percent (higher proposed MCL) and 90 percent (lower proposed MCL) of wells in crystalline-rock aquifers located in the Northeast,

the central and southern Appalachians, and Colorado. Nitrate was present at concentrations greater than the MCL more frequently in agricultural areas than in other land-use settings. Contaminant concentrations also were related to geochemical conditions. For example, uranium concentrations were correlated with concentrations of dissolved oxygen in addition to showing regional patterns of occurrence; relatively high iron and manganese concentrations occurred everywhere, but were inversely correlated with dissolved oxygen concentrations.

Mixtures of two or more contaminants at concentrations greater than human-health benchmarks occurred in only about 4 percent of wells, but mixtures of two or more contaminants with concentrations greater than one-tenth of their benchmarks occurred in about 73 percent of wells. The more complex mixtures, with the largest numbers of contaminants, were most common in several aquifers in the western and south-central United States in ground water with high concentrations of dissolved solids overall. Two-thirds of the unique mixtures of contaminants with concentrations greater than one-tenth of their benchmarks that occurred in 5 percent or more of wells were composed of two or more of six contaminants—nitrate, arsenic, radon, and uranium, and to a lesser extent, molybdenum and manganese. Organic compounds were rarely components of unique mixtures of contaminants at concentrations greater than human-health benchmarks or greater than one-tenth of their benchmarks. However, mixtures of naturally occurring contaminants at concentrations greater than one-tenth of their benchmarks and organic compounds detected at any concentration were common, occurring in about 90 percent of wells. Several combinations of organic compounds in mixtures with possible health effects were identified—specifically, atrazine and deethylatrazine, atrazine or simazine with nitrate, and perchloroethene and three other solvents—but combined concentrations either were less than the health benchmarks or no benchmarks were available for the mixtures. These co-occurrences may be a potential concern for human health, but the long-term cumulative effects of low concentrations of multiple contaminants on human health currently are unknown.

Introduction

More than 43 million people—about 15 percent of the population of the United States—rely on privately owned household wells for their drinking water (Hutson and others, 2004). The quality and safety of these water supplies, known as private or domestic wells, are not regulated under Federal or, in most cases, state law. Rather, individual homeowners are responsible for maintaining their domestic well systems and for any routine water-quality monitoring. The Safe Drinking Water Act (SDWA) governs the Federal regulation and monitoring of public water supplies. Although the SDWA does not include regulation of domestic wells, its approach to evaluating the suitability of drinking water for public supplies provides a useful approach for evaluating the quality of drinking water obtained from domestic wells. The SDWA defines terminology related to water supply and the process by which drinking-water standards, called Maximum Contaminant Levels (MCLs), are established to ensure safe levels of specific contaminants in public water systems. The SDWA defines a contaminant as “any physical, chemical, biological, or radiological substance or matter in water” (U.S. Senate, 2002), whether potentially harmful or not (see sidebar on page 3).

When the SDWA was passed in 1974, it mandated a national study of rural water systems, including domestic wells. In that study, which focused on indicator bacteria and inorganic contaminants, contaminant concentrations were found to be greater than health benchmarks, which included available MCLs, in more than 15 percent of the domestic wells in the United States (National Statistical Assessment of Rural Water Conditions, or NSA; U.S. Environmental Protection Agency, 1984). Studies of many geographic areas and contaminants since then have shown that a variety of contaminants can be present in domestic wells, although usually at concentrations that are unlikely to have adverse human-health effects.

Comprehensive and reliable information on the occurrence of contaminants in domestic wells is essential for the protection of public health. Although few in number (averaging less than 20 outbreaks per year), about 20 to 40 percent of the waterborne-disease outbreaks from drinking water that were reported to the U.S. Centers for Disease Control and Prevention (CDC) from 1999 to 2002 were attributed to contaminants in domestic well water; gastrointestinal illness associated with the consumption of domestic well water is likely underreported (Blackburn and others, 2004; Liang and others, 2006). Health risks associated with contaminants in domestic well water also have been noted to include exposure to elevated concentrations of nitrate, arsenic, radon, lead, and organic compounds (U.S. Centers for Disease Control and Prevention, 2003). Information on contaminants in domestic wells also is important for the management and regulation of chemical use, pesticides for example, and a number of surveys have been conducted for these purposes (Brook and others, 2002; Townsend and others, 1998; Troiano and others, 2001).

Most ground water in the United States is generally considered of good quality and safe to drink (U.S. Environmental Protection Agency, 2000a, 2002a). However, the large number and widespread presence of potential sources of contaminants make water-quality testing fundamental to determining the safety of consuming water from domestic wells. State and local regulations, where they exist, provide for a minimum amount of testing of water from domestic wells. Existing regulations apply primarily at the time of well installation and are limited in scope. Fewer than half of the states require testing of new domestic wells, typically for bacteria and nitrate only. County or other local testing requirements for new wells also exist in some states. Water-quality testing at the time of home sales is a condition of some home loans and also is required by a few states (Oregon Department of Human Services, 2003; Veterans Benefits Administration, 2005; New Jersey

What is a Contaminant?

A contaminant is defined by the SDWA as "any physical, chemical, biological, or radiological substance or matter in water" (U.S. Senate, 2002; 40 CFR 141.2). This broad definition of contaminant includes every substance that may be found dissolved or suspended in water—everything but the water molecule itself. Another term sometimes used to describe a substance in water is "water-quality constituent," which has a meaning similar to the SDWA definition of contaminant.

The presence of a contaminant in water does not necessarily mean that there is a human-health concern. Whether a particular contaminant in water is potentially harmful to human health depends on its toxicity and concentration in drinking water. In fact, many contaminants are beneficial at certain concentrations. For example, many naturally occurring inorganic contaminants, such as selenium, are required in small amounts for normal physiologic function, even though higher amounts may cause adverse health effects (Eaton and Klaassen, 2001). On the other hand, anthropogenic organic contaminants, such as pesticides, are not required by humans, but may or may not have adverse effects on humans, depending on concentrations, exposure, and toxicity. As a first step toward evaluating whether a particular contaminant may adversely affect human health, its concentration measured in water can be compared to a U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL) or a U.S. Geological Survey (USGS) Health-Based Screening Level (HBSL). Concentrations greater than these water-quality benchmarks indicate the potential for health effects (see discussion in the section, "Water-Quality Benchmarks for Human Health").

The types of contaminants measured in this study are listed below (see "Methods" section for a complete description of measurements and methods). There are other types of contaminants, such as pathogens and other organic compounds, that were not measured in this study.

Types of Contaminants Measured in this Study

- Inorganic
  - Major ions (such as chloride)
  - Trace elements (such as arsenic)
  - Radionuclides (such as radon)
- Nutrients (such as nitrate)
- Organic
  - Volatile organic compounds (such as chloroform)
  - Pesticides (such as atrazine)
- Microorganisms
  - Fecal indicator bacteria (such as *Escherichia coli*)

These contaminants originate from a wide range of natural and anthropogenic sources. The inorganic chemicals, nutrients, and microorganisms measured in this study occur naturally, but their concentrations in ground water may be altered by human activities. For example, nitrate from natural sources is present in many wells, but concentrations are often increased by contributions from anthropogenic sources in agricultural and urban areas. In contrast, the organic contaminants measured in this study are anthropogenic, though some also may form in ground water through various chemical and biological transformation processes.

Eaton, D.L., and Klaassen, C.D., 2001, Principles of toxicology, in Klaassen, C.D., ed., Casarett and Doull's Toxicology—The Basic Science of Poisons (6th ed.): New York, McGraw-Hill, p. 1236.

U.S. Senate, 2002, Title XIV of the public health service act; safety of public water systems (Safe Drinking Water Act); Part A—Definitions (as amended through P.L. 107–377): U.S. Senate, updated December 31, 2002, accessed July 29, 2008, at http://epw.senate.gov/sdwa.pdf.

Department of Environmental Protection, 2008). A few states conduct free voluntary testing programs or test high-risk wells (Riding and Quilter, 2004; State Water Resources Control Board, 2005; Florida Department of Health, 2006). Many public health agencies, environmental protection agencies, and non-profit organizations advise homeowners on testing procedures and recommend annual testing (U.S. Environmental Protection Agency, 2002a; National Ground Water Association, 2006). These programs, regulations, and recommendations all contribute to the safety of drinking water supplied by domestic wells. However, the limited number of contaminants assessed, the small numbers of wells tested, and the infrequent and (or) voluntary nature of testing that results from these programs, regulations, and recommendations do not provide domestic well users the same level of protection afforded to users of public water systems.

In the absence of comprehensive, routine monitoring, information from a wide variety of sources is commonly used to assess the occurrence and distribution of contaminants in domestic wells. Potential sources of information to address specific questions about the quality of water from domestic wells include one-time statewide or regional surveys, voluntary testing programs, and ambient ground-water monitoring programs (Appendix 1). Results of these surveys and programs are useful for prioritizing contaminants for further study, identifying areas of particular concern for specific contaminants, guiding public-health programs and local testing recommendations, and identifying factors that potentially affect the occurrence of contaminants in wells. Differences in study design, methods, and target contaminants, however, make available survey studies difficult to compare or extrapolate (Ray and Schock, 1996). Many statewide or regional studies have focused on vulnerable aquifers or land uses that were more likely to be affected by human activities than other areas, and voluntary testing programs may be biased toward wells with high contaminant concentrations (Peters and others, 1999).

A retrospective analysis of USGS data from 1986–2001 from domestic wells recently provided information on the occurrence of 26 contaminants in a large number of wells in every state and Puerto Rico (Focazio and others, 2006). The retrospective study included data from the National Water-Quality Assessment (NAWQA) Program (some of which is also included in the present study) as well as data from many other studies, including those in known problem areas. Findings were that arsenic (11 percent) and nitrate (8 percent) exceeded USEPA MCLs most often, while uranium, mercury, and fluoride also exceeded MCLs in smaller numbers. Organic compounds rarely exceeded drinking-water standards or other human-health benchmarks. The present analysis expands the scope of the retrospective study by considering a larger number of contaminants and properties, by using USGS Health-Based Screening Levels (HBSLs) and MCLs to evaluate concentrations of potential health concern, and by assessing the co-occurrence of contaminants. The present study also includes only NAWQA Program data, which characterize ambient water-quality conditions in major aquifers used for water supply.

The present study synthesizes and describes water-quality conditions for 2,167 domestic wells sampled in major hydrogeologic settings of 30 regionally extensive aquifers used for water supply (principal aquifers) in the United States. The domestic wells were sampled for the NAWQA Program during 1991–2004 as part of interdisciplinary assessments of surface- and ground-water quality in study areas across the United States (fig. 1; Gilliom and others, 1995; Lapham and others, 2005; http://water.usgs.gov/nawqa). There were three primary objectives for the present study:

1. *Assess the occurrence and distribution of water-quality conditions for domestic wells and evaluate contaminant concentrations in relation to human-health benchmarks for drinking water.* Physical properties (such as temperature and specific conductance), major ions, nutrients, radon, trace elements, pesticides, and volatile organic compounds were measured; fecal indicator bacteria and additional radionuclides also were measured in some wells. Measured concentrations of contaminants were compared to USEPA MCLs and USGS HBSLs to evaluate their potential importance to human health.

2. *Describe the variation in water quality among principal aquifers and rock types*. Water-quality conditions in domestic wells were described at the national scale, by principal aquifer, and by principal aquifer rock type. Principal aquifers provide a framework for regional synthesis and extrapolation of water quality; comparisons at this and the national scale are made possible by consistent sampling design used for the NAWQA aquifer assessment studies.

3. *Assess the co-occurrence of contaminants as mixtures*. The comprehensive suite of contaminants analyzed in each well made it possible to investigate the co-occurrence of multiple contaminants. Historically, toxicologists have evaluated the potential health effects from exposure to individual contaminants, but assessing the potential effects of chemical mixtures is an area of active research (U.S. Environmental Protection Agency, 2001c; Argonne National Laboratory, 2005), and current understanding is limited. Information on the occurrence of contaminant mixtures obtained from the NAWQA studies can contribute to this research by describing the mixtures commonly found in water samples from domestic wells. Co-occurrence is investigated in this study using 1,389 wells, located in 25 principal aquifers and 45 states, with uniform and complete chemical analyses.

The NAWQA studies were designed as integrated assessments of the water resources within hydrologic systems of the Nation, not as a single, national-scale assessment of domestic well water quality or of water quality within

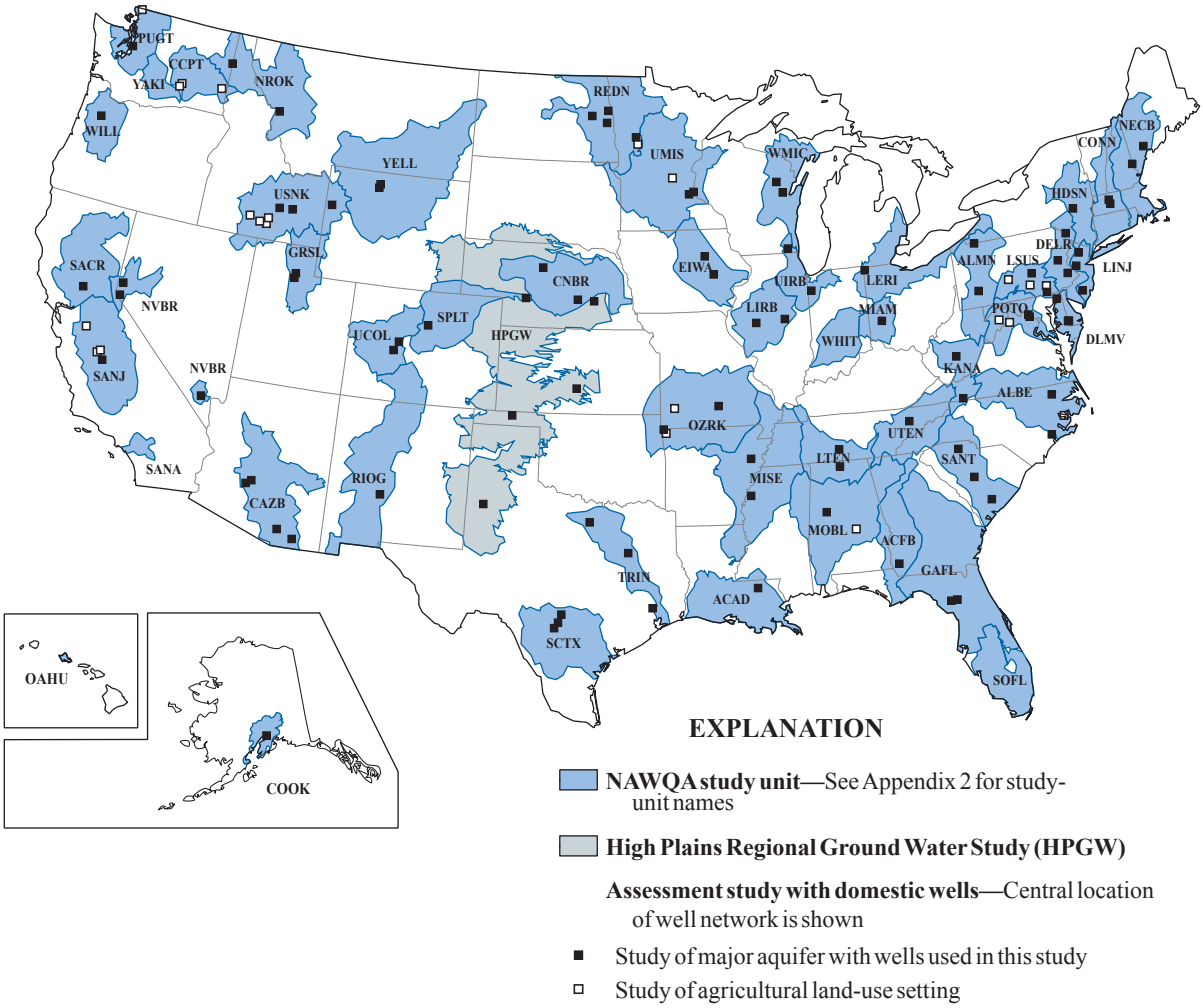


Figure 1. NAWQA study units and assessment studies in which domestic wells were sampled, 1991–2004.

principal aquifers. Consequently, several characteristics and limitations are important to consider when the findings about domestic wells presented in this report are interpreted:

- NAWQA assessment studies describe ambient conditions within the areas that were targeted for sampling, without focus on specific sites or areas with known water-quality problems.
- The targeted sampling areas were defined geographically by the extent of major hydrogeologic settings. Thus, the domestic wells sampled in NAWQA assessment studies are not uniformly distributed across the United States or within principal aquifers, and they are not a statistically representative sample of all domestic wells in the United States.
- Water samples were collected prior to any in-home distribution plumbing or treatment systems, and thus represent the quality of source water from domestic wells rather than water consumed by homeowners.
- USGS analytical methods were designed to measure concentrations as low as economically and technically feasible, which, particularly for organic compounds, were well below available standards or guidelines for drinking water. Thus, some contaminants may have been frequently detected at concentrations that are not expected to have adverse effects.

Methods

Methods used in the present study for well selection, sample collection and documentation, chemical analysis, and quality assurance and quality control that are described here are those used by the NAWQA Program for assessment studies conducted in major river basins and aquifers throughout the United States during 1991–94. Methods of data treatment and analysis used in the present study and described here are consistent with those used by national-scale syntheses of the NAWQA water-quality data on pesticides, volatile organic compounds, and nutrients (U.S. Geological Survey, 1999; Gilliom and others, 2006; Zogorski and others, 2006). Methods of data presentation and analysis used in the present study also are described in this section.

Well Selection

The wells included in the present study were sampled as part of assessment studies that were designed to describe the water quality of major hydrogeologic settings or major aquifers used for drinking water within NAWQA study units (Gilliom and others, 1995; 2006, fig. 1). Each assessment study used a sampling network of about 20 to 30 wells, randomly selected within a target area that represented the extent of the aquifer or hydrogeologic setting (Scott, 1990). Most of these were domestic wells, that is, privately owned wells that supply water for household use (Zogorski and others, 2006). Other types of wells that may have been sampled in the original assessment studies were not included in the present study. A total of 2,167 domestic wells were included in the present study. The wells were part of 93 assessment studies (fig. 1), and the numbers of domestic wells ranged from 1 to 104 domestic wells per study with a median of 25. Results of the individual studies are described in reports for NAWQA study units (http://water.usgs.gov/nawqa). Additional information on the assessment studies and NAWQA study units is given in Appendix 2.

In some NAWQA study units, studies were conducted to assess the quality of shallow ground water beneath specific land uses, such as agriculture, within a major aquifer or hydrogeologic setting. Monitoring wells composed large proportions of the wells in these studies, but domestic wells were included in some cases. Domestic wells or monitoring wells were selected by location using a random sampling design such as that used for major aquifer assessment studies. Water-quality data on some contaminants in domestic wells sampled for the NAWQA agricultural land-use assessment studies are summarized in this report to aid in describing the potential effects of agricultural land-use practices on the ground water in the aquifers studied. Data from 436 wells in agricultural land-use settings, primarily near the east and west coasts of the United States, are summarized. Information on these wells also is provided in Appendix 2. In general, however, water-quality results described in this report do not include results for wells from the agricultural land-use studies unless specifically indicated.

Specific criteria for well selection and documentation are described by Lapham and others (1995; 1997) and Koterba (1998). Criteria included the proximity of the well to the randomly selected site, the availability of well-construction and aquifer information, and the availability of a suitable sampling location. Ancillary data for each well, collected during or near the time of sample collection, included latitude and longitude; topographic setting; well depth, diameter, screened interval, and casing material; lithology and aquifer(s) or rock units contributing water to the well; static water level (depth to water); and potential sources of contamination and land use near the well.

Wells used in the present study were categorized in terms of the principal aquifers from which they withdrew water. A principal aquifer is defined as "… a regionally extensive aquifer or aquifer system that has the potential to be used as a source of potable water" (U.S. Geological Survey, 2003a). Principal aquifers were mapped by USGS and are described in the National Atlas of the United States by name and by rock type (Miller, 2000; U.S. Geological Survey, 2003a, 2003b, hereafter referred to as the "National Atlas"). The principal aquifers associated with individual domestic wells in this study were identified using information from NAWQA regional aquifer assessments (T.L. Arnold, U.S. Geological Survey, written commun., 2005; Lapham and others, 2005) and using lithologic information available for the wells in the USGS National Water Information System (NWIS) databases (Koterba, 1998). Principal aquifer definitions, extent, and lithologic groupings followed those used in the National Atlas (Miller, 2000; U.S. Geological Survey, 2003a, 2003b), with a few modifications. Unconsolidated sand and gravel aquifers were divided into two categories: (1) basin-fill and other non-glacial sand and gravel aquifers, and (2) glacial sand and gravel aquifers. Glacial sand and gravel aquifers were further split into eastern, central, west-central, and western glacial aquifers, on the basis of geography and differing source materials (Warner and Arnold, 2006). Also, the areal extent of glacial sand and gravel aquifers used in this study extends farther west than shown in the National Atlas, and include deposits of both Laurentide and Cordilleran continental glaciations (Warner and Arnold, 2006). The Valley and Ridge aquifers, which are combined as sandstone/carbonate-rock aquifers in the National Atlas, were separately defined as Valley and Ridge sandstone aquifers and Valley and Ridge carbonate-rock aquifers. Finally, wells in the New England and Rocky Mountain Front Range crystalline-rock aquifers and in some alluvial aquifers, which are described as local aquifers, or are not described, in the National Atlas, were sampled. These aquifers are included with principal aquifers in this study.

Sample Collection and Analysis

Water samples were collected and processed using methods designed to yield samples that were representative of environmental conditions, minimally affected by contamination, and comparable among NAWQA study units nationwide. Sampling methods are described in Koterba and others (1995), U.S. Geological Survey (variously dated), Kolpin and others (1998), Embrey and Runkle (2006), and Moran and others (2006). The samples were collected directly from the wells before any water treatment and, in most instances, before any pressure or holding tanks. Because the water samples were collected before any treatment systems that may have been operating within homes or distribution plumbing, they characterize the quality of the raw source water supplied to households, rather than the finished water consumed by household residents in some cases.

The physical properties of water—pH, temperature, specific conductance, and dissolved oxygen—were measured in the field during sampling. Samples were collected for laboratory analysis of alkalinity, major ions, nutrients, dissolved organic carbon, trace elements, pesticides, volatile organic compounds (VOCs), and radon, and, at some wells, for analysis of fecal indicator bacteria, gross alpha- and beta-particle radioactivities, and radium. Water samples were analyzed at the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colorado. Sampling and analytical methods are described in detail in Appendix 3; analytes are listed in Appendix 4.

Quality Assurance and Quality Control

Procedures to ensure and assess data quality in the NAWQA Program include written protocols for well selection, sample collection, and chemical analysis; the collection of field and laboratory quality-control (QC) samples; and field-measurement and laboratory evaluation programs (Moran and others, 2006). Procedures and protocols for well selection, sampling, and analysis have been described previously. The quality of field measurements made by USGS personnel is assessed by the USGS Branch of Quality Systems, National Field Quality Assurance Program, which has conducted assessments annually since 1979 (Stanley and others, 1998; U.S. Geological Survey, 2006b). Quality assurance and QC procedures at the NWQL include method QC samples, blind-sample programs, and interlaboratory performance-evaluation studies (Ludtke and Woodworth, 1997; Pirkey and Glodt, 1998; U.S. Geological Survey, 2006c). Field QC samples, which were an important part of the NAWQA assessment study design (Koterba and others, 1995), can be used to assess bias and variability in the water-quality analytical data at the study unit and national scale. Results of national-scale investigations of field QC data on nutrients, trace elements, pesticides, VOCs, fecal indicator bacteria, and radionuclides and summaries of field QC data in study unit reports are described in detail in Appendix 3. These assessments indicated that the analytical data for samples from domestic wells collected for the NAWQA Program are reproducible and representative of environmental conditions.

Data Sources and Treatment

Well site information, ancillary data, and most water-quality data were obtained from the USGS NAWQA Data Warehouse (Bell and Williamson, 2006; http://water.usgs.gov/nawqa/data). Data were retrieved from the Data Warehouse mostly from December 2004 to May 2005. Data from samples collected from 1991 through June 2004 were retrieved. Data from one sample per well, the primary sample used to characterize water quality at the well and typically the sample with greatest number of analytes, were used. Samples from the first 10-year monitoring period of the NAWQA Program were used for wells that were sampled in both the first and second 10-year monitoring periods. Data on fecal indicator bacteria were those used in an analysis by Embrey and Runkle (2006; S.S. Embrey, U.S. Geological Survey, written commun., 2005). The data on radium isotopes were those used in a national analysis of radionuclide data collected for the NAWQA Program (Zoltan Szabo, U.S. Geological Survey, written commun., 2006 and 2008).

Censored water-quality data (non-detects) from the Data Warehouse, particularly for organic compounds, incorporated the different reporting conventions (minimum reporting levels and laboratory reporting levels, or MRLs and LRLs) that were used by the NWQL during the study period and are not strictly comparable (Helsel, 2005a). Thus, censored values that were reported relative to LRLs were redefined relative to their associated long-term method-detection levels (LT-MDLs) using information on historical LT-MDLs for analytical methods used by the NWQL (see Appendix 3 for further discussion). This procedure was used to improve consistency of the reporting conventions in the data set and to avoid any potential bias in summary statistics that might result from the inclusion of estimated values below LRLs (Helsel, 2005a).

The numerical values of MRLs and LT-MDLs for many individual analytes changed during the study period. MRLs and LT-MDLs also differed considerably among analytes (Appendix 4). Differing reporting or detection levels cause problems in some analyses of water-quality data. Contaminants for which analytical methods provided lower detection limits may seem to occur more frequently in the environment relative to other contaminants with higher analytical detection limits. Regional patterns of occurrence of a contaminant may be distorted by greater numbers of detections in study areas where analytical methods with lower detection limits were used. Correlation analyses also may be distorted by differing reporting or detection levels (Helsel, 2005b). In this study, water-quality data that are compared, illustrated on maps, or correlated with other variables have been recensored to common reporting levels. This recensoring was done by

converting measured values that were less than the common reporting level to "less-than" values or non-detections relative to the common reporting level. Common reporting levels were applied to values of trace elements and organic compounds, as groups, and to values of major ions, nutrients, and alpha-particle radioactivity, individually. Common reporting levels were chosen as the most frequently used MRL or LT-MDL in the data set to minimize the number of recensored data values. For trace elements, a common reporting level of 1 µg/L was used (for all elements except boron, iron, and strontium). Three common reporting levels, 0.02, 0.1, and 0.2 µg/L, were used for organic compounds that represented frequently used MRLs or LT-MDLs for subsets of these data (Gilliom and others, 2006; Zogorski and others, 2006). For major ions and nutrients, common reporting levels varied by analyte and ranged from 0.01 to 0.1 mg/L. A common reporting level of 3 pCi/L was used for alpha-particle radioactivity. Differing reporting levels were acceptable for major ions and nutrients because detection frequencies for these commonly occurring contaminants were not compared.

When common reporting levels were used, values reported as less than a detection limit that was higher than the common reporting level were removed from the data set. This generally resulted in the elimination of less than 2 percent of data values per contaminant for major ions, trace elements, and pesticides. These data values usually were isolated cases that resulted from problems in the laboratory. During the study period, VOC data were reported relative to MDLs that differed by an order of magnitude because of improvements to laboratory analyses. Before 1997, most VOCs were reported relative to MRLs of about 0.2 µg/L. Consequently, when VOC data were recensored to a common reporting level of 0.02 µg/L, about 30 percent of the VOC samples were removed from the data set, including all observations, detections and non-detections, that resulted from analyses when the MRL or LT-MDL was 0.2 µg/L. This was necessary to avoid biasing the calculated detection frequencies in the direction of greater detections, which would have resulted if only those observations below the method detection limit were removed.

Spatial data such as those for land use, soil properties, and other characteristics relevant to water quality were determined by USGS using national-scale data sets that included those described in U.S. Geological Survey (1999), Vogelmann and others (2001), Nakagaki and Wolock (2005), and Price and others (2007) for land use; U.S. Department of Agriculture (1994), Wolock (1997), and Schwarz and Alexander (1995) for soils; and Ruddy and others (2006) for nitrogen fertilizer applications. Land-use characteristics, soil properties, and other characteristics were determined as area-weighted averages for circular areas with radii of 500 m (1,640 ft or 0.3 mi) around the sampled wells (Nakagaki and Wolock, 2005). The soil characteristic used in correlations in this study is the State Soil Geographic (STATSGO) database soil drainage-class number. Nitrogen fertilizer applications used in correlations are the averages of annual estimates for 1992 to 2001 of nitrogen to farmland and non-farmland. Population density is the average of densities derived from the 1990 and 2000 censuses.

Statistical Methods and Data Presentation

Statistical methods included the calculation of summary statistics (median and percentile concentrations) and correlation analysis. Summary statistics for contaminants with less than 10 percent censored data values were calculated using the Statview software package (version 5.0, SAS Institute, 1998). The robust ROS (regression on order statistics) method, as implemented in the NADA (Nondetects and Data Analysis for Environmental Data) package of the *R* statistical software program, was used to calculate summary statistics for contaminants with more than 10 percent censored data values; this method allows for multiple detection limits in the data set (Helsel, 2005b; Lee, 2005). Nonparametric, rank-based methods were used for comparison of contaminant concentrations or physical property values to one another or to potential explanatory variables. The Spearman correlation was used for correlation of two continuous variables; and the Mann-Whitney test was used for analyses with one continuous and one categorical value. When these methods were used, all observations below the common reporting levels were tied at the lowest rank (Helsel, 2005a).

Water types were determined from concentrations of major ions. A single cation or anion was identified as characterizing the water type of a sample when that ion made up more than 50 percent of the total concentrations of cations or anions, in milliquivalents per liter (Hem, 1985). Two cations or ions were identified as characterizing the water type of a sample when they together made up more than 80 percent of the total concentrations of cations or anions, in milliequivalents per liter. Other combinations of multiple cations or ions resulted in samples that were identified as being of mixed cation or anion water type.

In map figures showing the geographic distribution of contaminants, the large number and close proximity of wells resulted in overlapping symbols in many areas. Well symbols are layered such that symbols showing higher concentrations are on top of symbols showing lower concentrations, and symbols showing detections are on top of symbols showing non-detections. Graphical presentation of data in boxplots required a minimum of 20 data points per category.

Water-Quality Benchmarks for Human Health

Contaminants in drinking-water supplies may be of concern when they approach concentrations that may be harmful to human health. Several types of benchmarks are available to identify contaminant concentrations of concern. USEPA MCLs are legally enforceable standards for drinking water

that specify the maximum permissable level of a contaminant in water that is delivered by public water systems. MCLs are set as close as feasible to levels at which there is no known or anticipated adverse human-health effects, and they include a margin of safety (U.S. Environmental Protection Agency, 2006a). Currently (2009), MCLs have been established for about 90 elements and compounds.

Information also is available on potential human-health effects in drinking water of many elements and compounds for which MCLs have not been established (unregulated compounds). This information has been used by USEPA to calculate Lifetime Health Advisories (concentrations not expected to cause adverse effects from a lifetime of exposure) for noncarcinogens and Cancer Risk Concentrations (concentrations associated with specified lifetime cancer risks) for carcinogens (U.S. Environmental Protection Agency, 2006a). Every 5 years, USEPA evaluates at least five unregulated contaminants for possible regulation in drinking water. To date, USEPA has evaluated 19 contaminants, including 13 analyzed in this study (including manganese and boron), and has determined that no regulatory action was appropriate for these contaminants (U.S. Environmental Protection Agency, 2003a; 2008a).

In 1998, the USGS began a collaborative effort with USEPA to use standard USEPA methods and the most current USEPA toxicity information to calculate HBSLs for some compounds and elements for which drinking-water standards were not available (Toccalino and others, 2003). HBSLs are non-enforceable benchmark concentrations that can be used in screening-level assessments to evaluate water-quality data within the context of human health; they are available in a web-based database (Toccalino and others, 2005; Toccalino and Norman, 2006; Toccalino and others, 2006). Because HBSLs are calculated using USEPA toxicity information and standard USEPA Office of Water equations for establishing drinking-water guideline values, HBSLs are equivalent to existing USEPA Lifetime Health Advisory and Cancer Risk Concentration values (when they exist), except for unregulated compounds for which more recent toxicity information has become available (Toccalino, 2007).

Water-quality data from domestic wells in the present study were compared to USEPA MCLs and USGS HBSLs in a screening-level assessment, which can provide an initial perspective on the potential significance of contaminant occurrence to human health and can help prioritize future studies (Toccalino and others, 2006; Toccalino, 2007). This kind of assessment also provides a perspective on the areas in which adverse effects of contaminants in domestic well water are more likely to occur, based on the NAWQA data, and which contaminants may be responsible for those effects (Gilliom and others, 2006). A screening-level assessment is not designed to evaluate specific effects of contaminants in domestic well water on human health, nor is it suitable for a comprehensive risk assessment, which generally includes additional factors such as multiple avenues of exposure (Toccalino and others, 2006).

Water-quality benchmarks, including MCLs and HBSLs, were available for 154 of the 214 contaminants measured in this study. MCLs were available for 52 contaminants (U.S. Environmental Protection Agency, 2006a), and HBSLs were available for 96 contaminants (Toccalino and others, 2006; values used in this report were current as of March 2009; see http://water.usgs.gov/nawqa/HBSL). USEPA screening or action levels also were used as human-health benchmarks for a few contaminants (for example, copper and lead; Appendix 4). Specific MCLs and HBSLs are presented in sections of this report where water-quality results are described and in Appendix 4. Contaminants that occurred in concentrations greater than MCLs and HBSLs were identified, and the frequencies at which they occurred at these elevated concentrations were calculated. Contaminant concentrations that are less than but approaching MCLs and HBSLs also may be of interest, for example, for prioritizing further study or increased monitoring. Contaminant concentrations that were less than MCLs or HBSLs were evaluated by identifying measured concentrations that were greater than one-tenth (or 10 percent) of the contaminant's MCL or HBSL value (Toccalino, 2007). These concentration levels can be used to identify contaminants that may warrant additional monitoring in order to analyze trends in occurrence and to provide an early indication of contaminant concentrations that approach human-health benchmarks (U.S. Environmental Protection Agency, 1997a; Toccalino and Norman, 2006; Toccalino, 2007).

Water-quality data from domestic wells in the present study also were compared to non-health guidelines for drinking-water quality. Non-health guidelines are recommended maximum concentrations of various contaminants that can have adverse cosmetic effects (such as tooth staining) or result in water that is unpleasant for use (due to color, taste, or odor; U.S. Environmental Protection Agency, 2006a). Non-health guidelines for drinking water used in the present study are primarily USEPA Secondary Maximum Contaminant Levels (SMCLs), which are non-enforceable guidelines (U.S. Environmental Protection Agency, 2006a).

Domestic Wells Sampled for the NAWQA Program, 1991–2004

The 2,167 domestic wells sampled for the NAWQA Program between 1991 and June 2004 were located in 48 of the 50 states (fig. 2). The wells also were distributed among 30 regionally extensive aquifers (table 1) and thus represent about half of the principal aquifers of the United States (U.S. Geological Survey, 2003a). The principal aquifers sampled with the domestic wells in the present study were grouped according to lithology into eight categories following the classification used in the National Atlas (fig. 2). Aquifers within these rock-type categories share common characteristics of ground-water flow and, in some cases, overall geochemistry. The categories are (A1) unconsolidated basin-fill, fluvial, and

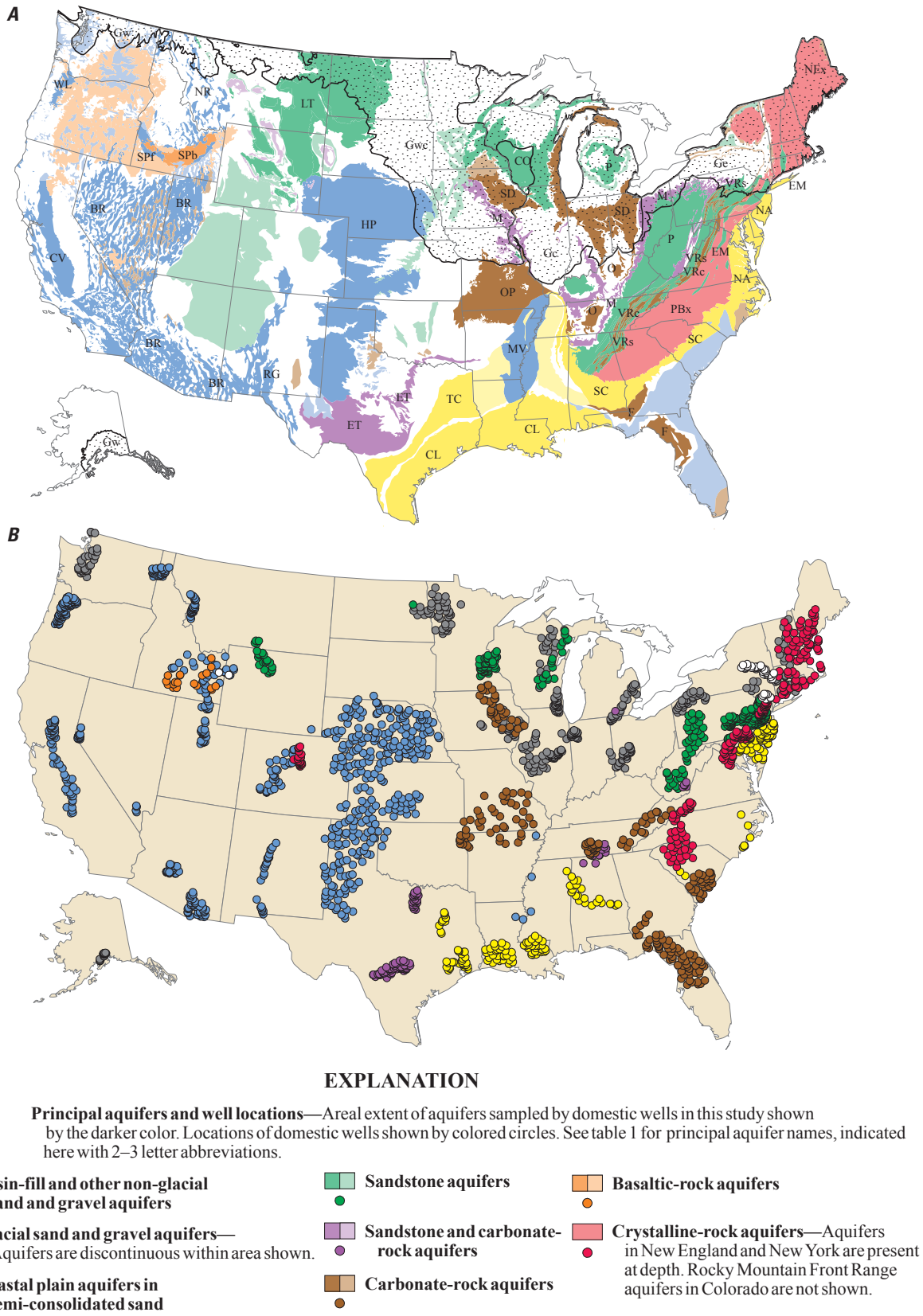


Figure 2. *(A)* Principal aquifers of the United States and *(B)* domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004. Names of principal aquifers sampled in this study are listed in table 1. The uppermost aquifer is shown, unless otherwise indicated; therefore, the full areal extent of underlying aquifers may not be shown. Areal extent of aquifers from U.S. Geological Survey (2003a) and U.S. Geological Survey, NAWQA Program, written commun., 2007.

other non-glacial sand and gravel aquifers (basin-fill sand and gravel, BFSG; including the National Atlas's basin-fill and blanket aquifers); (A2) unconsolidated glacial sand and gravel aquifers (glacial, GLAC), which occur discontinuously in the northern states; (B) coastal plain aquifers in semi-consolidated sand (coastal plain, CP), consisting of interbedded sediments that occur in eastern and southeastern coastal states; (C) sandstone aquifers (SS), widespread across the United States; (D) interbedded sandstone and carbonate aquifers (sandstone/carbonate, SS/CARB) in Texas, the Appalachian region, and the Midwest; (E) carbonate aquifers (CARB), which occur mostly in the central and southeastern United States; (G) basaltic-rock aquifers (basaltic, BAS), in the Northwest; and (H) crystalline-rock aquifers (crystalline, CRYS), which are igneous and metamorphic fractured-rock aquifers that supply water in the Northeast, the Appalachian region, and locally in other parts of the United States (Miller, 2000).

Descriptions of wells—well numbers and other characteristics—are listed in table 1 by principal aquifer; information on wells, grouped by principal aquifer and NAWQA assessment study, is given in Appendix 2. Well characteristics varied among principal aquifers, with well depths and depths to water typically shallower and closer to land surface in the glacial, coastal plain, sandstone, and carbonate aquifers than in the basin-fill sand and gravel and sandstone/carbonate aquifers (fig. 3). The median well depth overall was 147 ft (average 174 ft), with most (80 percent) well depths between 50 and 335 ft; the median depth to water was 38 ft (average 67 ft), with most depths to water between 9 and 164 ft. Depth to the top of the open interval of wells was between 25 and 248 ft below land surface for most wells, with a median value of 81 ft (average 114 ft) below land surface (table 1). The wells were nearly all (94 percent) drilled wells, rather than dug or driven wells, with steel or polyvinylchloride casings, 4 to 8 in. in diameter. The wells also were relatively young, with an average age of 22 years and with most between 10 and 45 years in age.

The NAWQA assessment studies were not specifically designed as a single, national-scale assessment of domestic well water quality. Thus, the domestic wells sampled for the NAWQA Program do not provide a statistically based sampling of all domestic wells in the United States. However, the distribution of domestic wells sampled by NAWQA compares favorably with the national distribution of domestic water use, as indicated by county-based water-use data for 1995 (Solley and others, 1998). Many areas of relatively high populations served by domestic wells, for example in the eastern half of the country and along the west coast, are represented by the wells sampled (fig. 4A). The domestic wells sampled for the NAWQA Program also represent some, though not all, of the areas where the population density is sparse but where users of domestic well water account for a large part of the total population, for example in the northern High Plains (fig. 4B).

The principal aquifers, represented by domestic wells sampled for the NAWQA Program, were some of those most heavily used for public water supplies in the United States, and, therefore, those most likely to be frequently tapped by domestic wells. (Information on water withdrawals by domestic wells for principal aquifers was not available, but the characteristics of aquifers that favor their use for public supplies also likely lead to their frequent use for domestic supplies). Two-thirds of the 42 principal aquifers that supplied 95 percent of public-water withdrawals in 2000 were represented by the NAWQA domestic wells (fig. 5; Maupin and Barber, 2005). The glacial aquifers, which extend across a large part of the northernmost and north-central United States (fig. 2), were sampled most frequently, accounting for 18 percent of the NAWQA domestic wells. These aquifers were the largest source of water for public supply in 2000, providing 12 percent of public-supply withdrawals. The glacial aquifers also are likely to be the largest source of domestic supply, and may provide about 25 to 50 percent of total self-supplied domestic withdrawals (M.A. Horn, U.S. Geological Survey, written commun., 2005; K.L. Warner, U.S. Geological Survey, written commun., 2005).

Most of the domestic wells included in the present study were originally selected to characterize the water quality within major hydrogeologic settings of more limited extent than the regionally extensive principal aquifers. (Wells in the High Plains aquifer are an exception.) Consequently, the wells are geographically clustered within principal aquifers, leaving extensive areas without representation, and do not represent a statistically based sample of ground water or domestic wells within principal aquifers (fig. 2). Sampling density also was variable; most (80 percent) principal aquifers were represented by 19 to 109 wells each. However, the targeted major hydrogeologic settings represent important hydrologic systems within principal aquifers, and the sampled domestic wells were randomly selected within those settings.

Principal aquifers provide a useful framework for regional synthesis of water-quality data within units of broadly similar permeability, rock type, geologic or depositional setting, and climate (Lapham and others, 2005). However, water-quality conditions vary substantially within principal aquifers, reflecting the heterogeneity of natural systems. In some areas, principal aquifers also may overlie or underlie less extensive local aquifers that have different water-quality characteristics, so that water-quality conditions described for a principal aquifer do not describe the quality of water from all domestic wells in the geographic area.

Table 1. Characteristics of domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, by principal aquifer.

[**Map identifier:** 2–3 letter abbreviation identifying principal aquifer location in figure 2. Number of wells used for well depth, depth to top of open interval, and depth to water may differ. --, not available or not applicable]

Map identifier	Principal aquifer	Number of wells	Median well depth, in feet below land surface	Median depth to top of open interval, in feet below land surface	Median depth to water, in feet below land surface
	Basin-fill and other non-glacial sand and gravel aquifers (BFSG)				
BR	Basin and Range basin-fill aquifers	129	241	200	112
CV	Central Valley aquifer system	57	158	118	57
HP	High Plains aquifer	298	200	170	93
MV	Mississippi River Valley alluvial aquifer	5	80	50	12
NR	Northern Rocky Mountains Intermontane Basins aquifer system	57	83	114	33
OS[1]	Other stream valley alluvial aquifers	44	55	43	11
RG	Rio Grande aquifer system	25	178	173	12
SPf	Snake River Plain basin-fill aquifers	34	135	92	12
WL	Willamette Lowland basin-fill aquifers	69	60	50	16
All aquifers	--	*718*	*168*	*139*	*70*
	Glacial sand and gravel aquifers (GLAC)				
Ge	Eastern glacial aquifers	73	86	80	24
Gc	Central glacial aquifers	185	69	63	20
Gwc	West central glacial aquifers	80	66	64	15
Gwc	Western glacial aquifers	51	75	67	41
All aquifers	--	*389*	*72*	*67*	*22*
	Coastal plain aquifers in semi-consolidated sand (CP)				
CL	Coastal lowlands aquifer system	85	140	117	39
NA	North Atlantic Coastal Plain aquifer system	65	88	75	22
SC	Southeastern Coastal Plain aquifer system	26	141	121	53
TC	Texas coastal uplands aquifer system	10	102	--	25
All aquifers	--	*186*	*105*	*92*	*32*
	Sandstone aquifers (SS)				
CO	Cambrian-Ordovician aquifer system	70	173	126	41
EM	Early Mesozoic basin aquifers	69	175	50	25
LT	Lower Tertiary and Upper Cretaceous aquifers	24	158	85	29
P	Pennsylvanian aquifers	46	98	24	46
VRs	Valley and Ridge sandstone and shale aquifers	56	169	62	39
All aquifers	--	*265*	*157*	*64*	*38*
	Sandstone and carbonate-rock aquifers (SS/CARB)				
ET	Edwards-Trinity aquifer system	69	239	150	72
M	Mississippian aquifers	18	100	50	40
All aquifers	--	*87*	*205*	*98*	*57*

Table 1. Characteristics of domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, by principal aquifer. —Continued

[**Map identifier:** 2–3 letter abbreviation identifying principal aquifer location in figure 2. Number of wells used for well depth, depth to top of open interval, and depth to water may differ. --, not available or not applicable]

Map identifier	Principal aquifer	Number of wells	Median well depth, in feet below land surface	Median depth to top of open interval, in feet below land surface	Median depth to water, in feet below land surface
	Carbonate-rock aquifers (CARB)				
F	Floridan aquifer system	96	120	81	22
O	Ordovician aquifers	21	140	20	21
OP	Ozark Plateaus aquifer system	49	170	74	51
SD	Silurian-Devonian aquifers	32	223	150	59
VRc	Valley and Ridge carbonate-rock aquifers	19	265	64	80
All aquifers	--	*217*	*160*	*79*	*41*
	Basaltic-rock aquifers (BAS)				
SPb	Snake River Plain basaltic-rock aquifers	19	260	85	183
	Crystalline-rock aquifers (CRYS)				
NEx	New England crystalline-rock aquifers	113	225	40	18
PBx	Piedmont and Blue Ridge crystalline-rock aquifers	100	157	58	33
RMx[1]	Rocky Mountain Front Range crystalline-rock aquifers	27	225	82	--
All aquifers	--	*240*	*200*	*50*	*26*
	Aquifer not determined				
--	Aquifer not determined	46	125	91	6
	All aquifers				
All aquifers	--	*2,167*	*147*	*81*	*38*

[1]Aquifer not shown on figure 2.

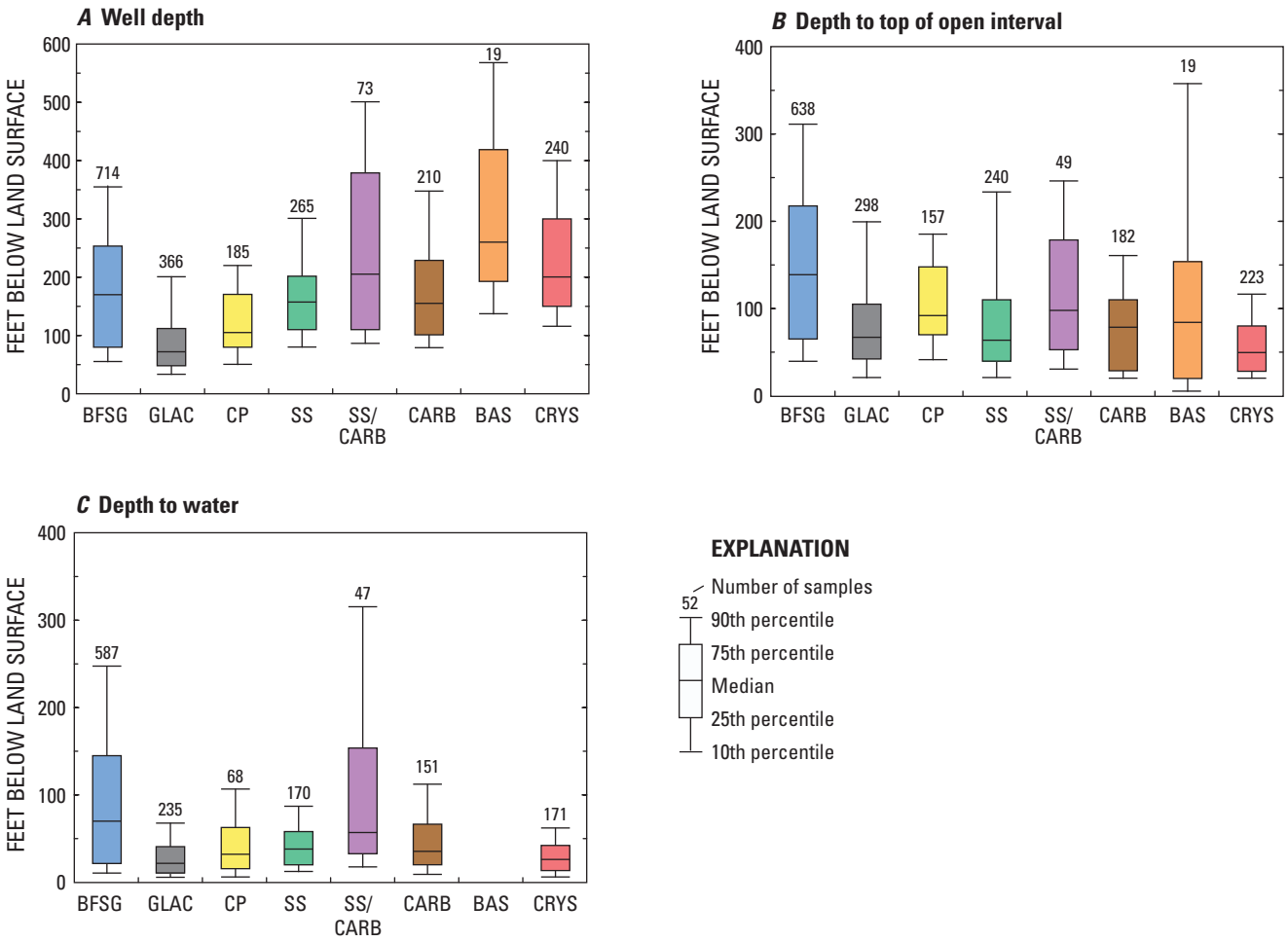
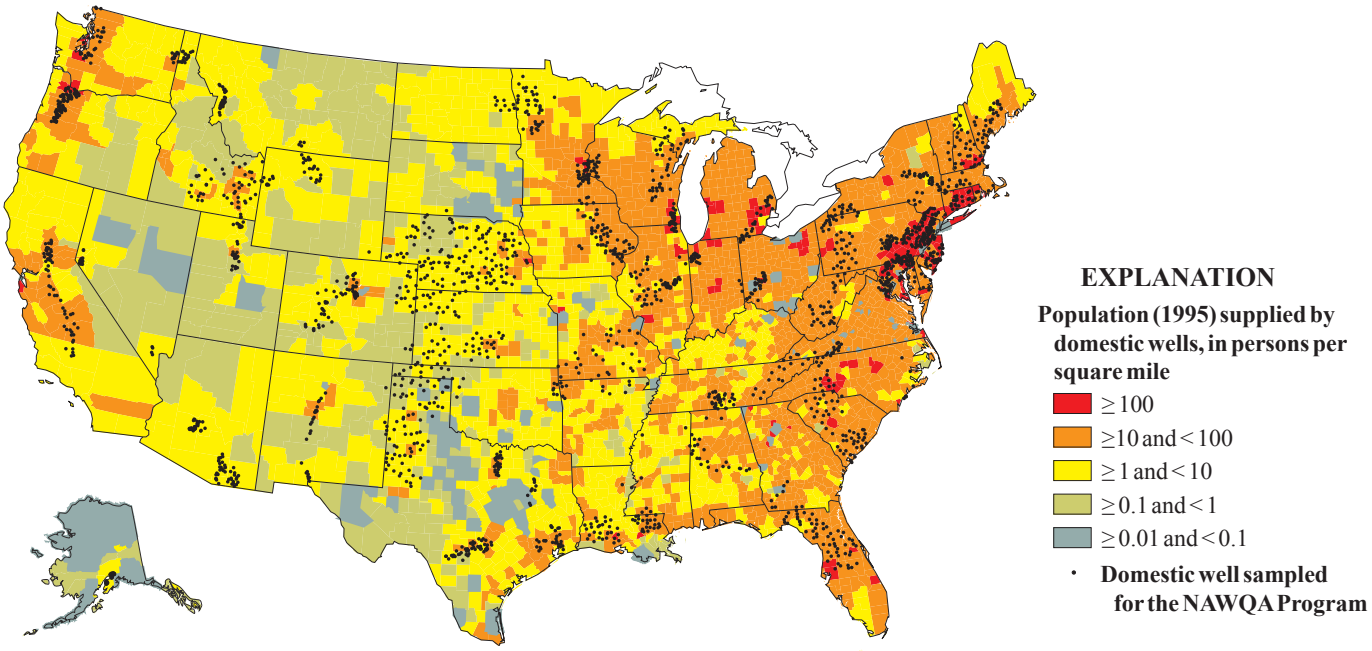


Figure 3. *(A)* Well depth, *(B)* depth to top of open interval, and *(C)* depth to water in domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004. BFSG, basin-fill and other non-glacial sand and gravel aquifers; GLAC, glacial sand and gravel aquifers; CP, coastal plain aquifers in semi-consolidated sand; SS, sandstone aquifers; SS/CARB, sandstone/carbonate-rock aquifers; CARB, carbonate-rock aquifers; BAS, basaltic-rock aquifers; and CRYS, crystalline-rock aquifers.

A **Population density**



B **Population as percent of total county population**

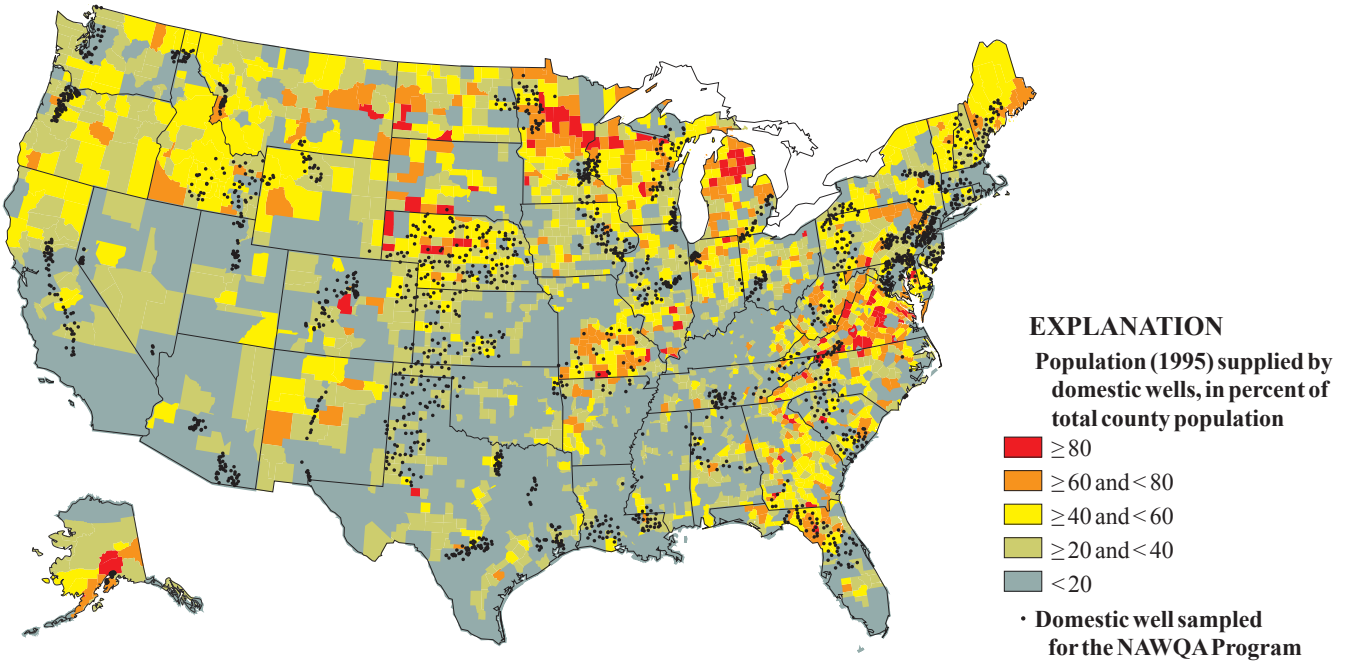


Figure 4. Population supplied by domestic wells by county in the United States in 1995 by *(A)* population density and *(B)* population as percent of total county population. Water use data from Solley and others (1998). Domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, also are shown. ≥, greater than or equal to; <, less than.

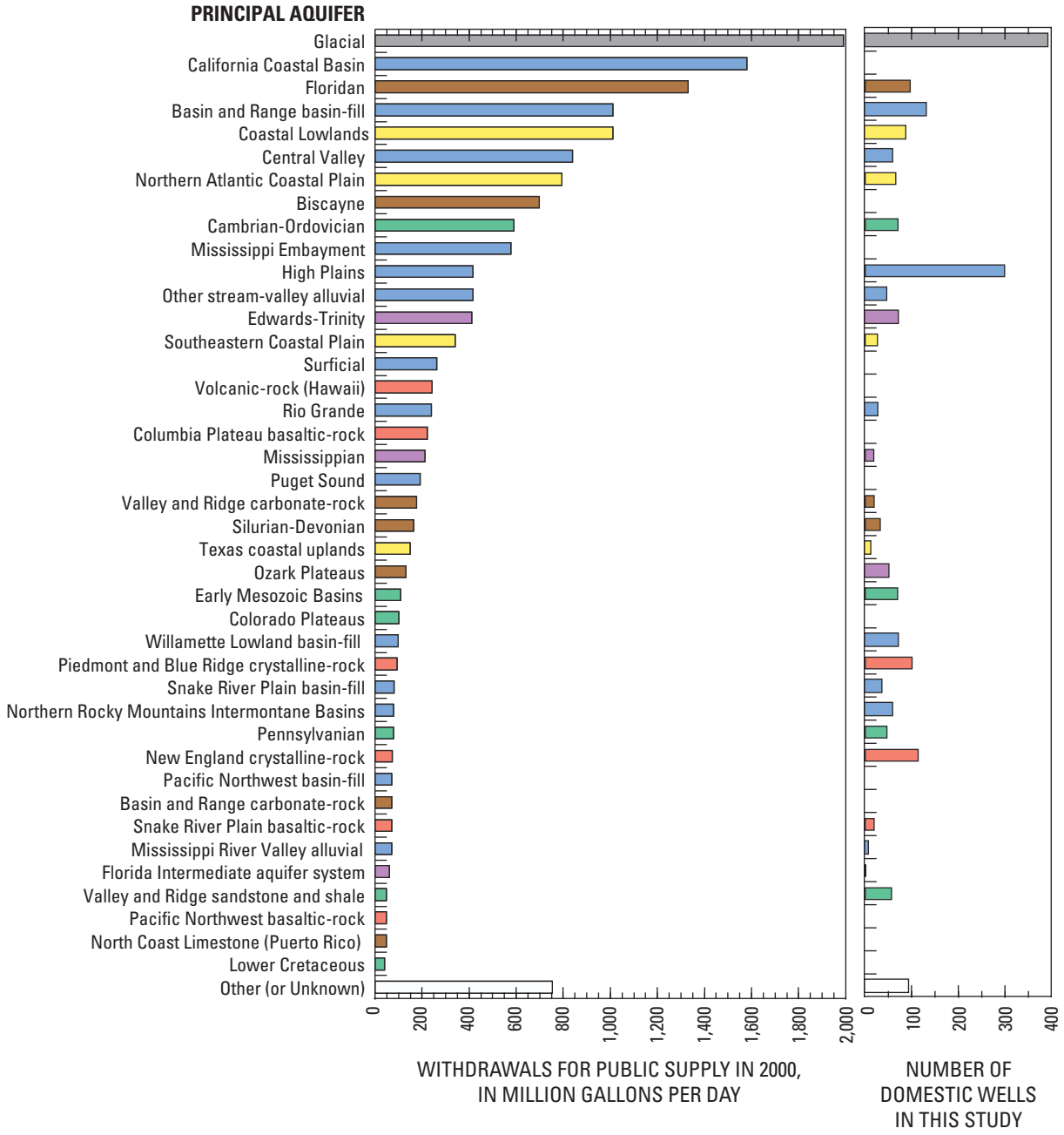


Figure 5. Water withdrawals for public supply in the United States in 2000 and numbers of domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, by principal aquifer. Water withdrawals from Maupin and Barber (2005); aquifers listed provided 95 percent of withdrawals for public supply in 2000. Shading indicates rock type of principal aquifer. Basin-fill and other non-glacial sand and gravel aquifers, blue; glacial sand and gravel aquifers, grey; coastal plain aquifers, yellow; sandstone aquifers, green; sandstone/carbonate-rock aquifers, purple; carbonate-rock aquifers, brown; and basaltic-rock and crystalline-rock aquifers, orange.

Quality of Water from Domestic Wells

Physical properties and contaminant concentrations for the domestic wells sampled for the NAWQA Program in aquifer studies are summarized and compared to human-health benchmarks and non-health guidelines in several tables in this section. Physical properties and contaminant concentrations are summarized and compared to health benchmarks and non-health guidelines, by principal aquifer and by principal aquifer rock type, in Appendixes 5 and 6. Detection frequencies for organic compounds at several common reporting levels are listed in Appendix 7. Appendixes 5, 6, and 7 include data for wells sampled for the NAWQA Program in aquifer studies and also for wells sampled for agricultural land-use studies for reference purposes. Physical properties and contaminant concentrations discussed in the text are for wells from aquifer studies only, unless otherwise indicated.

Physical Properties and Dissolved Solids

Specific conductance, pH, alkalinity, dissolved oxygen, and water temperature are general indicators of water quality and affect how chemical contaminants behave in the water. Variability in these properties results from natural sources—precipitation chemistry, soil properties, and the physical and chemical characteristics of aquifer materials—and from the effects of human activity. The total dissolved solids content of water is another indicator of water quality and of the overall suitability of water for drinking and other uses. The dissolved solids in water mostly result from the dissolution of soil and aquifer materials but can be augmented by the effects of human activities, such as irrigation and waste disposal. No health guidelines have been established for physical properties or dissolved solids, but extreme values of pH, alkalinity, dissolved oxygen, and dissolved solids may cause aesthetic problems or may affect the concentrations of other contaminants that are important to human health. Non-health recommendations or guidelines are available for several of these properties and contaminants (U.S. Environmental Protection Agency, 2006a; World Health Organization, 2004).

Specific conductance is a measure of the ability of the water to conduct an electric current; this ability results from ions dissolved in the water. Dissolved ions make up a large fraction of the total dissolved solids in natural waters, and specific conductance and dissolved solids were closely related in the domestic wells sampled in this study (linear R^2 equal to 0.92). Specific conductance of most (80 percent) of the wells

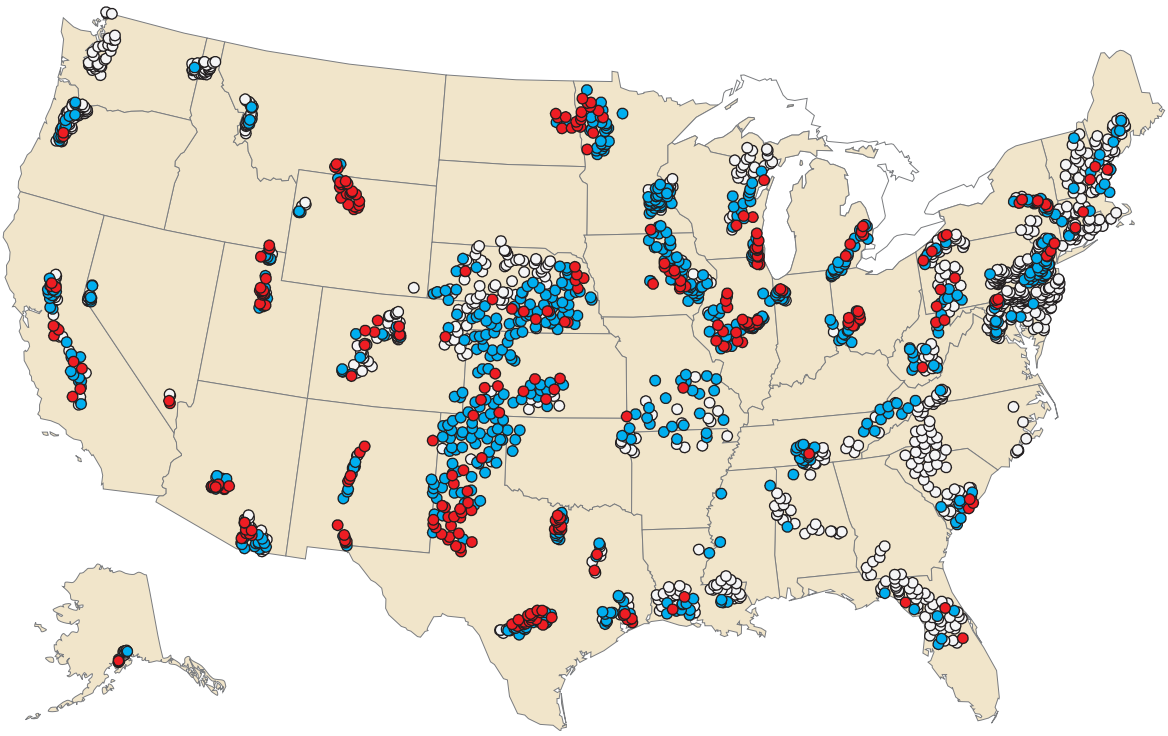
Table 2. Summary statistics for physical properties of, and major ions in, samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004.

[**Common reporting level:** Most common level for data set is shown; µS/cm, microsiemens per centimeter at 25 degrees Celsius (°C); mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; --, not applicable; <, less than]

Property or major ion	Number of samples	Number of detections	Common reporting level	Concentration or value				
				Percentile				
				10th	25th	Median	75th	90th
Physical properties								
Specific conductance, in µS/cm at 25°C	2,138	2,137	1	116	224	417	625	945
pH, in standard units	2,144	2,144	--	6.1	6.9	7.3	7.6	7.9
Temperature, in °C	2,140	2,140	--	10.2	11.9	13.9	17.7	22.1
Dissolved oxygen, in mg/L	2,053	1,972	0.1	<0.1	0.2	3.0	6.3	8.2
Alkalinity as $CaCO_3$, in mg/L	2,033	2,030	1	32.0	78.0	156	241	325
Major ions, in mg/L								
Bromide	2,058	1,875	0.01	0.01	0.02	0.04	0.09	0.20
Calcium	2,160	2,160	0.02	7.2	20.6	43.0	70.0	95.3
Chloride	2,157	2,155	0.1	1.3	3.1	8.6	23.0	62.8
Fluoride	2,156	1,509	0.1	<0.1	<0.1	0.2	0.4	1.1
Magnesium	2,160	2,159	0.01	1.7	4.4	11.0	23.0	36.0
Potassium	2,160	2,148	0.1	0.50	0.9	1.7	3.5	6.6
Silica	2,160	2,160	0.01	8.4	12.0	19.0	31.2	50.5
Sodium	2,160	2,159	0.2	2.8	5.2	11.0	29.0	78.7
Sulfate	2,157	2,083	0.1	0.8	4.7	14.4	36.0	94.0
Hardness as $CaCO_3$	2,160	2,160	0.05	30.3	76.2	162	267	370
Total dissolved solids	2,102	2,100	10	81.0	146	254	381	590

ranged from 116 to 945 µS/cm at 25°C, with a median value of 417 µS/cm at 25°C (table 2). Concentrations of dissolved solids for most wells ranged from 81.0 to 590 mg/L, with a median value of 254 mg/L (fig. 6).

The USEPA SMCL for dissolved solids is 500 mg/L, and dissolved solids concentrations in 14.8 percent of the wells were greater than this value (table 3). Wells with dissolved solids concentrations greater than the SMCL were distributed across the United States and in most aquifer types (fig. 6), but concentrations greater than the SMCL occurred most frequently in samples from about 40 percent or more of the wells in several principal aquifers in the western and south-central United States. These include the Basin and Range and Rio Grande basin-fill aquifers, the Lower Tertiary/Upper Cretaceous sandstone aquifers, and the Edwards-Trinity sandstone/carbonate aquifer (fig. 7; Appendix 6). Relatively high concentrations of dissolved solids in ground water would be expected in areas with more soluble and easily eroded rock types and sediments, irrigation seepage, and low precipitation (Hem, 1985), and high concentrations of dissolved solids could be attributed to these conditions in several of the sampled aquifers (for example, gypsum dissolution and irrigation seepage in the Basin and Range aquifers; Coes and others, 2000; Edmonds and Gellenbeck, 2002). Dissolved solids typically increase with ground-water age and distance along the flow path, as a result of longer contact times between the water and the aquifer materials. Thus, old water can have relatively high concentrations of dissolved solids (for example, in Upper Cretaceous aquifers in the Red River of the North Basin, and in the glacial and underlying Lower Tertiary/Upper Cretaceous aquifers underlying the Yellowstone River Basin; Cowdery, 1998; Bartos and others, 2005). Dissolved solids concentrations greater than the SMCL occurred infrequently and specific conductance values were relatively low in the coastal plain aquifers, in crystalline-rock aquifers of the eastern United States, and in some glacial, sandstone, and carbonate-rock aquifers.



EXPLANATION

Dissolved solids concentration, in milligrams per liter

● > 500 ● > 250 and ≤ 500 ○ ≤ 250

Figure 6. Geographic distribution of dissolved solids concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. >, greater than; ≤, less than or equal to.

Table 3. Comparison of physical properties and concentrations of major ions in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, with human-health benchmarks and non-health guidelines for drinking water.

[MCLs and SMCLs are U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Levels (MCLs) and Secondary Maximum Contaminant Levels (SMCLs) for public water supplies; HBSLs are Health-Based Screening Levels developed by the U.S. Geological Survey using USEPA toxicity data and methods (Toccalino and Norman, 2006); µS/cm, microsiemens per centimeter at 25 degrees Celsius (°C); mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; --, not applicable]

Property or major ion	Benchmark or guideline				Wells exceeding benchmarks or non-health guidelines					
	Human-health benchmark		Non-health guideline		Human-health benchmark		One-tenth of human health benchmark		Non-health guideline	
	Value	Type	Value	Type	Value	Percent	Value	Percent	Value	Percent
Physical properties										
Specific conductance, in µS/cm at 25°C	--	--	--	--	--	--	--	--	--	--
pH, in standard units	--	--	[1]6.5–8.5	SMCL	--	--	--	--	350	16.3
Temperature, in °C	--	--	--	--	--	--	--	--	--	--
Dissolved oxygen, in mg/L	--	--	--	--	--	--	--	--	--	--
Alkalinity as $CaCO_3$, in mg/L	--	--	--	--	--	--	--	--	--	--
Major ions, in mg/L										
Bromide	--	--	--	--	--	--	--	--	--	--
Calcium	--	--	--	--	--	--	--	--	--	--
Chloride	--	--	250	SMCL	--	--	--	--	46	2.13
Fluoride	4	MCL	2.00	SMCL	25	1.16	--	--	87	4.04
Magnesium	--	--	--	--	--	--	--	--	--	--
Potassium	--	--	--	--	--	--	--	--	--	--
Silica	--	--	--	--	--	--	--	--	--	--
Sodium	--	--	--	--	--	--	--	--	--	--
Sulfate	--	--	250	SMCL	--	--	--	--	82	3.79
Hardness as $CaCO_3$	--	--	--	--	--	--	--	--	--	--
Total dissolved solids	--	--	500	SMCL	--	--	--	--	310	14.8

[1]Guidelines recommend that pH values be within this range.

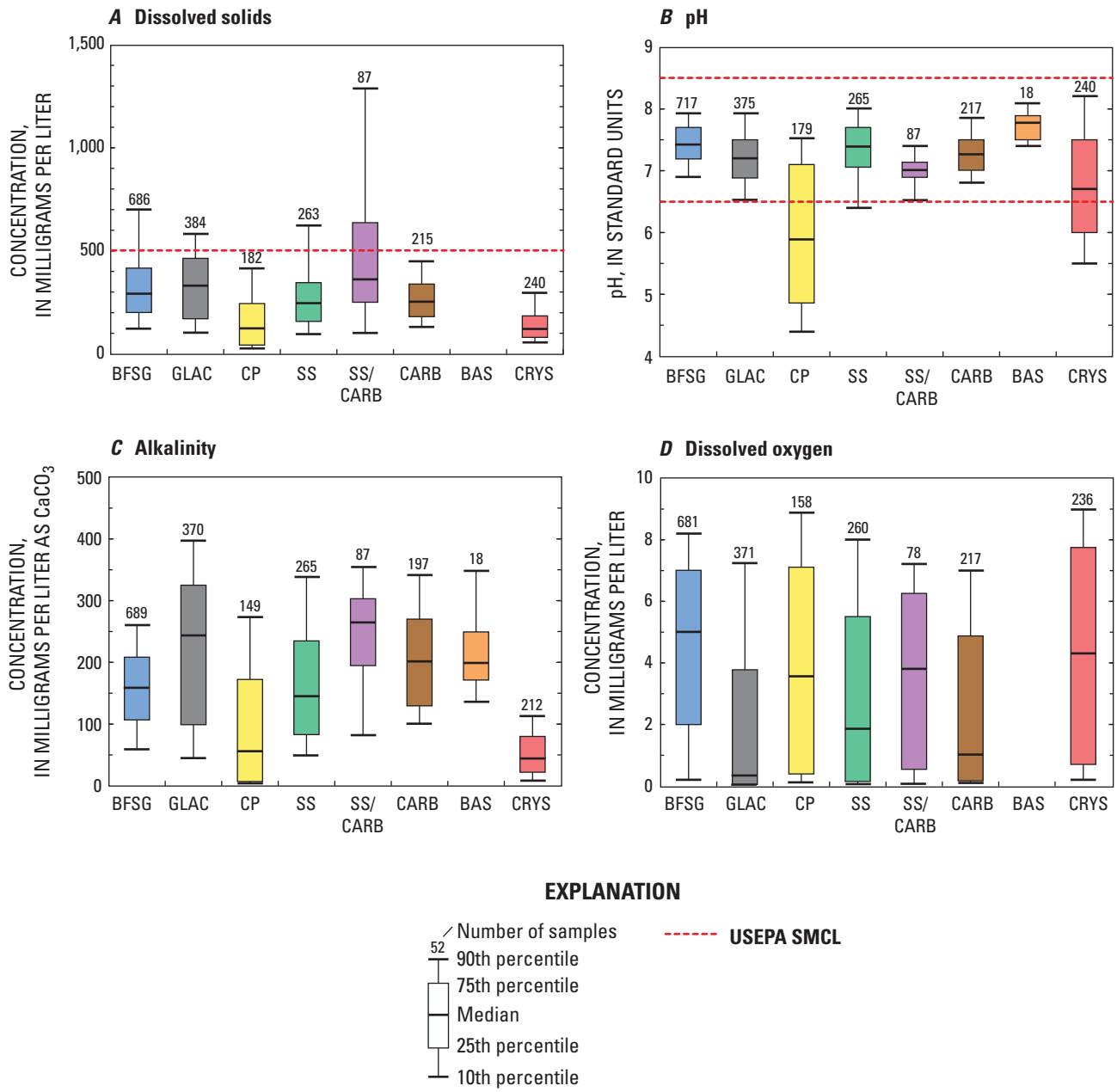


Figure 7. *(A)* Dissolved solids, *(B)* pH, *(C)* alkalinity, and *(D)* dissolved oxygen in samples collected from domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, by aquifer rock type. BFSG, basin-fill and other non-glacial sand and gravel aquifers; GLAC, glacial sand and gravel aquifers; CP, coastal plain aquifers in semi-consolidated sand; SS, sandstone aquifers; SS/CARB, sandstone/carbonate-rock aquifers; CARB, carbonate-rock aquifers; BAS, basaltic-rock aquifers; CRYS, crystalline-rock aquifers; $CaCO_3$, calcium carbonate; and SMCL, U.S. Environmental Protection Agency Secondary Maximum Contaminant Level.

The pH of most (80 percent) samples ranged from 6.1 to 7.9, with a median value of 7.3 (table 2). pH is a measure of the acidity of water and is an important control on the solubility of many metals. Highly acidic (low pH) or highly alkaline (high pH) water can be corrosive to pipes and may have an unpleasant taste (World Health Organization, 2004). The USEPA recommends a pH of drinking water from 6.5 to 8.5 (U.S. Environmental Protection Agency, 2006a). Although samples from most of the domestic wells in this study were within the recommended range, the pH of samples from 16.3 percent of the wells was less than (14.4 percent) or greater than (1.9 percent) the recommended range. Low pH values (less than 6.5) occurred in the East and in the Pacific Northwest (fig. 8). This is similar to geographic patterns in the acidity of precipitation across the United States (National Atmospheric Deposition Program, 2005). The samples with low pH values were from wells in aquifers of relatively resistant rock types with less capability to neutralize acid precipitation, including some of the rock types and principal aquifers with low specific conductance and dissolved solids (fig. 7).

Alkalinity, a measure of the ability of water to neutralize acid, ranged from 32 to 325 mg/L as calcium carbonate ($CaCO_3$) in most samples, with a median value of 156 mg/L as $CaCO_3$. There are no guidelines for alkalinity in drinking water, but alkalinity concentrations often must be considered in the operation of water-treatment systems. Alkalinity in natural waters is almost entirely from dissolved bicarbonate and carbonate, which originate from the atmosphere and other sources, such as dissolution of carbonate rocks or organic respiration (Hem, 1985). Alkalinity was variable in samples from wells in most aquifers, but tended to be relatively high in carbonate-rock aquifers and in some sandstone/carbonate-rock and glacial aquifers; alkalinity was relatively low in the same

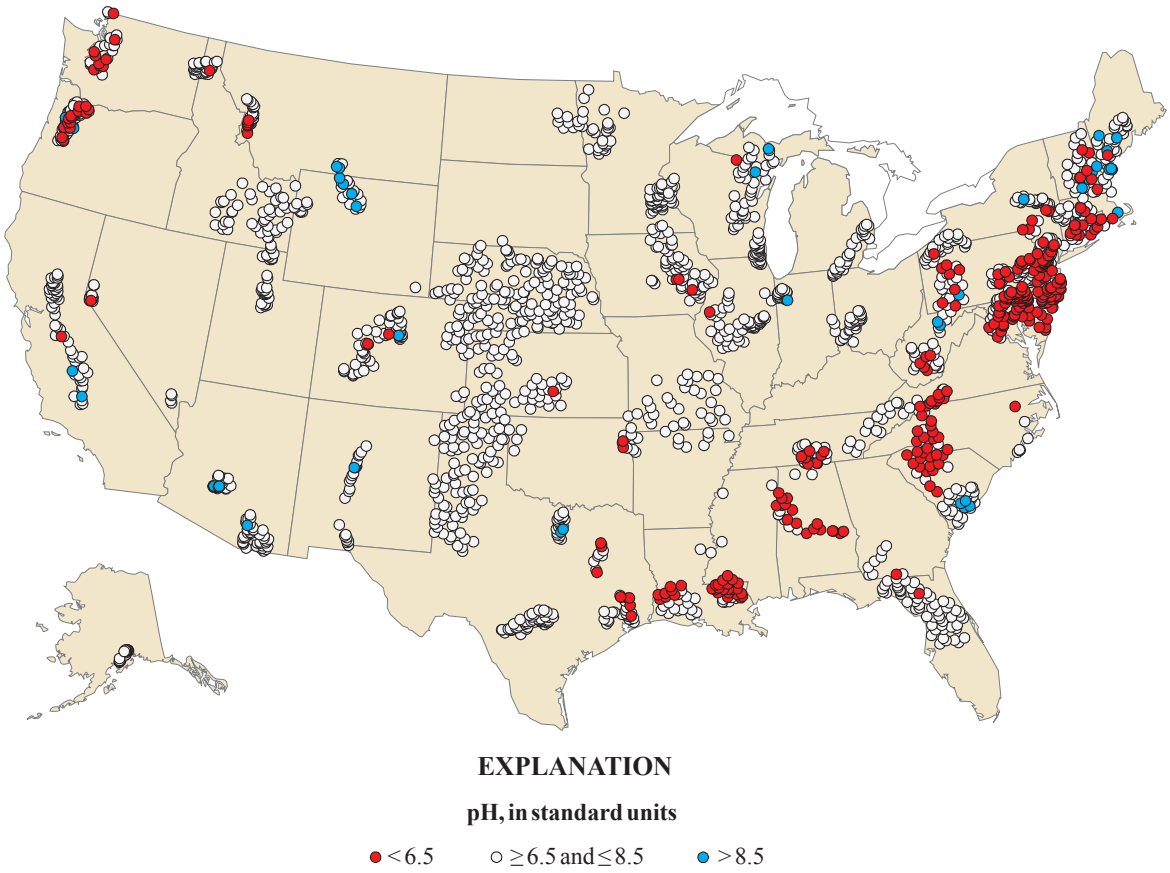


Figure 8. Geographic distribution of pH in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. <, less than; ≥, greater than or equal to; ≤, less than or equal to; >, greater than.

aquifer rock types in which specific conductance, dissolved solids, and pH were low (fig. 7). Geographically, alkalinity concentrations were highest in the east-central United States, reflecting in part the general distribution of the sampled carbonate-rock aquifers (fig. 9).

Concentrations of dissolved oxygen in most (80 percent) samples from the domestic wells in this study ranged from less than 0.1 to 8.2 mg/L. The dissolved oxygen in ground water originates primarily from the atmosphere and is depleted along a flow path through reaction with organic material and reduced minerals. Thus, shallow ground water commonly contains more dissolved oxygen than does older, deeper ground water. There are no guidelines for dissolved oxygen concentrations in drinking water. Like pH, however, the dissolved oxygen content of water is an important control on the solubility of some metals. Dissolved oxygen concentrations varied widely in most aquifer types (fig. 7). However, low concentrations were found more frequently in samples from wells in the glacial aquifers and in some sandstone/carbonate-rock aquifers. Low concentrations of dissolved oxygen also were found more consistently in samples from wells that withdrew water from aquifers that were considered, on the basis of available data, to be confined, than in wells that were considered to be under water-table, or unconfined, conditions (fig. 10). This is consistent with the expectation that, in general, water under confined conditions would be older than water under unconfined conditions, although residence times vary among and within aquifers. Dissolved oxygen concentrations also were negatively correlated with dissolved organic carbon concentrations (Spearman's rho equal to -0.28, p value less than 0.0001).

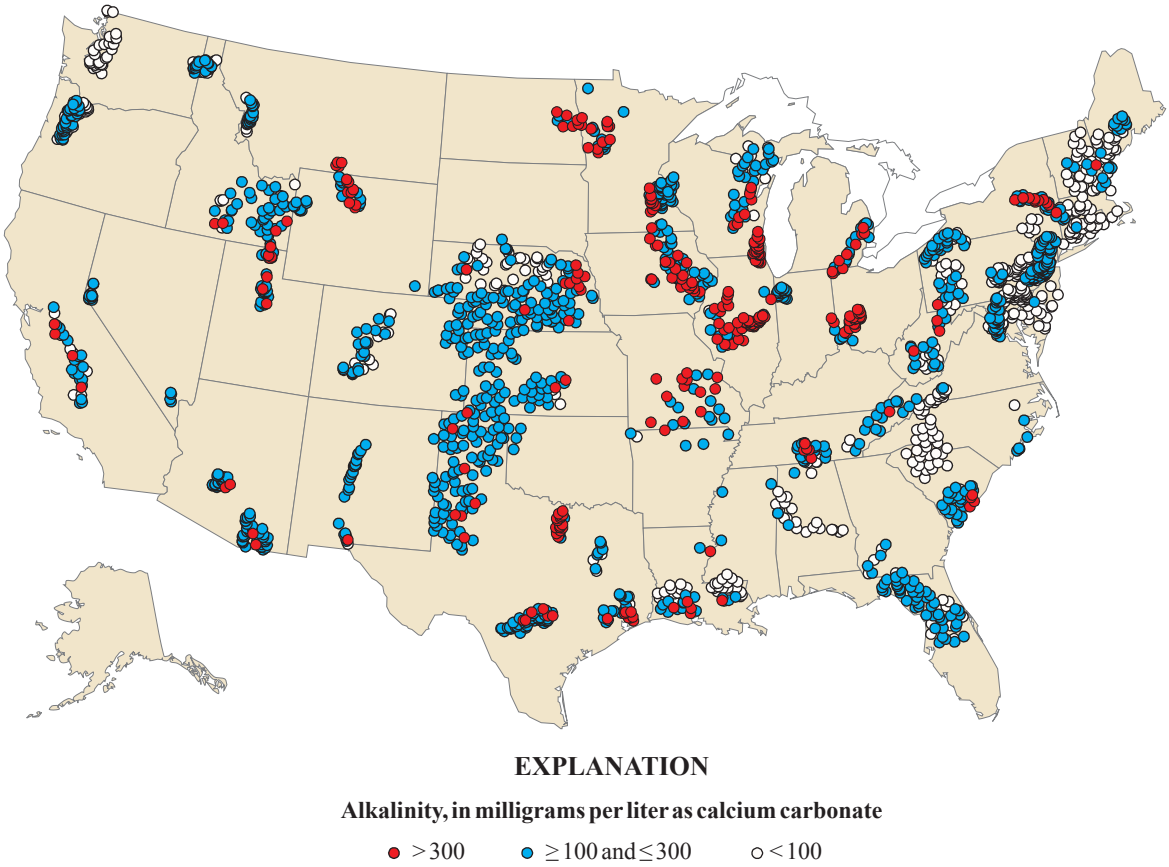


Figure 9. Geographic distribution of alkalinity in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. >, greater than; ≥, greater than or equal to; ≤, less than or equal to; <, less than.

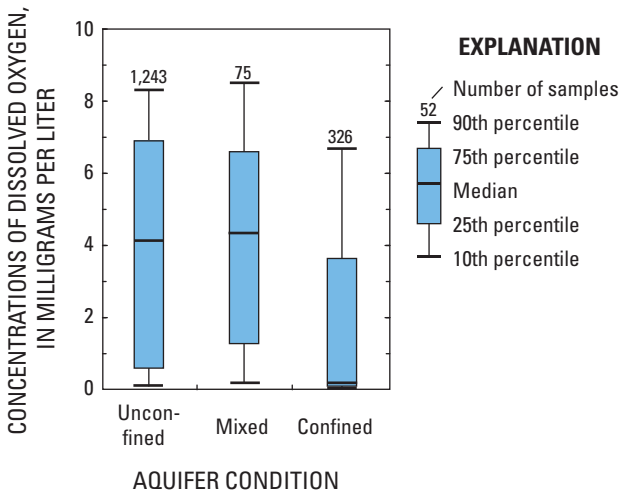


Figure 10. Dissolved oxygen concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, by aquifer condition.

Major Ions

The major ions in water from the sampled domestic wells were the cations calcium, magnesium, sodium, and potassium and the anions bicarbonate (reported as alkalinity), silica, sulfate, and chloride (table 2). Calcium was the most abundant cation (in milliequivalents) and bicarbonate was the most abundant anion. Water samples from about one-half the wells were calcium-bicarbonate type. Other common water types were calcium-magnesium-bicarbonate and mixed cation-bicarbonate types. Ionic composition was variable in most aquifer rock types, reflecting the range of lithologies and geochemical processes in these broadly defined categories (fig. 11). Calcium and bicarbonate were especially dominant in the carbonate-rock aquifers, in which calcite dissolution exerts a strong control on water chemistry (fig. 11F). In the coastal plain aquifers, sodium, calcium, and mixed-cation types were about equally common (fig. 11C). The relative prominence of sodium in ground water may result from cation exchange of calcium for sodium on aquifer materials and reflect relatively long residence times; other possible explanations are mixing with brines, the abundance of sodium-bearing minerals, the absence of calcium-bearing minerals, the effects of sea spray, and the effects of human activities. In several aquifers, sodium was more prominent in water from deeper wells or in older water, and cation exchange, long residence times, leakage of saline water from confining units, or mixing with brines are possible explanations (Chapelle and McMahon, 1991; Szabo and others, 1997; Cowdery, 1998; Fong and others, 1998; Reutter and Dunn, 2000; Bartos and others, 2005). Calcium-magnesium and mixed-ion bicarbonate water types were more common than calcium-bicarbonate water types in the basaltic-rock aquifers, reflecting the abundance of mafic minerals in those rock types (fig. 11G). Chloride was the dominant anion in water samples from some wells (17 percent) in the coastal plain aquifers (fig. 11C), perhaps reflecting the effects of sea spray and the non-reactive character (absence of reactive carbonate or aluminosilicate minerals) of the coastal plain aquifer sediments.

Calcium and magnesium are the principal contributers to hardness, a property of water that is used to describe the effectiveness of soap in water and the tendency for scale deposition in water heaters. Hardness is reported here as milligrams per liter of $CaCO_3$. Water with less than 60 mg/L as $CaCO_3$ of hardness is generally considered “soft,” and water with more than 120 mg/L as $CaCO_3$ of hardness is generally considered “hard” (Hem, 1985); hard or very hard (more than 180 mg/L as $CaCO_3$) water often requires treatment. Hard water used for drinking-water supply can be treated with a water softener, through which dissolved calcium and magnesium ions are exchanged with sodium ions. The hardness of water from most wells (80 percent) sampled in this study ranged from 30.3 to 370 mg/L as $CaCO_3$ (table 2). Hard and very hard water occurred in the central United States, with a geographic distribution similar to that of alkalinity and dissolved solids (fig. 12). Hard and very hard water occurred in principal aquifer rock types that are relatively soluble and that contain calcium- and magnesium-bearing minerals, such as the some glacial, basaltic-rock, sandstone/carbonate-rock, and carbonate-rock aquifers (Appendix 5A).

Concentrations of sulfate in water from most (80 percent) of the sampled wells ranged from 0.8 to 94.0 mg/L (table 2), less than half of the USEPA SMCL of 250 mg/L (table 3). Drinking water with high concentrations of sulfate has a tendency for scale deposition on heating, can cause unpleasant taste, and may cause gastrointestinal effects (World Health Organization, 2004). Sulfate may be contributed to ground water by gypsum dissolution, oxidation of sulfide-bearing minerals, fertilizer application, and other sources, and may be reduced to sulfide under low-oxygen conditions. Sulfate concentrations were greater than the SMCL of 250 mg/L in 3.79 percent of wells (table 3). Concentrations greater than the SMCL occurred in most parts of the United States and in all aquifer rock types, except in the coastal plain aquifers in the Southeast and in the crystalline-rock aquifers, which were mostly in the Northeast (Appendix 5A). High concentrations of sulfate were correlated with high concentrations of dissolved solids (Spearman’s rho equal to 0.67, p value less than 0.0001).

Chloride concentrations in water from most wells ranged from 1.3 to 62.8 mg/L and were greater than the SMCL of 250 mg/L in 2.1 percent of sampled wells (tables 2 and 3). High concentrations of chloride can impart an unpleasant taste to drinking water (World Health Organization, 2004). Chloride concentrations were positively correlated with concentrations

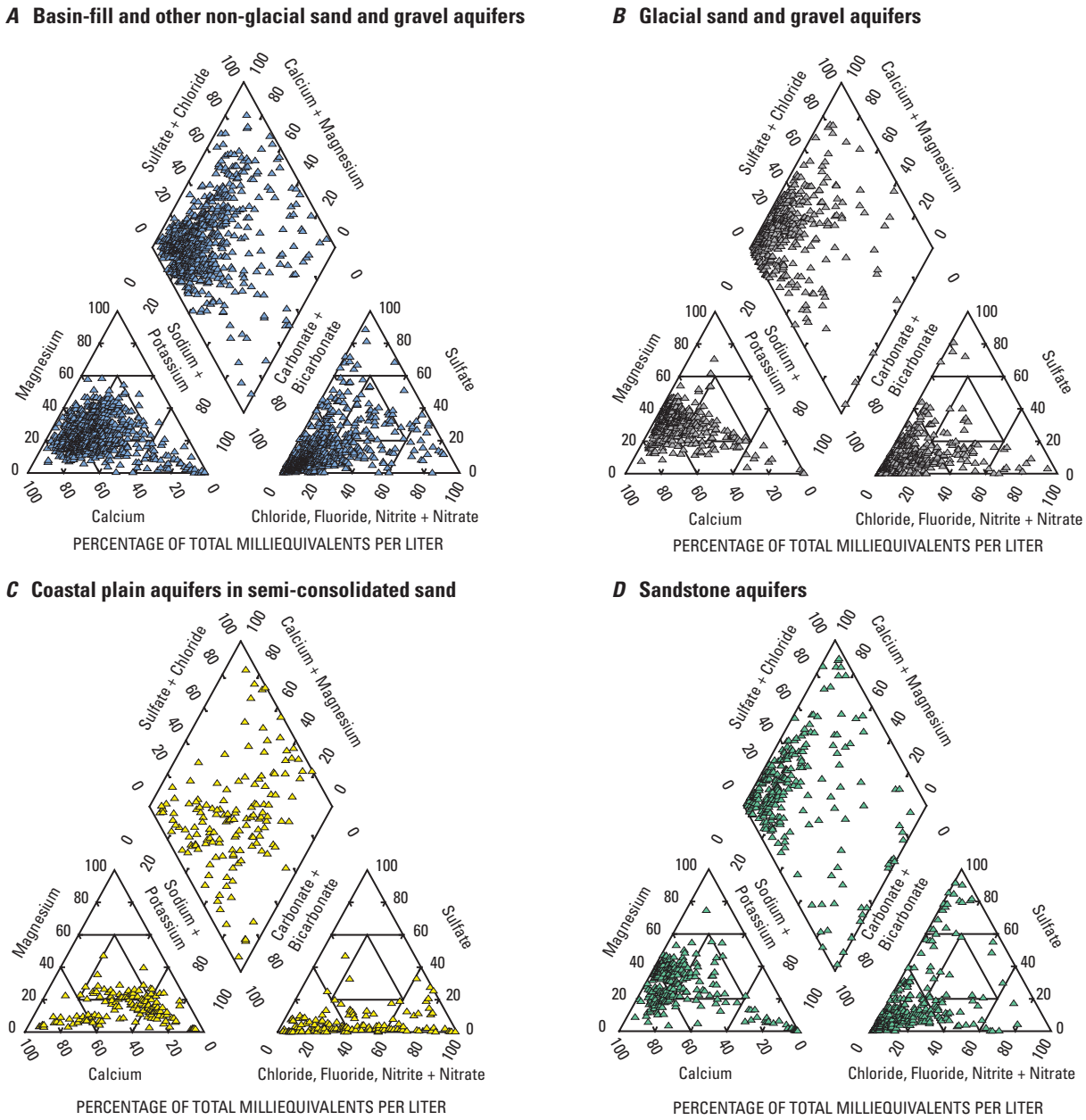


Figure 11. Trilinear diagrams of the ionic composition of water in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, by principal aquifer rock type in *(A)* basin-fill and other non-glacial sand and gravel aquifers, *(B)* glacial sand and gravel aquifers, *(C)* coastal plain aquifers in semi-consolidated sand, *(D)* sandstone aquifers, *(E)* sandstone and carbonate-rock aquifers, *(F)* carbonate-rock aquifers, *(G)* basaltic-rock aquifers, and *(H)* crystalline-rock aquifers.

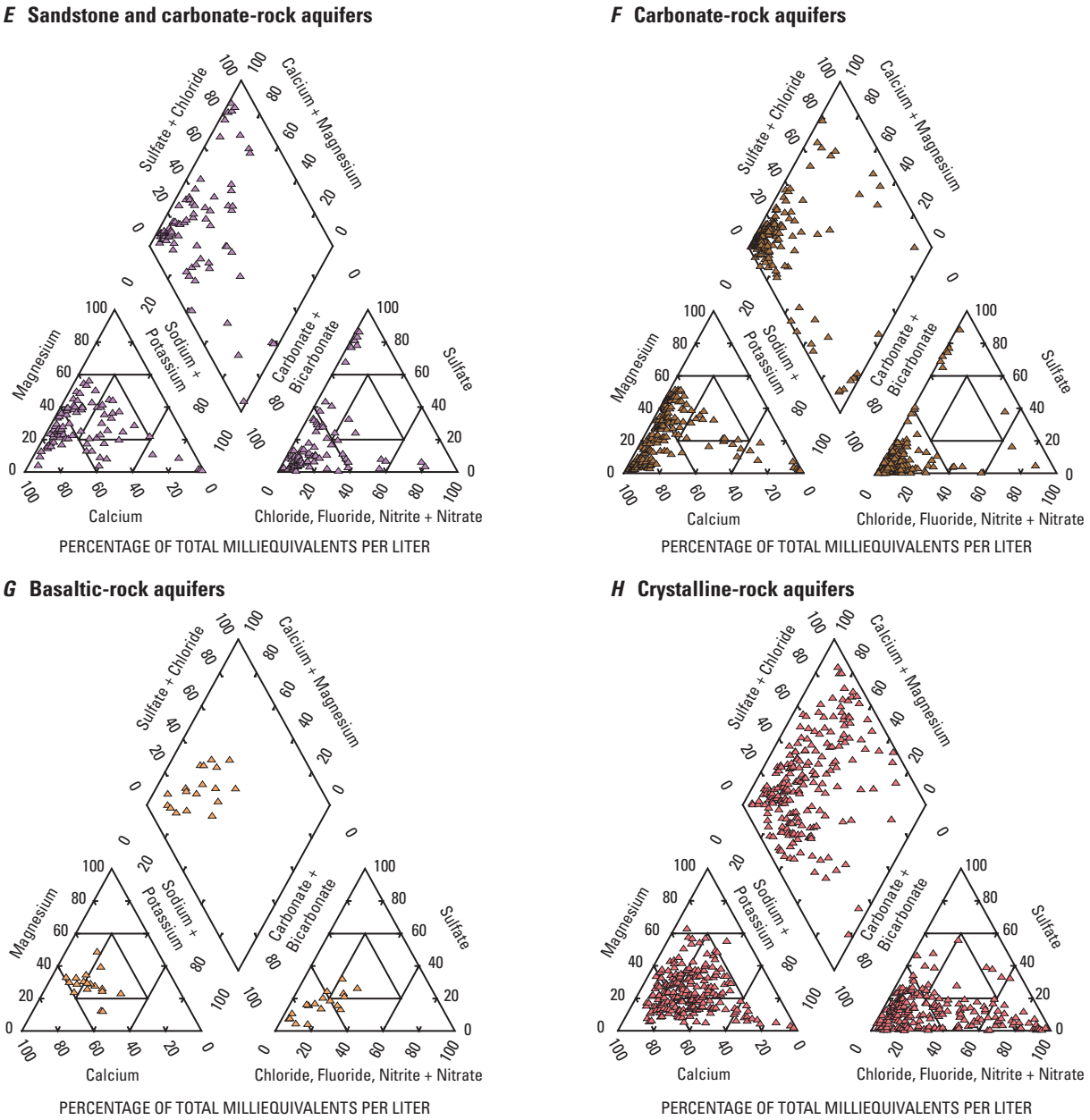


Figure 11. Trilinear diagrams of the ionic composition of water in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, by principal aquifer rock type in *(A)* basin-fill and other non-glacial sand and gravel aquifers, *(B)* glacial sand and gravel aquifers, *(C)* coastal plain aquifers in semi-consolidated sand, *(D)* sandstone aquifers, *(E)* sandstone and carbonate-rock aquifers, *(F)* carbonate-rock aquifers, *(G)* basaltic-rock aquifers, and *(H)* crystalline-rock aquifers.—Continued

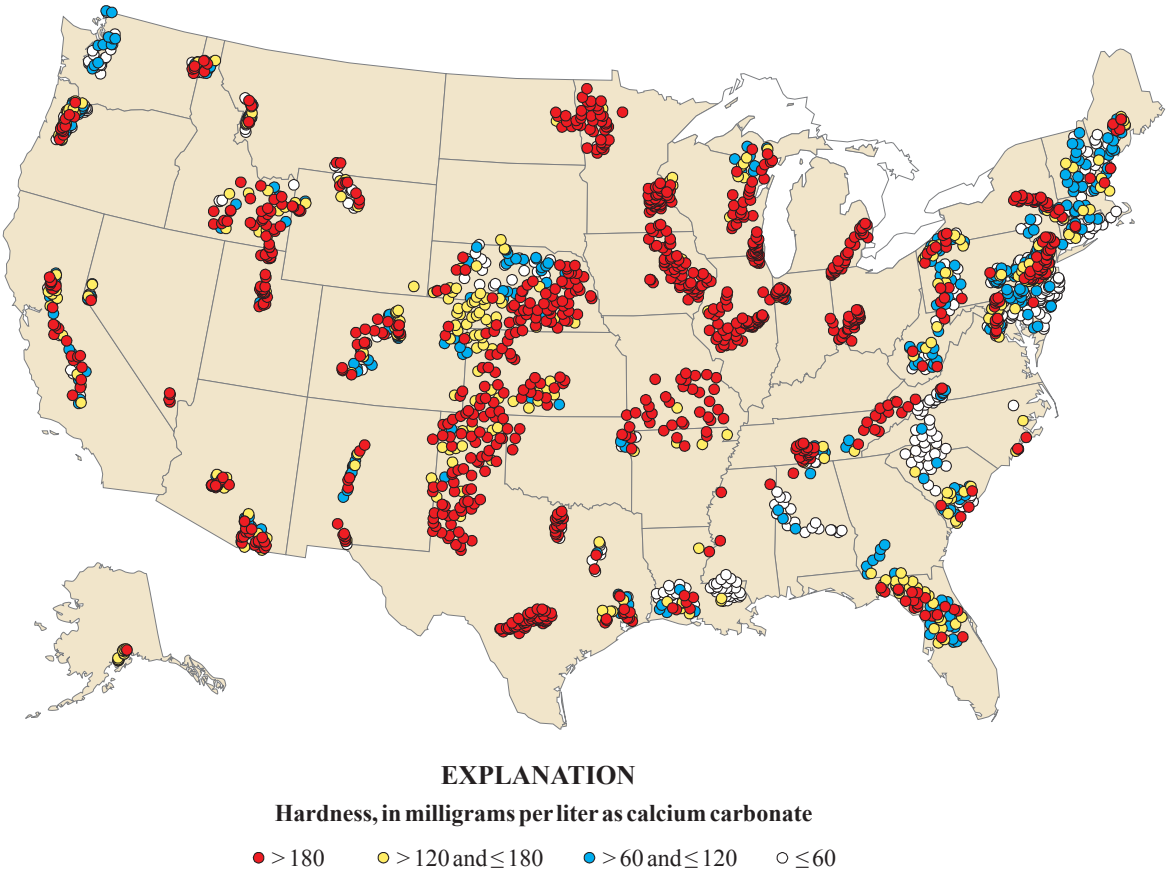


Figure 12. Geographic distribution of hardness of water in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. >, greater than; ≤, less than or equal to.

of dissolved solids (Spearman's rho equal to 0.58, *p* value less than 0.0001). Concentrations greater than the SMCL were scattered across the United States, and were present most frequently in some of the aquifers characterized by high dissolved solids, such as the Basin and Range and Rio Grande basin-fill sand and gravel aquifers.

Fluoride concentrations were less than 1.0 mg/L in the samples from 90 percent of wells (table 2). Fluoride in low concentrations can prevent tooth decay, but high concentrations in drinking water can lead to staining of teeth, and very high concentrations can cause bone damage. The USEPA MCL for fluoride in drinking water is 4 mg/L; USEPA also has established a SMCL of 2 mg/L. Samples from slightly more than 1 percent of the domestic wells in this study had concentrations greater than the MCL for fluoride, and 4.0 percent had concentrations greater than the SMCL (fig. 13). A range of concentrations, 0.7 to 1.2 mg/L, is recommended in drinking water by the CDC to prevent tooth decay (U.S. Centers for Disease Control and Prevention, Fluoride Recommendations Work Group, 2001). In public drinking-water systems, fluoride often is added to attain these concentrations in finished water, although fluoridation of public water has been controversial in some cases (Institute of Medicine, 1997). Of the domestic wells sampled in this study, nearly all (85 to 91 percent) had fluoride concentrations less than the recommended concentrations to prevent tooth decay (fig. 13).

Fluoride occurs in many rock types, but can occur in higher concentrations in some igneous and sedimentary rocks and in volcanic rocks and sediments. In this study, fluoride concentrations were greater than the MCL in samples from the Basin and Range, High Plains, Rio Grande, and Lower Tertiary/Upper Cretaceous aquifers (four aquifers with high dissolved solids overall); the Floridan aquifer; and the New England crystalline-rock aquifers. Fluoride concentrations also exceeded the SMCL in samples from these and several other aquifers (Appendix 6A). In most aquifer types, concentrations of fluoride were positively correlated with concentrations of dissolved solids (Spearman's rho from 0.29 to 0.65, *p* value

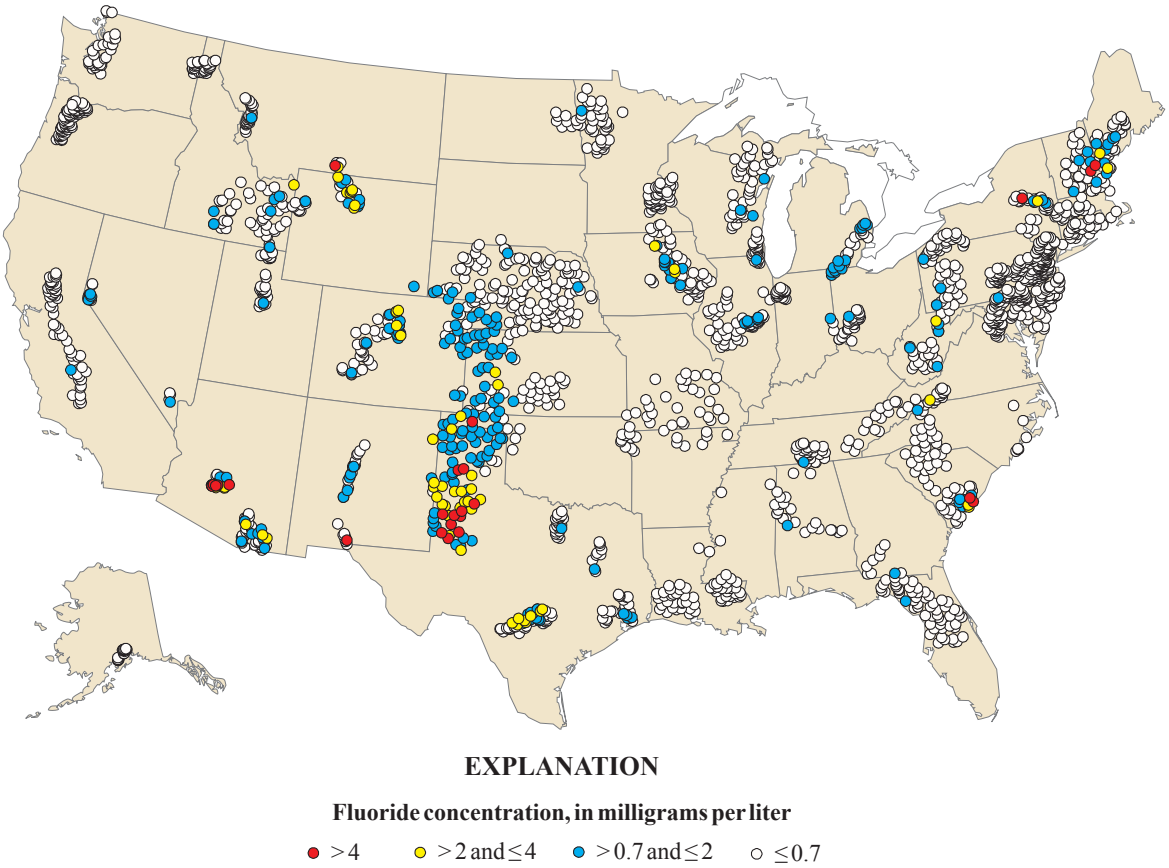


Figure 13. Geographic distribution of fluoride concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. >, greater than; ≤, less than or equal to.

less than 0.0001, excluding sandstone and basaltic-rock aquifers) and negatively correlated with dissolved oxygen (Spearman's rho from 0.31 to 0.55, *p* values less than 0.0001, excluding glacial and basaltic-rock aquifers). The inverse relation between fluoride and dissolved oxygen may be related to ground-water age, in that older water is more likely to have higher concentrations of solutes overall, as well as lower concentrations of dissolved oxygen in some cases.

Trace Elements

Trace elements include metals and semi-metallic elements that typically are found in natural waters at concentrations less than 1 mg/L. These elements originate primarily from rock weathering; concentrations of trace elements in ground water reflect their abundance in aquifer materials, geochemical conditions, concentrations of other constituents, and attenuation processes such as adsorption. Many trace elements may occur as multiple ionic species in natural waters that, depending on redox conditions and pH, have different solubility characteristics. Human activities such as mining and waste disposal also can affect concentrations of trace elements in ground water. At high concentrations, many trace elements can have adverse health effects, whereas others may present aesthetic or nuisance problems. Trace elements were not analyzed in samples from all of the wells sampled in this study. The concentrations of 16 trace elements were analyzed in about two-thirds (about 1,600) of the sampled wells (table 4). Iron and manganese were analyzed in nearly all (about 2,160) of the wells, and five trace elements—boron, lithium, strontium, thallium, and vanadium—were analyzed in about one-quarter (about 500 to 600) of the sampled wells.

Many trace elements were minor constituents in the domestic well water sampled in this study. Aluminum, arsenic, barium, boron, chromium, copper, iron, lithium, manganese, molybdenum, nickel, strontium, vanadium, uranium, and zinc were each detected in about one-half or more of the sampled

Table 4. Summary statistics for trace elements in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004.

[µg/L, micrograms per liter; <, less than]

Trace element	No common reporting level							Common reporting level of 1 µg/L		
	Number of samples	Number of detections	Concentration percentile, in µg/L					Number of samples	Number of detections	Frequency of detections, in percent
			10th	25th	Median	75th	90th			
Aluminum	1,454	842	0.32	0.68	1.89	3.73	5.28	1,408	831	59.0
Antimony	1,552	263	<1	<1	<1	<1	<1	1,535	8	0.52
Arsenic	1,774	976	0.11	0.28	0.92	3.42	7.53	1,774	816	46.0
Barium	1,593	1,556	5.42	19.0	50.0	116	219	1,593	1,556	97.7
Beryllium	1,572	51	<1	<1	<1	<1	<1	1,555	8	0.51
Boron	535	474	6.65	10.9	24.0	63.5	218	535	[1]334	62.7
Cadmium	1,639	138	<1	<1	<1	<1	<1	1,620	6	0.37
Chromium	1,614	879	0.17	0.37	0.81	2.08	4.00	1,591	744	46.8
Cobalt	1,572	537	0.03	0.06	0.11	0.23	0.52	1,543	56	3.63
Copper	1,619	1,094	0.17	0.42	1.07	3.71	12.3	1,599	825	51.6
Iron	2,157	1,234	0.17	1.24	8.53	110.0	1,110	2,142	[2]955	44.5
Lead	1,639	492	0.01	0.02	0.08	0.30	1.09	1,605	202	12.6
Lithium	662	642	0.71	1.93	5.87	18.5	43.8	649	558	86.0
Manganese	2,159	1,380	0.05	0.28	2.06	36.0	172	2,105	1,246	59.2
Molybdenum	1,572	921	0.13	0.30	0.92	2.88	6.00	1,545	763	49.4
Nickel	1,572	925	0.10	0.23	0.70	2.00	3.00	1,546	710	45.9
Selenium	1,625	537	0.13	0.28	0.59	1.19	3.02	1,565	390	24.9
Silver	1,573	4	<1	<1	<1	<1	<1	1,551	3	0.19
Strontium	488	485	30.0	85.0	207	679	2,240	488	[2]485	99.4
Thallium	613	114	<1	<1	<1	<1	<1	611	0	0.0
Uranium	1,725	934	0.01	0.06	0.39	3.00	8.03	1,720	692	40.2
Vanadium	662	452	0.12	0.34	1.29	8.4	20.4	600	326	54.3
Zinc	1,594	1,424	1.00	2.36	8.57	34.1	99.9	1,552	1,414	91.1

[1]Common reporting level for boron is 16 µg/L.

[2]Common reporting level for iron and strontium is 10 µg/L.

wells (using a common reporting level of 1 µg/L for most trace elements, table 4). Antimony, beryllium, cadmium, silver, and thallium were detected infrequently. These elements were detected in less than 1 percent of the sampled wells (using a common reporting level of 1 µg/L). Concentrations of most trace elements were less than available human-health benchmarks for drinking water in 99 percent or more of wells (table 5). Exceptions were arsenic, boron, manganese, strontium, and uranium, all of which exceeded health benchmarks in about 1 to 7 percent of wells. Concentrations of aluminum, iron, and manganese were greater than USEPA SMCLs in about 7 to 21 percent of wells (table 5).

Aluminum is a common constituent of aquifer materials. Aluminum produced by rock weathering, however, is readily immobilized through precipitation and adsorption reactions. Concentrations of aluminum in most wells ranged from less than 1 to 5.28 µg/L (table 4) and showed no readily apparent regional patterns of occurrence. High concentrations of aluminum in drinking water can result in undesirable color and turbidity (World Health Organization, 2004), and the USEPA recommends that concentrations do not exceed 50 to 200 µg/L. Concentrations of aluminum greater than the lower end of the recommended range occurred in 1.51 percent of the sampled wells (table 5). These wells were completed in several aquifer rock types but typically had water with low pH, which is consistent with desorption of aluminum.

Arsenic concentrations in most wells ranged from less than 1 to 7.53 µg/L (table 4), less than the USEPA MCL of 10 µg/L for drinking water. Arsenic in drinking water can contribute to skin, bladder, and lung cancers and has been associated with cardiovascular and neurological effects (National Research Council, 2001; World Health Organization, 2004). Concentrations of arsenic were greater than the MCL in 6.75 percent of all wells and in more than 10 percent of wells in several aquifer types, including crystalline-rock aquifers in New England; basin-fill aquifers in California, Nevada, Arizona and New Mexico, Texas, and Nebraska; and the Snake River basaltic-rock aquifers in Idaho (figs. 14 and 15 and Appendix 6A). Relatively low arsenic concentrations were found in coastal plain, sandstone/carbonate-rock, and carbonate-rock aquifers. These findings are consistent with previous national-scale studies of arsenic in ground water that showed elevated concentrations in the West, Midwest and Northeast, and lowest concentrations in the Southeast (Ryker, 2001; Welch and others, 2000). The percentages of domestic wells and public-supply wells with arsenic concentrations greater than the MCL appear similar, based on findings of this study and the estimate of 7.6 percent for public-supply systems in the United States (Focazio and others, 2000).

Sources of arsenic to ground water include arsenic sulfides and other common minerals in which arsenic is an accessory; arsenic compounds also have been used as pesticides. Geochemical conditions and the distribution of arsenic sources, however, have important roles in controlling arsenic in ground water, through processes that differ among aquifers. For example, processes that result in elevated arsenic in ground water include arsenic release from iron oxides, which is favored by low dissolved oxygen concentrations and high pH and is common in glacial aquifers and some crystalline-rock aquifers (Welch and others, 2000; Ayotte and others, 2003; Kolker and others, 2003; Erickson and Barnes, 2005; Kelly and others, 2005; Thomas, 2007). In the present study, arsenic concentrations were negatively correlated with dissolved oxygen concentrations in samples from wells in several principal aquifers, consistent with this process, including the Basin and Range and Central Valley basin-fill aquifers (rho equal to -0.333 and -0.494, respectively, and p values less than 0.001); the eastern, central, and western glacial aquifers (rho from -0.459 to -0.621, p values less than or equal to 0.004); the Coastal Lowlands coastal plain aquifer (rho equal to -0.551, p values less than 0.001), and the New England crystalline-rock aquifers (rho equal to -0.315, p value less than 0.003). Arsenic concentrations also were positively associated with pH in these and other aquifers (rho from 0.241 to 0.763, p values less than 0.05). Oxidation of sulfide-bearing minerals in some sandstone aquifers and mined areas, evaporative concentration in some basin-fill aquifers in the Southwest, and the influence of geothermal water locally in the western United States are other processes that can result in elevated arsenic concentrations in ground water (Bexfield and Plummer, 2003; Welch and others, 2000; Ryker, 2001; Kolker and others, 2003; Schreiber and others, 2003). Arsenic concentrations also can vary considerably over short distances or even within a single well over time (Gotkowitz and others, 2004; Kelly and others, 2005).

Boron concentrations were greater than the HBSL of 1,000 µg/L in 1.30 percent of wells (table 5). In most wells, boron concentrations ranged from <16 to 218 µg/L. Boron is transported with little attenuation in ground water (Hem, 1985; Barber and others, 1988). Thus, high concentrations typically reflect the distribution of boron sources in the environment. Boron in water may originate from natural sources (for example, evaporite deposits, geothermal water, and saline ground water) or from anthropogenic sources (including sewage disposal) because it is used in the production of glass, cleaning agents, fire retardants, and other products (U.S. Environmental Protection Agency, 2008b). Relatively high concentrations of boron in the domestic wells sampled in this study were most often in the basin-fill aquifers in California, in the southern High Plains basin-fill aquifers, and in the Lower Tertiary/Upper Cretaceous sandstone aquifers underlying the Yellowstone River Basin in Wyoming (Appendix 6A); these high concentrations may be associated with evaporate deposits or saline ground water (Bartos and others, 2005; Bruce and others, 2007). Health effects of boron include gastrointestinal, reproductive, and developmental effects (World Health Organization, 2004; U.S. Environmental Protection Agency, 2008b).

Manganese- and iron-bearing minerals are common constituents of unconsolidated sediments and aquifer materials; iron and manganese are more soluble under conditions of low dissolved oxygen concentrations (reducing

Table 5. Comparison of concentrations of trace elements in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, with human-health benchmarks and non-health guidelines for drinking water.

[MCLs and SMCLs are U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Levels (MCLs) and Secondary Maximum Contaminant Levels (SMCLs) for public water supplies; HBSLs are Health-Based Screening Levels developed by the U.S. Geological Survey using USEPA toxicity data and methods (Toccalino and Norman, 2006); --, not applicable. Action level is a concentration which, if exceeded, triggers treatment or other requirements in USEPA regulations for public water supplies. All benchmarks and guidelines are in micrograms per liter]

Trace element	Benchmark or guideline				Wells exceeding benchmarks or non-health guidelines					
	Human-health benchmark		Non-health guideline		Human-health benchmark		One-tenth of human-health benchmark		Non-health guideline	
	Value	Type	Value	Type	Value	Percent	Value	Percent	Value	Percent
Aluminum	--	--	50 to 200	SMCL	--	--	--	--	7 to 22	0.48 to 1.51
Antimony	6	MCL	--	--	1	0.06	11	0.71	--	--
Arsenic	10	MCL	--	--	120	6.75	758	42.7	--	--
Barium	2,000	MCL	--	--	0	0.00	185	11.6	--	--
Beryllium	4	MCL	--	--	1	0.06	15	0.95	--	--
Boron	1,000	HBSL	--	--	7	[1]1.30	108	[1]20.2	--	--
Cadmium	5	MCL	--	--	2	0.12	6	0.37	--	--
Chromium	100	MCL	--	--	0	0.00	21	1.30	--	--
Cobalt	--	--	--	--	--	--	--	--	--	--
Copper	1,300	Action level	1,000	SMCL	1	0.06	13	0.80	1	0.06
Iron	--	--	300	SMCL	--	--	--	0	412	19.1
Lead	15	Action level	--	--	0	0.00	126	7.69	--	--
Lithium	--	--	--	--	--	--	--	--	--	--
Manganese	300	HBSL	50	SMCL	113	5.22	579	26.8	461	21.3
Molybdenum	40	HBSL	--	--	9	0.57	257	16.35	--	--
Nickel	100	HBSL	--	--	1	0.06	22	1.40	--	--
Selenium	50	MCL	--	--	3	0.18	92	5.65	--	--
Silver	100	HBSL	100	SMCL	0	0.00	0	0.00	0	0.00
Strontium	4,000	HBSL	--	--	36	[1]7.32	169	[1]34.6	--	--
Thallium	2	MCL	--	--	0	[1]0.00	8	[1]1.30	--	--
Uranium	30	MCL	--	--	30	1.74	420	24.35	--	--
Vanadium	--	--	--	--	--	--	--	--	--	--
Zinc	2,000	HBSL	5,000	SMCL	0	0.00	79	4.94	0	0.00

[1]Total numbers of samples were about one-third those of other trace elements; see table 4 for sample numbers.

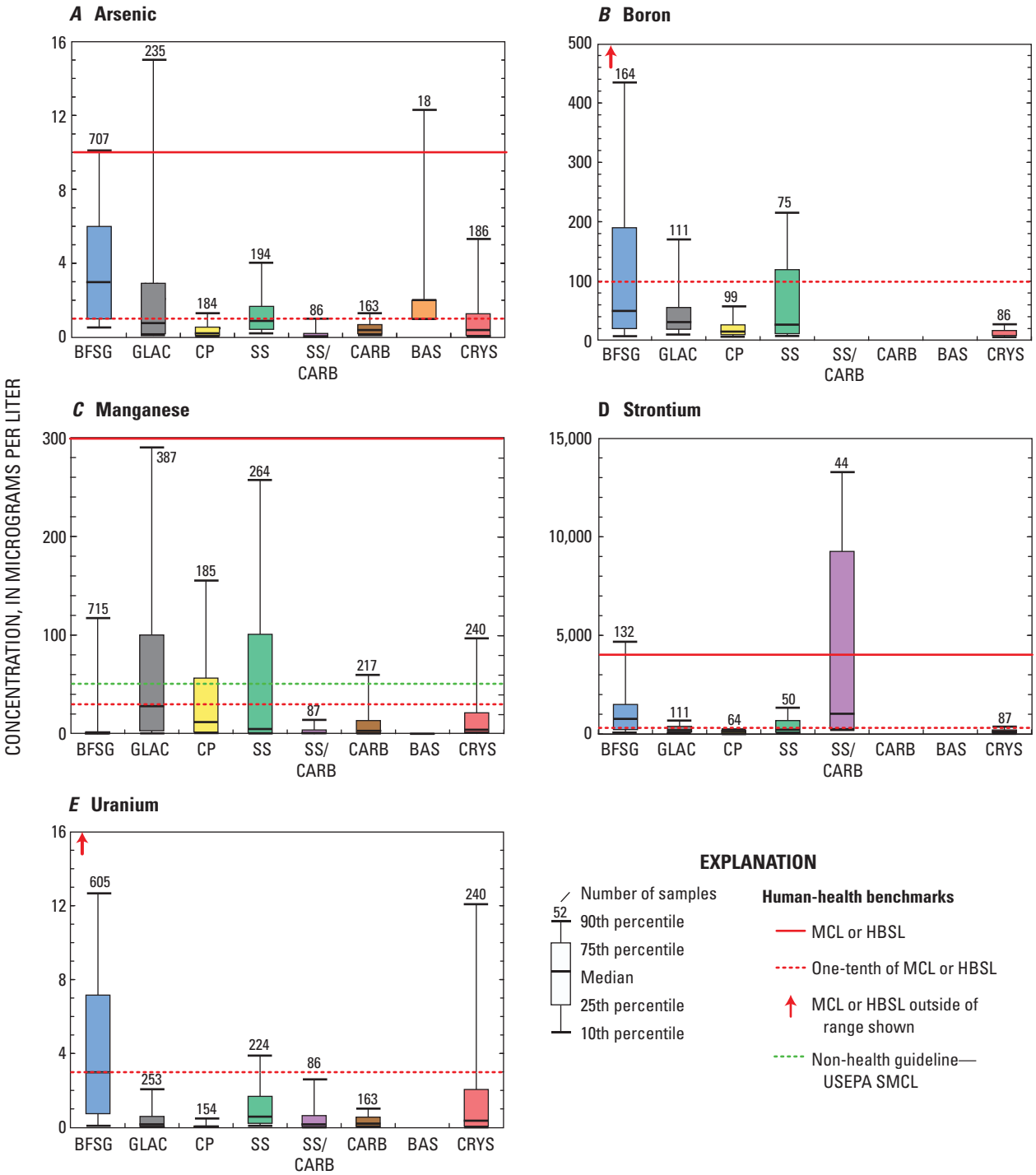


Figure 14. Concentrations of *(A)* arsenic, *(B)* boron, *(C)* manganese, *(D)* strontium, and *(E)* uranium in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2001, by aquifer rock type. BFSG, basin-fill and other non-glacial sand and gravel aquifers; GLAC, glacial sand and gravel aquifers; CP, coastal plain aquifers in semi-consolidated sand; SS, sandstone aquifers; SS/CARB, sandstone/carbonate-rock aquifers; CARB, carbonate-rock aquifers; BAS, basaltic-rock aquifers; CRYS, crystalline-rock aquifers; MCL, U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level; HBSL, Health-Based Screening Level; SMCL, Secondary Maximum Contaminant Level. The common reporting level is 1 microgram per liter.

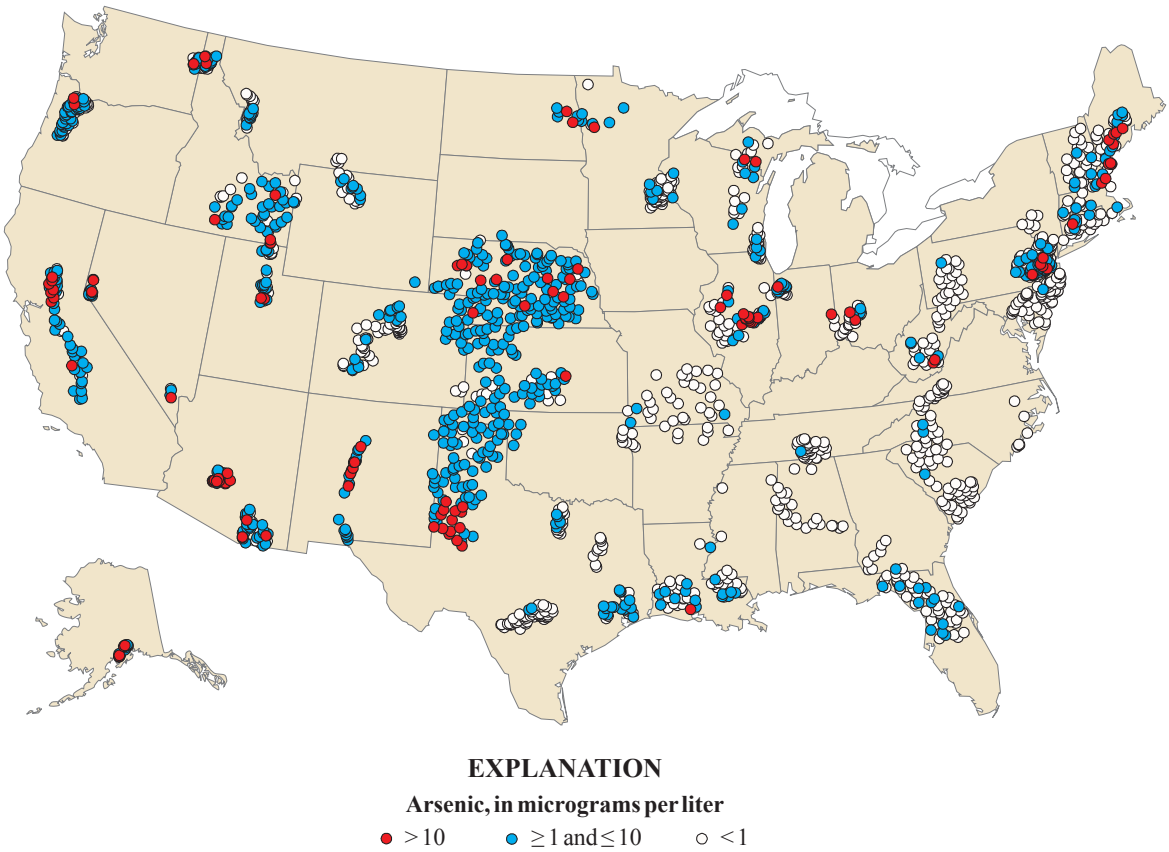


Figure 15. Geographic distribution of arsenic concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. >, greater than; ≥, greater than or equal to; ≤, less than or equal to; <, less than.

conditions) and low pH. Manganese is an essential trace element for human health but may have adverse neurological effects at high doses; food is the primary source of exposure for people rather than drinking water, however (Agency for Toxic Substances and Disease Registry, 2008). Iron also is an essential trace element, with no human-health benchmarks (World Health Organization, 2004). Both iron and manganese have recommended SMCLs in order to avoid poor water taste and the staining of laundry and plumbing fixtures. Manganese concentrations in most wells ranged from <1 to 172 µg/L (table 4), and concentrations were greater than the HBSL for drinking water of 300 µg/L in 5.22 percent of wells (table 5). Manganese concentrations greater than the HBSL were present in wells completed in nearly every principal aquifer rock type, but most frequently in wells in the glacial aquifers, in sandstone aquifers in Pennsylvania and West Virginia, and in coastal plain aquifers in Louisiana and Texas (figs. 14 and 16 and Appendixes 5A and 6A). This distribution of relatively high manganese concentrations among principal aquifers also was documented by McMahon and Chapelle (2007), who showed through an analysis of geochemical conditions in domestic wells sampled by the NAWQA Program that anoxic conditions occurred most frequently in ground water from the glacial and sandstone aquifers compared to other aquifer types, nationally. The SMCL for manganese of 50 µg/L was exceeded in 21.3 percent of the wells, and the SMCL for iron of 300 µg/L was exceeded in 19.1 percent of wells (table 5). Consistent with the control of dissolved concentrations by redox conditions and pH, concentrations of both manganese and iron were inversely correlated with those of dissolved oxygen for all wells (Spearman's rho equal to -0.635 and -0.620, respectively, and p values less than 0.0001) and for most principal aquifers; manganese also was negatively correlated with pH for all wells (Spearman's rho equal to -0.096 and p value less than 0.0001).

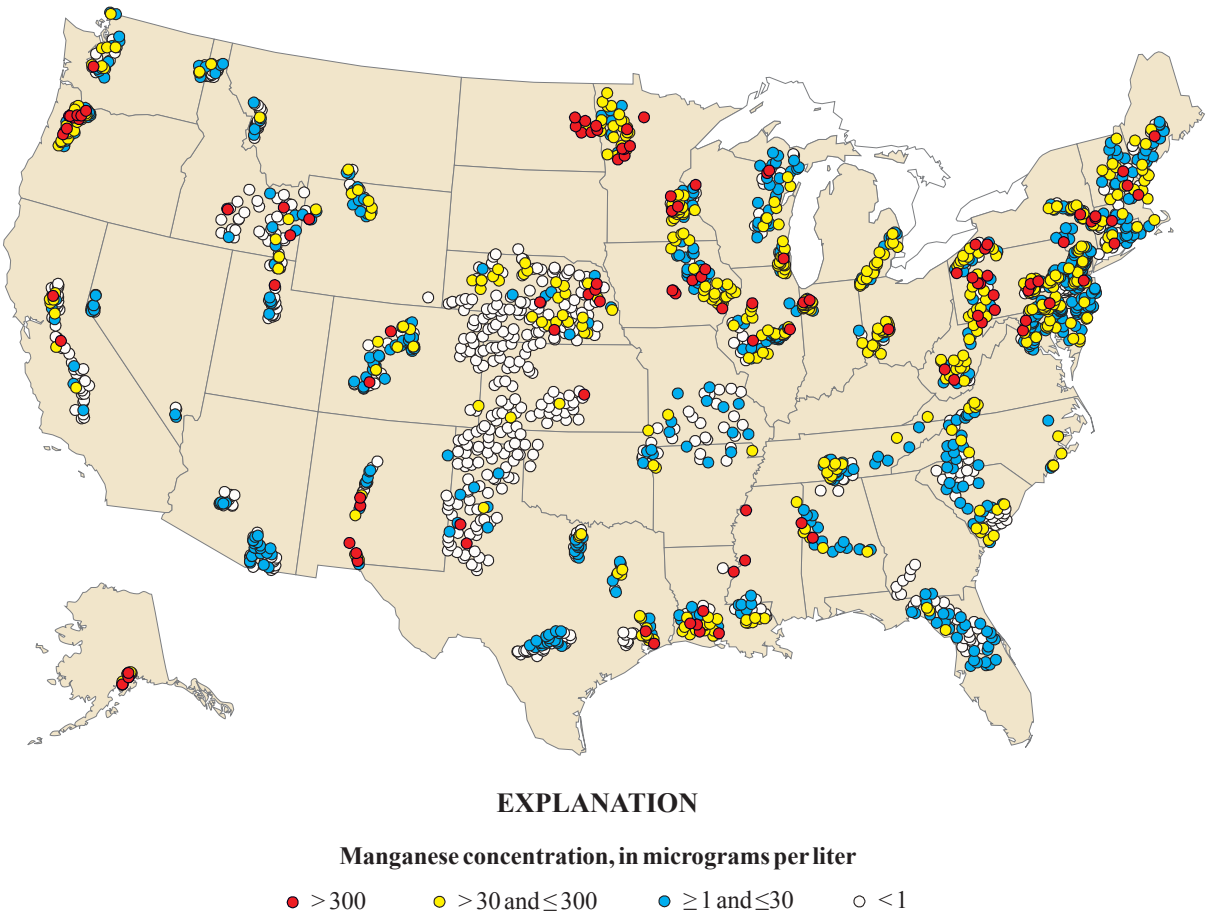


Figure 16. Geographic distribution of manganese concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. >, greater than; ≤, less than or equal to; ≥, greater than or equal to; <, less than.

Strontium concentrations in most wells ranged from 30 to about 2,200 µg/L. Concentrations of strontium exceeded the HBSL of 4,000 µg/L in 7.32 percent of wells. Relatively high concentrations occurred most frequently in the southwestern and south-central United States, in the Edwards-Trinity sandstone/carbonate-rock aquifer, the southern High Plains aquifer, and parts of the Basin and Range basin-fill aquifers (Appendixes 5A and 6A). Strontium is geochemically similar to calcium and is commonly found in carbonate and sulfate rocks and deposits. Health effects include abnormal bone development at high doses (Agency for Toxic Substances and Disease Registry, 2004a).

Uranium concentrations were greater than the USEPA MCL of 30 µg/L in 1.74 percent of wells (table 5). In most wells (80 percent), concentrations of uranium were less than one-third of the MCL, ranging from less than 1 to 8.03 µg/L (table 4). Health effects of uranium in drinking water include possible harm to kidneys (World Health Organization, 2004). High concentrations and concentrations greater than the MCL occurred most frequently in basin-fill aquifers in the West and in crystalline-rock aquifers in the Northeast and Colorado (figs. 14 and 17). Concentrations were low (less than 2 µg/L) or below detection in the coastal plain and carbonate-rock in the Southeast and in glacial aquifers in east-central United States. Uranium is a common trace element in many rock types, but is particularly enriched in certain types of rocks, such as granites (Hess and others, 1985). Like arsenic, manganese, and iron, its presence in ground water is affected by geochemical conditions, including dissolved oxygen concentrations. The combination of elevated source-rock concentrations and the conditions that favor uranium solubility—dissolved oxygen and carbonate alkalinity—have led to relatively high concentrations of uranium in ground water in various hydrogeologic settings, including the Central Valley of California, the Newark Basin sediments of northern New Jersey, and the crystalline-rock aquifers of New England

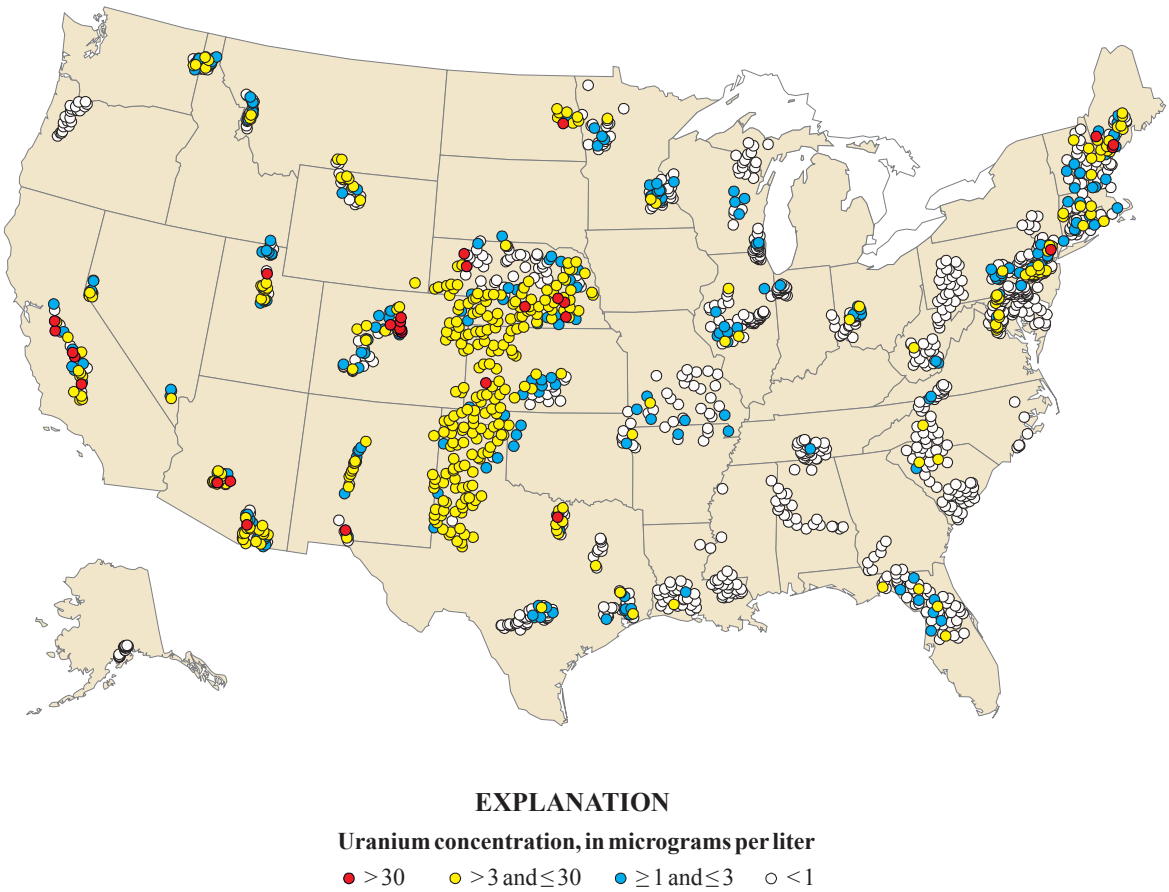


Figure 17. Geographic distribution of uranium concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. >, greater than; ≤, less than or equal to; ≥, greater than or equal to; <, less than.

(Szabo and Zapecza, 1991; Ayotte and others, 2007; Jurgens and others, 2008). In the domestic wells sampled in the present study, uranium concentrations were positively correlated with dissolved oxygen concentrations and pH (Spearman's rho equal to 0.112 and 0.331, respectively, and *p* values less than 0.0001). This is consistent with the greater solubility of the oxidized form of uranium and its greater stablility at higher pH (Hem, 1985). The association of uranium with dissolved oxygen was not as strong as that for iron or manganese with dissolved oxygen, probably because uranium sources are not as ubiquitous as sources of iron or manganese in aquifer materials and because uranium solubility is more complex. For example, dissolved uranium can form complexes with carbonate, phosphate, and other species that increase its solubility (Hem, 1985).

Concentrations of arsenic, boron, strontium, and uranium all were positively correlated with concentrations of total dissolved solids and with specific conductance (Spearman's rho from 0.304 to 0.739, *p* values less than 0.0001). This reflects the general pattern of relatively high trace-element concentrations in wells with relatively high solute concentrations overall, such as occurred in some aquifers in the western and south-central United States. Relatively high solute concentrations in this region could result from the effects of aquifer characteristics, relatively low precipitation, irrigation water use, and (or) ground-water age.

Nutrients and Dissolved Organic Carbon

Nitrogen and phosphorus species in ground water may originate from a variety of natural sources, including precipitation, leaching of organic debris, and aquifer materials, and human activities such as fertilizer application, animal production, and wastewater disposal. Transformations among nitrogen species in ground water are controlled by redox conditions and mediated by microorganisms. Nitrate is the most common form of nitrogen in ground water and is stable and mobile

under oxidizing conditions. Nitrate also is the only nutrient for which there is a human-health benchmark. Excessive nitrate can result in restriction of oxygen transport in the bloodstream, which is of particular concern in infants who lack the enzyme needed to correct this condition (resulting in methemoglobinemia, commonly known as blue baby syndrome).

Concentrations of nitrite, ammonia, ammonia plus organic nitrogen, total phosphorus, and orthophosphate were commonly at or near detection limits in the domestic wells sampled in this study (table 6). Ninety percent of nitrite concentrations were at or below the common reporting level of 0.01 mg/L as N, and 75 percent of ammonia plus organic nitrogen concentrations were below the common reporting level of 0.2 mg/L. Concentrations of ammonia ranged from less than 0.02 to 0.33 mg/L as N in most (80 percent) wells, with a median value equal to the common reporting level of 0.02 mg/L as N. Ammonia is a reduced form that is oxidized to nitrate when dissolved oxygen is present, and ammonia concentrations were inversely correlated with dissolved oxygen concentrations (Spearman's rho equal to -0.51, *p* value less than 0.0001). Ammonia also may be removed from solution by sorption to aquifer materials. Concentrations of total phosphorus and orthophosphate were less than 0.11 mg/L as P in 90 percent of wells, with median values of 0.01 and 0.02 mg/L as P, respectively. Orthophosphate is the most common form of phosphorus in ground water, and its mobility is limited in soils and ground water because it tends to precipitate and sorb onto aquifer materials.

Nitrate concentrations in most (80 percent) wells ranged from less than 0.05 to 5.79 mg/L as N, with a median value of 0.55 mg/L as N (table 6). It was a common contaminant and was detected at concentrations greater than 0.05 mg/L as N in 72 percent of the sampled wells (fig. 18). Concentrations of nitrate were greater than 1 mg/L as N, a level which is considered to result from the effects of human activities in many parts of the United States (Nolan and Hitt, 2003), in nearly one-half (41.4 percent) of the wells and in all principal aquifer rock types (fig. 19A). The USEPA MCL for nitrate is 10 mg/L as N. Concentrations in 95.6 percent of sampled domestic wells were less than the MCL, but nitrate concentrations were greater than 10 mg/L as N in 4.36 percent of the wells (table 7). Concentrations were greater than the MCL in more than 10 percent of wells in several aquifers, including the Basin and Range and Central Valley basin-fill aquifers in the Southwest and in California, the west-central glacial aquifers in the Upper Midwest, the North Atlantic coastal plain aquifers in the central Appalachian region, and the Piedmont crystalline-rock aquifers, also in the central Appalachian region (fig. 18 and Appendix 5A).

Several previous studies that used NAWQA data from domestic and monitoring wells found that nitrate concentrations at the national scale were related to a number of factors that described nitrate sources and aquifer vulnerability (Nolan and Stoner, 2000; Nolan, 2001; Nolan and others, 2002; Nolan and Hitt, 2006). These factors included nitrogen loading from fertilizer use, the extent of agricultural land (cropland or pasture) surrounding a well, population density, soil characteristics, depth to seasonally high water, and the presence or absence of sand and gravel aquifers. Other factors that appeared to affect nitrate concentrations in ground water regionally were denitrification of nitrate to nitrogen gas in the Southeast, and the presence of septic systems and cesspools locally in the Northeast (Nolan and Ruddy, 1996; Nolan, 1999).

In the domestic wells from aquifer studies included in the present study, nitrate concentrations were higher in areas of agricultural land use than in areas of other land uses and were correlated with several variables indicative of nitrogen sources, aquifer characteristics, and geochemical conditions that were consistent with the findings of previous studies. Concentrations were positively correlated with estimates of the amount of nitrogen fertilizer applied in areas surrounding the wells (Spearman's rho equal to 0.189, *p* value less than 0.0001) and were higher in areas with well drained soils (Spearman's rho equal to -0.213, *p* value less than 0.0001). Nitrate concentrations also were positively correlated with concentrations of dissolved oxygen (Spearman's rho equal to 0.611, *p* value less than 0.0001), suggesting the effects of denitrification (which occurs in the absence of oxygen) and (or) ground-water age. Finally, nitrate concentrations were positively correlated with the percentage of agricultural land use (Spearman's rho equal to 0.288, *p* value less than 0.0001) and negatively correlated with the percentage of undeveloped land use (Spearman's rho equal to -0.336, *p* value less than 0.0001) in buffer areas surrounding wells. Consequently, when wells were categorized according to land use within the surrounding 500-meter-radius buffer areas (table 8; Gilliom and others, 2006), wells in predominantly agricultural areas had nitrate concentrations that were higher and exceeded the MCL more frequently than those in wells in areas of other land uses (fig. 19B). Nitrate concentrations were greater than the MCL in 7.1 percent of wells in areas of predominantly agricultural land use (*n* equal to 843), 3.1 percent of wells in areas of urban land use (*n* equal to 193), 3.7 percent of wells in mixed land-use areas (*n* equal to 651), and 0.7 percent of wells in undeveloped areas (*n* equal to 445); median values for wells in agricultural, urban, mixed, and undeveloped land-use areas were 1.1, 0.68, 0.43, and 0.19 mg/L as N, respectively (fig. 19B). In wells used in NAWQA assessment studies that specifically targeted agricultural land-use areas (fig. 1), nitrate concentrations were greater than the MCL of 10 mg/L as N even more frequently, at 23.4 percent of the sampled wells (Appendix 5B). These findings are consistent with the many previous studies that have found relatively high nitrate concentrations in some agricultural areas of the Nation (for example: Kolpin and others, 1994; Mehnert and others, 1995; Townsend and others, 1998).

Dissolved organic carbon was detected in nearly all wells sampled in this study (table 6). Concentrations ranged from 0.2 to 1.9 mg/L in most wells, with a median value of 0.5 mg/L. Dissolved organic carbon originates naturally from organic material but also may be contributed to ground water

Table 6. Summary statistics for nutrients, dissolved organic carbon, radionuclides, and fecal indicator bacteria in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004.

[Radium-226 plus radium-228 data from Zoltan Szabo, U.S. Geological Survey, written communs., 2006 and 2008. Fecal indicator bacteria data from S.S. Embrey, U.S. Geological Survey, written commun., 2005. mg/L, milligrams per liter; pCi/L, picocuries per liter; CFU/100 mL, colony-forming units per 100 milliliters; <, less than; --, not determined]

Contaminant	No common reporting level							Common reporting levels as indicated			
	Number of samples	Number of detections	Concentration percentile					Common reporting level	Number of samples	Number of detections	Frequency of detections, in percent
			10th	25th	Median	75th	90th				
Nutrients and dissolved organic carbon (mg/L)											
Nitrite as N	2,141	281	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	2,141	244	11.4
Nitrate as N	2,132	1,555	<0.05	0.07	0.55	2.40	5.79	0.05	2,132	1,534	72.0
Ammonia as N	2,095	1,129	<0.02	<0.02	0.02	0.05	0.33	0.02	2,095	1,079	51.5
Ammonia plus organic nitrogen as N	2,086	656	<0.2	<0.2	<0.2	<0.2	0.4	0.2	2,086	358	17.2
Phosphorus, total	1,776	1,028	<0.01	<0.01	0.01	0.04	0.11	0.01	1,720	867	50.4
Orthophosphate as P	2,121	1,382	<0.01	<0.01	0.02	0.04	0.11	0.01	1,979	1,369	69.2
Dissolved organic carbon	1,932	1,818	0.2	0.3	0.5	0.9	1.9	0.10	1,895	1,818	95.9
Radionuclides (pCi/L)											
Radon	1,958	1,936	141	232	434	898	2,150	80	1,958	1,907	97.4
Gross alpha-particle radioactivity	378	158	<3	<3	<3	4.75	8.70	3	378	158	41.8
Gross beta-particle radioactivity	375	157	<4	<4	<4	5.57	10.8	4	375	157	41.9
Radium-226 plus radium-228	438	[1]304	--	--	--	--	--	--	--	--	--
Fecal indicator bacteria (CFU/100 mL)											
Total coliform bacteria	397	133	--	--	--	--	--	1	397	133	33.5
Escherichia coli bacteria	378	30	--	--	--	--	--	1	378	30	7.9

[1]Includes detection of only one or both radionuclides.

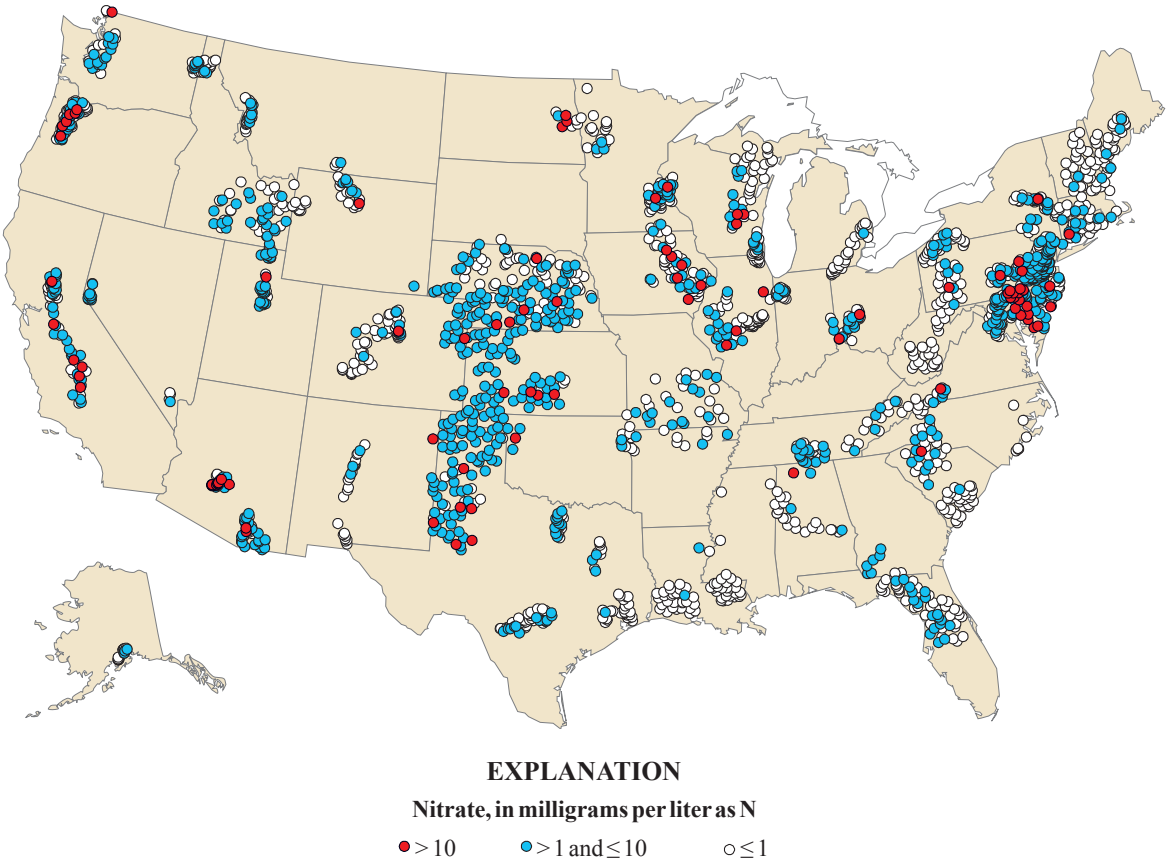


Figure 18. Geographic distribution of nitrate concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. >, greater than; ≤, less than or equal to.

through waste disposal and animal production. It can form complexes with metals that alter the solubility of the metals, and through its microbially mediated oxidation, dissolved organic carbon can affect redox conditions and the transformation of other chemical species in ground water. Dissolved organic carbon also can react with chlorine during water disinfection to form trihalomethanes, which are harazardous to human health.

Radon and Other Radionuclides

Radon (radon-222) is a water-soluble, radioactive gas that originates from radium-226, part of the uranium-238 decay series. Because its initial parent uranium occurs ubiquitously in trace amounts in the aquifer sediments and rocks, and because it is soluble, radon is common in ground water. Radon is chemically inert and does not react with aquifer materials or other chemical constituents, but it decays through alpha-particle emission and has a short half-life (3.8 days; Wanty and Nordstrom, 1993). Radon concentrations in ground water can be affected by multiple factors, including the distribution of uranium-bearing minerals in aquifer materials, aquifer physical characteristics, and geochemical conditions that affect the uranium and radium mobility (Hess and others, 1985; Wanty and others, 1992; Otton and others, 1993).

Radon and other naturally occurring radionuclides emit ionizing radiation and consequently are carcinogens. Radon can contribute to the risk of developing lung and gastrointestinal cancers (National Academy of Sciences, 1999). Adverse health effects from radon in drinking water result primarily from inhalation, after the gas is released from solution in the home, although the contribution from drinking water usually is small compared to other sources of radon in indoor air (Hopke and others, 2000). Water with about 10,000 pCi/L of radon contributes about 1 pCi/L of radon to indoor air (Otton and others, 1993); USEPA recommends that homes with indoor air concentrations at or above 4 pCi/L be fixed to reduce concentrations (U.S. Environmental Protection Agency, 1999). Two

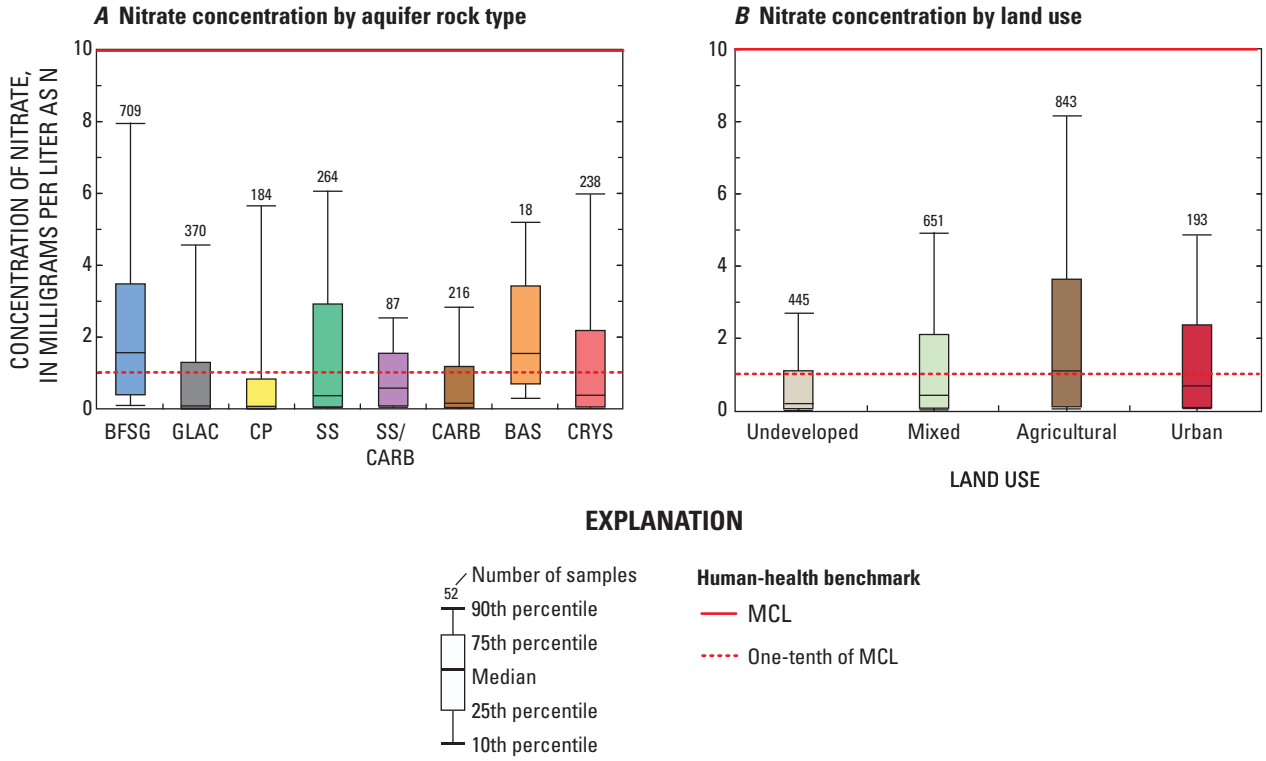


Figure 19. Nitrate concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, by *(A)* aquifer rock type and *(B)* land use. BFSG, basin-fill and other non-glacial sand and gravel aquifers; GLAC, glacial sand and gravel aquifers; CP, coastal plain aquifers in semi-consolidated sand; SS, sandstone aquifers; SS/CARB, sandstone/carbonate-rock aquifers; CARB, carbonate-rock aquifers; BAS, basaltic-rock aquifers; CRYS, crystalline-rock aquifers. Land uses are uses in circular areas of 500-meter radii surrounding wells; see table 8 for description of land-use categories. MCL, U.S. Environmental Protection Agency Maximum Contaminant Level.

human-health benchmarks, which are regulations proposed by USEPA in 1999 for public water systems, are used for comparison with radon concentrations in this study. The higher value, 4,000 pCi/L, is an alternative MCL that is proposed for public water systems for states or water-system service areas that have programs in place to reduce radon risks from all sources (U.S. Environmental Protection Agency, 1999; Hopke and others, 2000). The lower value, 300 pCi/L, is proposed as the MCL for states or service areas that do not have such programs.

Radon concentrations were measured in nearly all of the wells sampled in this study. Radon concentrations are reported in activity units, picocuries per liter (pCi/L), which describe the number of radioactive emissions (nuclear disintegrations) over time, rather than in mass concentration units. One picocurie per liter equals 2.2 radioactive disintegrations per minute per liter.

Radon concentrations in domestic wells sampled in this study ranged from 141 to 2,150 pCi/L in most (80 percent) wells (table 6). The median value, 434 pCi/L, and concentrations in 64.6 percent of the wells were greater than the lower proposed MCL of 300 pCi/L (table 7). Concentrations greater than the lower proposed MCL occurred in every principal aquifer and were distributed across the United States (figs. 20 and 21). Concentrations greater than the higher proposed MCL of 4,000 pCi/L occurred in 4.44 percent of wells (table 7). Radon concentrations were highest, and were present most frequently at concentrations greater than the proposed MCLs, in the crystalline-rock aquifers (fig. 21), including the New England, Piedmont, and Rocky Mountain Front Range crystalline-rock aquifers, which are located in the Northeast, the southern and central Appalachians, and Colorado (fig. 20 and Appendix 5A). Concentrations in about 30 percent of the sampled wells in these aquifers were greater

Table 7. Comparison of concentrations of nitrate and radionuclides in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, with human-health benchmarks and non-health guidelines for drinking water.

[MCLs are U.S. Environmental Protection Agency Maximum Contaminant Levels for public water supplies; mg/L, milligrams per liter; pCi/L, picocuries per liter; --, not applicable or not determined]

Contaminant	Benchmark or guideline				Wells exceeding benchmarks or non-health guidelines					
	Human-health benchmark		Non-health guideline		Human-health benchmark		One-tenth of human-health benchmark		Non-health guideline	
	Value	Type	Value	Type	Value	Percent	Value	Percent	Value	Percent
Nutrients (mg/L)										
Nitrate as N	10	MCL	--	--	93	4.36	883	41.4	--	--
Radionuclides (pCi/L)										
Radon	4,000	Proposed alternative MCL	--	--	87	4.44	1,044	53.3	--	--
	300	Proposed MCL	--	--	1,265	64.6	--	--	--	--
Gross alpha-particle radioactivity	15	MCL[1]	--	--	20	5.29	--	--	--	--
Gross beta-particle radioactivity	50	Screening level[2]	--	--	7	1.87	--	--	--	--
Radium-226 plus radium-228	5	MCL	--	--	10	2.28	--	--	--	--

[1]The MCL for alpha-particle radioactivity excludes alpha-particle radioactivity from uranium or radon. Values reported for domestic wells in this study are not corrected for uranium or radon, but almost all radon is removed from the water sample during the preparation steps for sample analysis (Zoltan Szabo, U.S. Geological Survey, written commun., 2008).

[2]Water samples from public supplies with gross beta-particle radioactivity greater than 50 pCi/L must have contributing radionuclides determined.

Table 8. Land-use classification used to categorize domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004.

[Modified from Gilliom and others (2006). Each well was classified according to the dominant land uses in a circular buffer area of 500-meter radius around the well, using land-use data and area-weighted land-use percentages as described in Nakagaki and Wolock (2005)]

Land-use category	Land-use classification criteria
Agricultural	Greater than 50 percent agricultural land and less than or equal to 5 percent urban land.
Urban	Greater than 25 percent urban land and less than or equal to 25 percent agricultural land.
Undeveloped	Less than or equal to 5 percent urban land and less than or equal to 25 percent agricultural land.
Mixed	All other combinations of urban, agricultural, and undeveloped land.

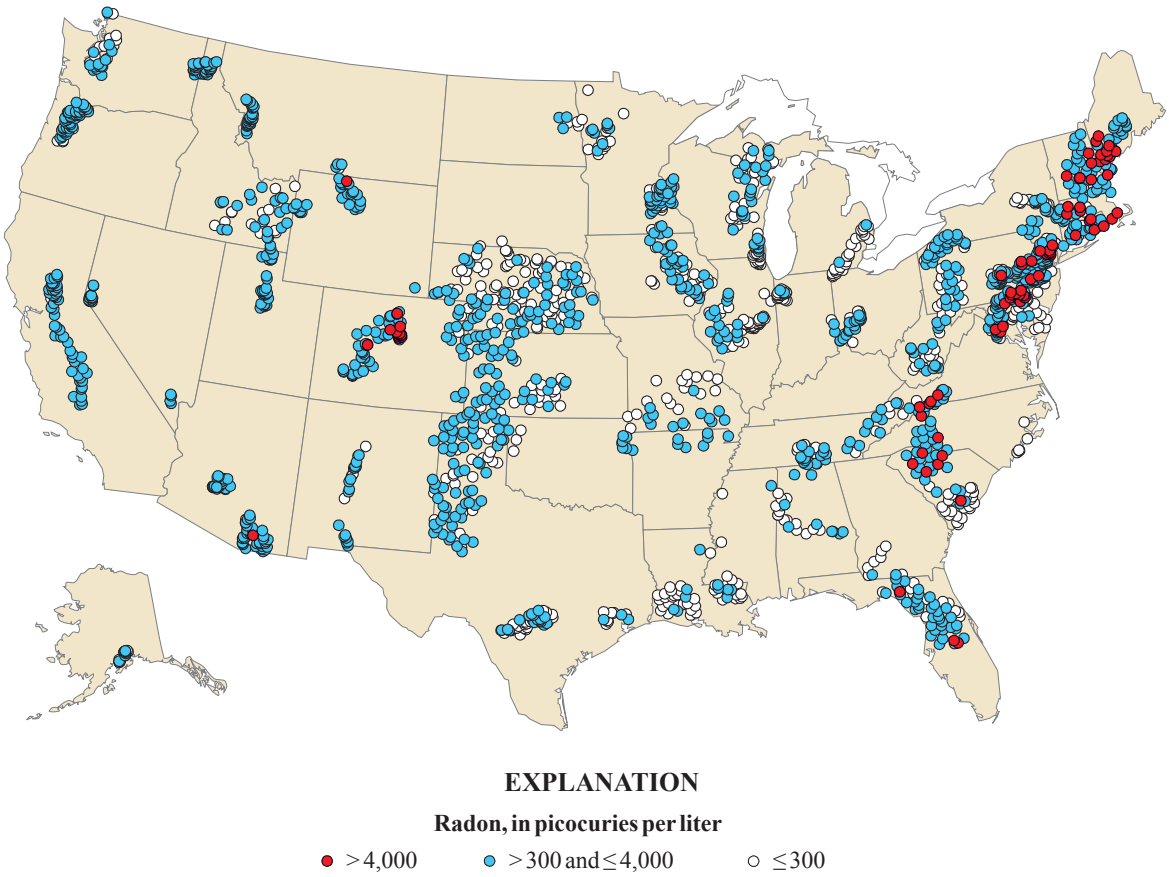


Figure 20. Geographic distribution of radon concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. >, greater than; ≤, less than or equal to.

than 4,000 pCi/L. The presence of high concentrations in ground water in these areas is well documented (Brutsaert and others, 1981; Hess and others, 1985; Loomis, 1987; Longtin, 1988; Lawrence and others, 1991; Senior, 1998; Ayotte and others, 2007). Relatively high radon concentrations are common in the crystalline-rock aquifers as a result of the prevalence of uranium-bearing minerals in granites, pegmatites, and their derivative metamorphic rocks and sediments (Otton and others, 1993; LeGrand, 1987). Enrichment of radium-226 along the surfaces of water-bearing fractures in these rocks also is a likely factor contributing to the elevated radon in these aquifers (Wood and others, 2004). Radon concentrations also were relatively high in several sandstone aquifers (fig. 21 and Appendix 5A). Uranium-rich reduced shales interbedded with the sandstone beds could be the source of radon (or the radium-226 parent) in these aquifers (Szabo and Zapecza, 1991; Becker and others, 2002). In wells completed in the crystalline-rock and sandstone aquifers and, to a lesser extent, in all wells, radon and uranium concentrations were positively correlated (Spearman's rho equal to 0.469, 0.305, and 0.180, respectively, p values less than 0.0001). This correlation reflects the coincidence of radon in water and elevated concentrations of uranium in source rocks, and also the occurrence of geochemical conditions (alkaline and oxidizing) that favor uranium mobility in some crystalline-rock, sandstone, and other aquifers.

Radionuclides and measures of radioactivity other than radon and uranium concentrations were determined for a subset of the domestic wells sampled in this study. Alpha- and beta-particle radioactivities and concentrations of the isotopes of radium were measured in samples from about 17 percent of the wells. These wells were completed in about one-half of

the 30 principal aquifers sampled in this study (Appendix 5A). Alpha- and beta-particle radioactivities and concentrations of radium isotopes, like radon concentrations, are measured in activity units (pCi/L). Radioactive isotopes of uranium were not measured individually; uranium was measured chemically as concentrations of the total mass of uranium, which is consistent with the current mass-based USEPA MCL. Mass concentrations of uranium were described previously, along with those of other trace elements. The radium radionuclides are carcinogens that have adverse health risks upon ingestion and affect different body parts (primarily bone) than radon (Mays and others, 1985).

Gross alpha-particle radioactivity is a measure of alpha-particle radiation emissions from all alpha-emitting radioactive sources in a water sample. It is a screening measurement that is used to determine high levels of alpha-particle radioactivity without identifying the specific radionuclides responsible for the activity. In most cases, alpha-particle radioactivity in ground water results from naturally occurring radionuclides, including uranium-238, uranium-234, radium-226, radium-224, radon-222, and other isotopes (Focazio and others, 2001). The USEPA MCL for alpha-particle radioactivity is 15 pCi/L, which applies to alpha-particle radioactivity exclusive of activity that is due to uranium or radon (U.S. Environmental Protection Agency, 2000b). Gross alpha-particle radioactivity reported here is not corrected for contributions for uranium or radon, but almost all radon is removed from the water sample during the preparation steps for sample analysis (Zolton Szabo, U.S. Geological Survey, written commun., 2008). In most (80 percent) of the domestic wells sampled in this study, alpha radioactivities ranged from less than 3 to 8.7 pCi/L (table 6), and activities were less than 15 pCi/L in 94.7 percent of the wells (table 7). Wells in which alpha radioactivities were greater than 15 pCi/L (5.29 percent) were completed in the New England crystalline-rock aquifers; in the Early Mesozoic, Lower Tertiary/Upper Cretaceous, and Valley and Ridge sandstone aquifers; and in the Rio Grande basin-fill aquifer. In these aquifers, 4 to 19 percent of wells in which alpha-particle radioactivity was measured had activities greater than 15 pCi/L (Appendix 6A). Most of these aquifers also had relatively high concentrations of uranium.

Gross beta-particle radioactivity is a measure of beta-particle radiation emissions from all beta-emitting radioactive sources in a water sample. Like alpha-particle radioactivity, it is a screening measurement. Radionuclides that contribute to beta-particle radioactivity in ground water are naturally occurring and anthropogenic (Welch and others, 1995; U.S. Environmental Protection Agency, 2000b). Naturally occurring radionuclides are primarily potassium-40 and radium-228 and, less frequently, lead-210 and short-lived progeny of uranium-238. The most common anthropogenic contributors include tritium (hydrogen-3), strontium-90 and cesium-137. The USEPA MCL for beta-particle radioactivity, 4 millirems per year, is given in dose-equivalent units, which measure the effect of the radiation on the body or organs. Concentrations of individual radionuclide species must be determined if measured beta-particle radioactivity, exclusive of naturally occurring postassium-40 activity, is greater than 50 pCi/L in public water supplies (Environmental Protection Agency, 2000b, 2001b). In the domestic wells sampled in this study, beta-particle radioactivity ranged from less than 4 to 10.8 pCi/L in most (80 percent) wells (table 6). Beta-particle radioactivity in seven wells, or 1.87 percent of all sampled wells, was greater than the screening level of 50 pCi/L for public water supplies (table 7). These wells were located in the New England crystalline-rock aquifers (5 wells) and in the Rio Grande basin-fill aquifer (2 wells; Appendix 5A), aquifers with relatively high concentrations of uranium.

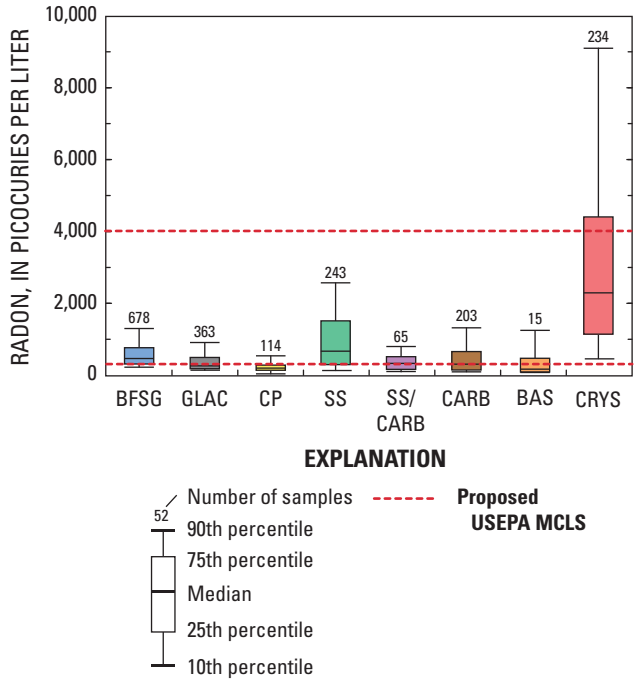


Figure 21. Radon concentrations in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, by aquifer rock type. BFSG, basin-fill and other non-glacial sand and gravel aquifers; GLAC, glacial sand and gravel aquifers; CP, coastal plain aquifers in semi-consolidated sand; SS, sandstone aquifers; SS/CARB, sandstone/carbonate-rock aquifers; CARB, carbonate-rock aquifers; BAS, basaltic-rock aquifers; CRYS, crystalline-rock aquifers; USEPA, U.S. Environmental Protection Agency; MCL, Maximum Contaminant Level.

Alpha- and beta-particle radioactivity were strongly correlated with uranium concentrations (Spearman rho equal to 0.528 and 0.335, respectively, *p* value less than 0.0001), and relatively high activities occurred in aquifers with relatively high uranium concentrations. Alpha-particle radioactivity also was correlated with radon concentrations (Spearman rho equal to 0.263, *p* value less than 0.0001). Uranium isotopes and radon, along with radium-226 and radium-224, are alpha-particle emitters. The association of beta-particle radioactivity with dissolved uranium may be due, in part, to the beta-particle emission from some uranium-238 progeny, but may also reflect the relatively high activities of other natural beta-particle emitters, such as radium-228 and potassium-40, in the same regional aquifers (Focazio and others, 2001).

Radium isotopes, which originate from the radioactive decay of uranium and thorium, occur as dissolved divalent cations in ground water (Zapecza and Szabo, 1986). Isotopes that occur frequently in ground water include radium-228, radium-226, and radium-224. The USEPA has established an MCL of 5 pCi/L for radium-226 and radium-228 combined. Radium-228 plus radium-226 were measured by several methods in the samples collected for the NAWQA Program. Concentrations of radium-226 plus radium-228 were less than 5 pCi/L in all 97.7 percent of the 438 wells for which radium isotopes were measured. The wells with activities greater than 5 pCi/L (2.28 percent) were completed in the North Atlantic and Coastal Lowlands coastal plain aquifers, the New England crystalline-rock aquifer, and the Early Mesozoic sandstone aquifer (Appendix 5A). Concentrations of combined radium greater than 5 pCi/L have been noted in these aquifers in previous studies of radionuclide occurrence (Szabo and Zapecza, 1991; Focazio and others, 2001; Szabo and others, 2005).

Organic Compounds

Anthropogenic organic compounds may be released to the environment from a variety of activities, including agriculture; combustion of fossil fuels; disposal of industrial, municipal, and domestic waste; and chemical spills. The occurrence of anthropogenic organic compounds in ground water depends on their use and sources, physical properties (solubility, volatility), mobility through soils and sediments, and the extent to which they are degraded chemically or biologically in the environment. Some organic compounds have been determined to be carcinogenic or have other adverse health effects (World Health Organization, 2004; U.S. Environmental Protection Agency, 2006a); the possible health effects of others are not known. Anthropogenic organic compounds in the environment commonly are categorized on the basis of use and properties as pesticides or volatile organic compounds (VOCs). Pesticides are substances used to kill or control undesirable plants, animals, or other organisms (Gilliom and others, 2006). VOCs are used for a variety of purposes but share properties that allow them to move readily into the air (Zogorski and others, 2006). Common VOCs include solvents, gasoline hydrocarbons, and refrigerants. In this study, 83 pesticides or pesticide breakdown products and 85 VOCs were analyzed. The complete list of analytes for pesticides and VOCs and numbers of wells in which each was analyzed are given in Appendix 4. About one-half of the pesticides and about two-thirds of the VOCs were measured in nearly all (about 90 percent or more, or about 2,000) of the sampled wells; other pesticides and VOCs were measured in about 60 percent (about 1,400 to 1,500) of the sampled wells.

Many of the anthropogenic organic compounds that were analyzed in this study (henceforth, referred to as organic compounds) were detected in samples from domestic wells, but infrequently and at low concentrations (with typical analytical detection limits of 0.001 to 0.12 µg/L). If detections at any concentration are considered, 69 percent (116) of the 168 organic compounds that were analyzed were detected. Most detections (83 percent) were at concentrations less than 0.2 µg/L, and nearly all detections (96 percent) were less than 1 µg/L. Some of these detections were at concentrations as low as 0.001 µg/L. Measured concentrations of 15 frequently detected compounds are shown in figure 22.

Whether or not a compound is detected depends on the laboratory analytical method detection limit as well as on the occurrence of the compound in the environment. When analytical methods with low detection limits are used, more compounds are detected, and detection frequencies are relatively high. In this study, detection limits for organic compounds varied among compounds and over time. Thus, the concentration data for organic compounds were reassessed in terms of common reporting levels, so that detection frequencies could be validly compared for different compounds and for the same compound in all samples. When concentration data are recast in terms of common reporting levels (fig. 23), some information is lost: when a higher common reporting level is used, more compounds and samples can be compared, but information about detections of some compounds (present at lower concentrations) in some samples is lost. Thus, several common reporting levels were used to describe the occurrence of organic compounds. For example, using a common reporting level of 0.2 µg/L, 34 percent (54) of the organic compounds that were analyzed were detected. At a lower common reporting level, 0.02 µg/L, 55 percent (86) of the analyzed compounds were detected (11 and 12 compounds were not assessed at 0.2 and 0.02 µg/L, respectively), and as stated previously, when no common reporting level was used (that is, a detection at any concentration counts, with typical analytical detection limits of 0.001 to 0.1 µg/L), 69 percent (116) of the analyzed compounds were detected.

Organic compounds were detected in many of the sampled wells (figs. 24 and 25). When detections at any concentration were considered, one or more organic compounds were detected in 60.1 percent of wells. Above a common reporting level of 0.02 µg/L, one or more organic compounds were detected in 41.5 percent of wells; at higher concentrations, above a common reporting level of 0.2 µg/L, one or more organic compounds were detected in 14.4 percent of

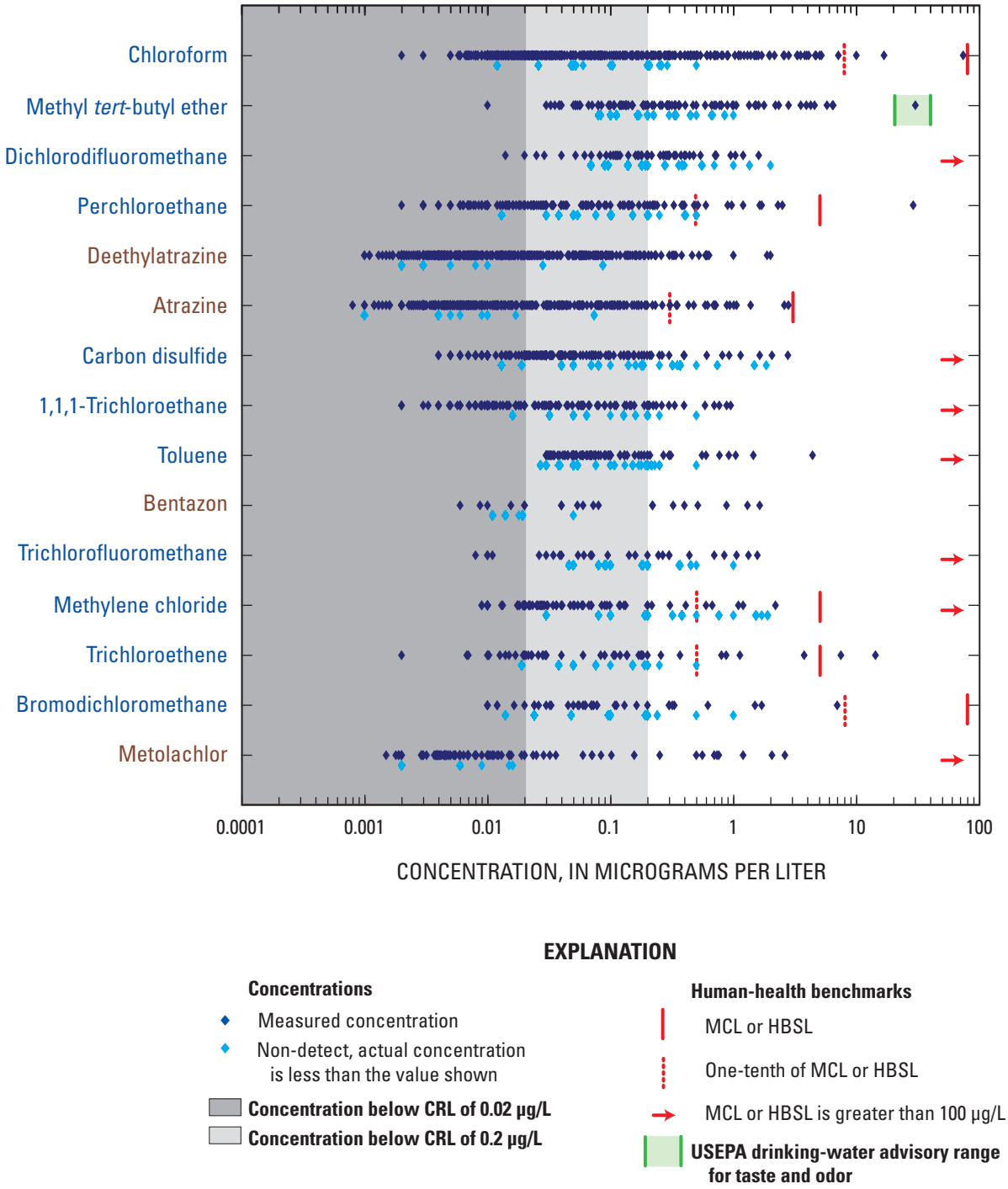


Figure 22. Concentrations of frequently detected organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. Data points for non-detects overlap and thus represent multiple values. Names of pesticides are shown in brown, and names of volatile organic compounds are shown in blue. CRL, common reporting level; MCL, U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level; HBSL, Health-Based Screening Level; µg/L, microgram per liter.

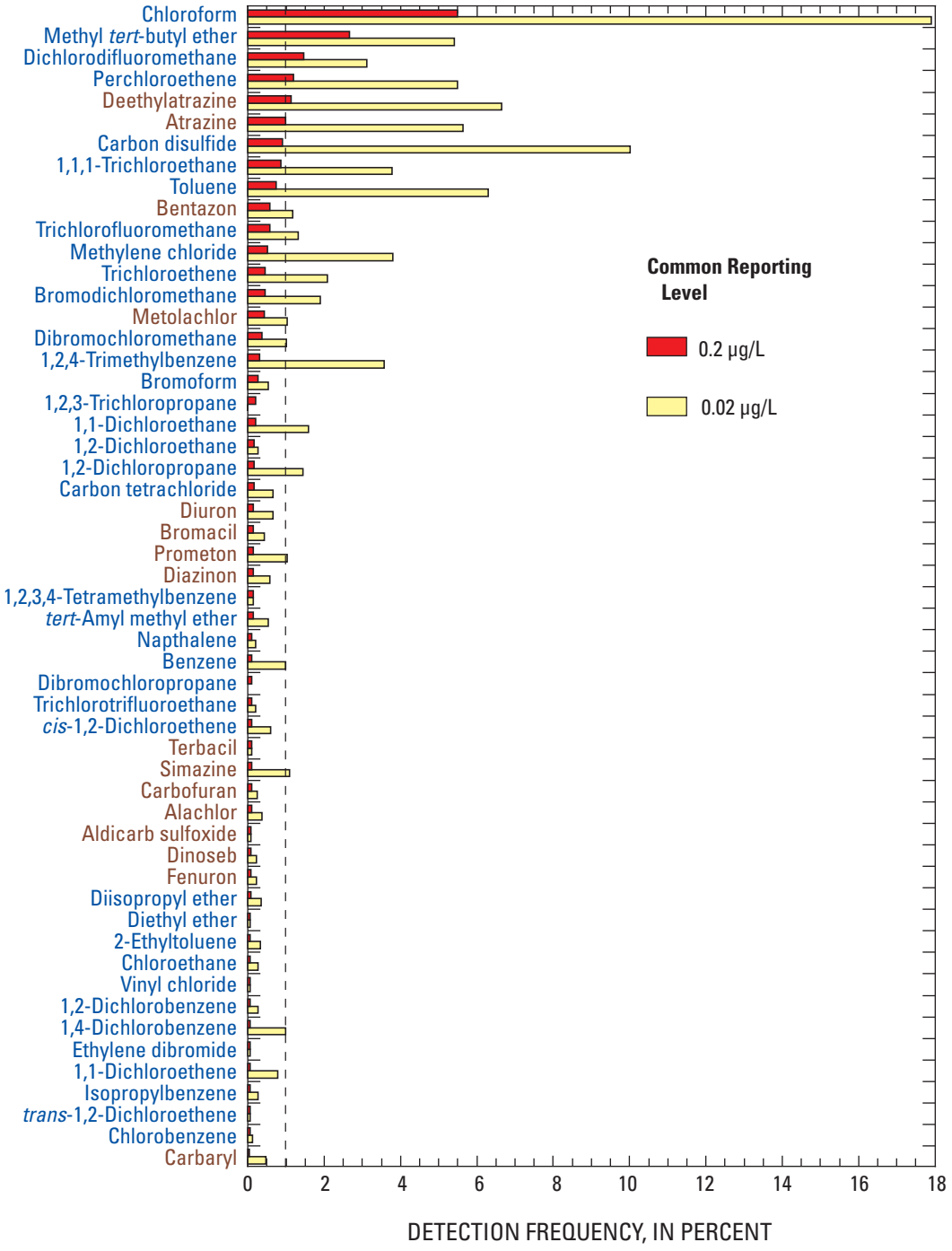


Figure 23. Detection frequency for frequently occurring organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. Detection frequencies are shown relative to common reporting levels of 0.2 and 0.02 micrograms per liter (µg/L); all compounds with detections above the 0.2 µg/L common reporting level are shown. Names of pesticides are shown in brown, and names of volatile organic compounds are shown in blue. Detection frequencies for toluene and 1,2,4-trimethylbenzene were evaluated at an assessment level of 0.3 and 0.05 µg/L, respectively, in order to limit the estimated probability of false detections due to random sample contamination to less than 1 percent, and thus are likely to underestimate the actual occurrence at or greater than 0.02 µg/L.

wells. VOCs were detected in more wells than pesticides at all common reporting levels (fig. 24). The frequency of detection of organic compounds in the sampled domestic wells is consistent with previous studies of low-level concentrations of organic compounds in ground water (Shapiro and others, 2004; Plummer and others, 2008) and of detection frequencies of pesticides and VOCs from all well types sampled for the NAWQA Program (Gilliom and others, 2006; Zogorski and others, 2006). Geographic patterns of occurrence or patterns among principal aquifers were not apparent for organic compounds overall (figs. 2 and 25; Appendix 7).

The most frequently detected organic compounds included both pesticides and VOCs (fig. 23). Compounds detected in 1 percent or more of wells above the common reporting level of 0.2 µg/L were chloroform, a trihalomethane or disinfection byproduct; the gasoline oxygenate methyl *tert*-butyl ether (MTBE); dichlorodifluoromethane, a refrigerant; perchloroethene, a solvent; and the agricultural herbicide atrazine and its degradate deethylatrazine. These compounds were detected in 1.13 to 5.49 percent of wells at concentrations above 0.2 µg/L. Using a lower common reporting level of 0.02 µg/L, these six compounds were still among the most commonly detected but at higher detection frequencies, which ranged from 3.13 percent to 17.9 percent (fig. 23). At the lower common reporting level, many other compounds also were detected in 1 percent or more of wells. These included additional gasoline hydrocarbons (1,2,4-trimethylbenzene and toluene), additional solvents (1,1,1-trichloroethane, methylene chloride, trichloroethene, and 1,1-dichloroethane), additional herbicides (simazine, bentazon, prometon, and metolachlor), a fumigant (1,2-dichloropropane), another refrigerant (trichlorofluoromethane), VOCs used in organic synthesis (chloromethane, carbon disulfide, and iodomethane) and additional disinfection byproducts (bromodichloromethane and dibromochloromethane). Detection frequencies for all compounds are given in Appendix 7. These results indicate that a wide variety of organic compounds, encompassing many uses, can be found in domestic wells.

Concentrations of organic compounds at concentrations of potential concern for human health were rarely present in samples from the domestic wells in this study. Four VOCs and one pesticide—dibromochloropropane (DBCP, a fumigant), ethylene dibromide, perchloroethene, trichloroethene, and dinoseb—were present in concentrations greater than MCLs, and two pesticides—diazinon and dieldrin—were present in concentrations greater than HBSLs. Each compound was present in these concentrations in less than 1 percent of wells (table 9). Samples from 17 wells, or 0.80 percent of the sampled domestic wells, had concentrations of one or more organic compounds greater than MCLs or HBSLs (fig. 25C; 0.33 percent greater than MCLs and 0.47 percent greater than HBSLs). Ten additional compounds occurred in concentrations less than, but greater than one-tenth of, an MCL (9 compounds) or HBSL (1 compound). These included the pesticides alachlor, atrazine, and diuron and the VOCs benzene, chloroform, 1,2-dichloroethane, 1,1-dichloroethene, 1,2-dichloropropane, methylene chloride, and vinyl chloride; each compound was present in less than 1 percent of wells at these concentrations (table 9). Samples from 63 wells, or 2.95 percent, contained compounds with concentrations greater than one-tenth of MCLs or HBSLs (2.34 percent of wells for compounds with MCLs and 0.66 percent of wells for compounds with HBSLs). Concentrations greater than one-tenth of benchmarks may be of interest for prioritizing further study or increased monitoring.

Although the various pesticides and VOCs measured in this study have many different sources and transport characteristics in ground water, they all originate from anthropogenic sources (though a few also have natural sources). Thus, their occurrence in the sampled domestic wells was associated with several factors that describe human influence or aquifer vulnerability. Several characteristics (fig. 3) indicative of the proximity of ground water in the wells to land surface were compared for wells in which organic compounds were and were not detected. Wells with detections of organic compounds at any concentration were

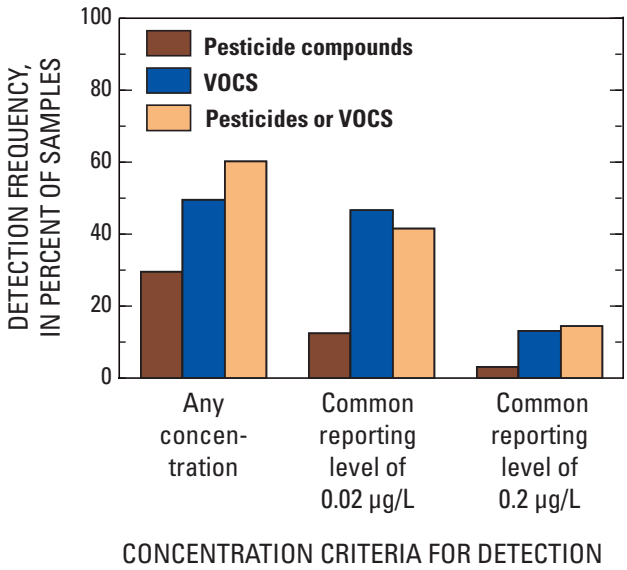


Figure 24. Percentage of samples in which one or more organic compounds were detected, at any concentration and at common reporting levels of 0.02 and 0.2 micrograms per liter (µg/L), for domestic wells sampled for the NAWQA Program, 1991–2004, in aquifer studies. A common reporting level is a concentration above which a measured concentration is considered a detection. Total number of wells for pesticides, 2,126 wells for all detection criteria; for volatile organic compounds, 1,957 wells for any concentration and for 0.2 µg/L, and 1,538 wells for 0.02 µg/L; and for pesticides and VOCs, 2,134 wells for any detection and for 0.2 µg/L, and 2,132 wells for 0.02 µg/L.

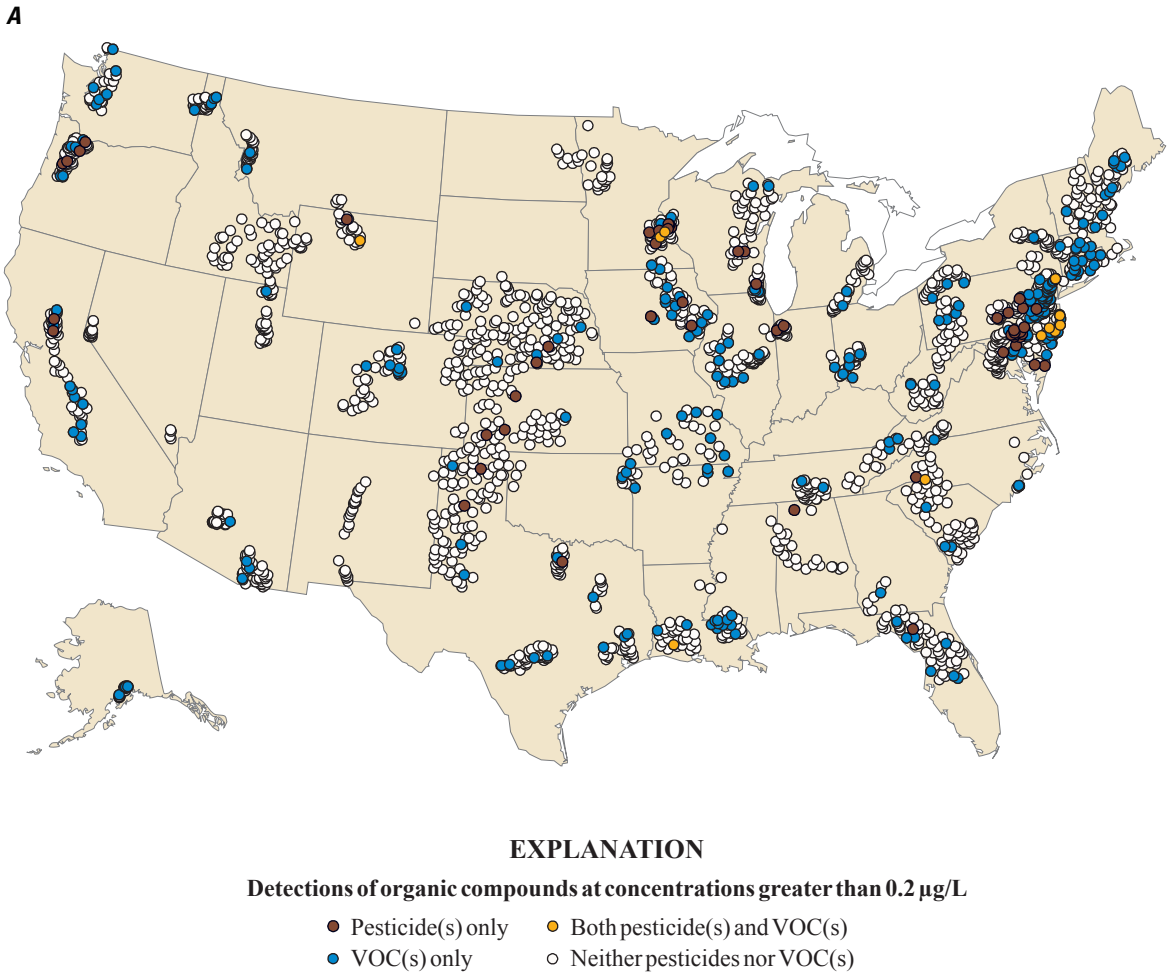


Figure 25A. Geographic distribution of organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, at *(A)* detections above a common reporting level of 0.2 microgram per liter (µg/L), *(B)* detections above a common reporting level of 0.02 µg/L, and *(C)* concentrations greater than human-health benchmarks. VOCs, volatile organic compounds.

not as deep and had open intervals that were not as far below land surface as those of wells in which no organic compounds were detected (Mann-Whitney test, *p* values less than 0.0001); these associations also were significant for pesticides and VOCs separately (except for VOCs and well depth). Average population density in the area surrounding the wells during 1990–2000 was greater for wells with detections of pesticides, VOCs, or any organic compound that for wells with no detections of any organic compounds (Mann-Whitney tests, *p* values less than 0.001). The areas surrounding the wells with pesticide detections consisted of less undeveloped land and more agricultural land than those without pesticide detections (Mann-Whitney test, *p* values less than 0.0001). The areas surrounding the wells with VOC detections consisted of greater amounts of urban (residential or commercial) land than those without VOC detections (Mann-Whitney test, *p* value less than 0.0001). The effects of land use also were apparent from the relatively high frequencies of detections of pesticides in domestic wells in NAWQA agricultural land-use studies (64 percent), which was more than twice as frequent as in domestic wells from NAWQA aquifer studies (29 percent).

The occurrence of organic compounds, particularly at concentrations approaching levels of potential concern for human health, also may be associated with relatively high concentrations of nitrate in some of the domestic wells sampled in the present study. The presence of nitrate, which at elevated concentrations (greater than 1 mg/L as N) typically results from anthropogenic sources, was widespread and, like organic compounds, was associated with developed land; concurrent sources may have included wastewater disposal and the use of fertilizer and pesticides together. Median concentrations of nitrate, 3.7 mg/L as N, in wells with organic compounds

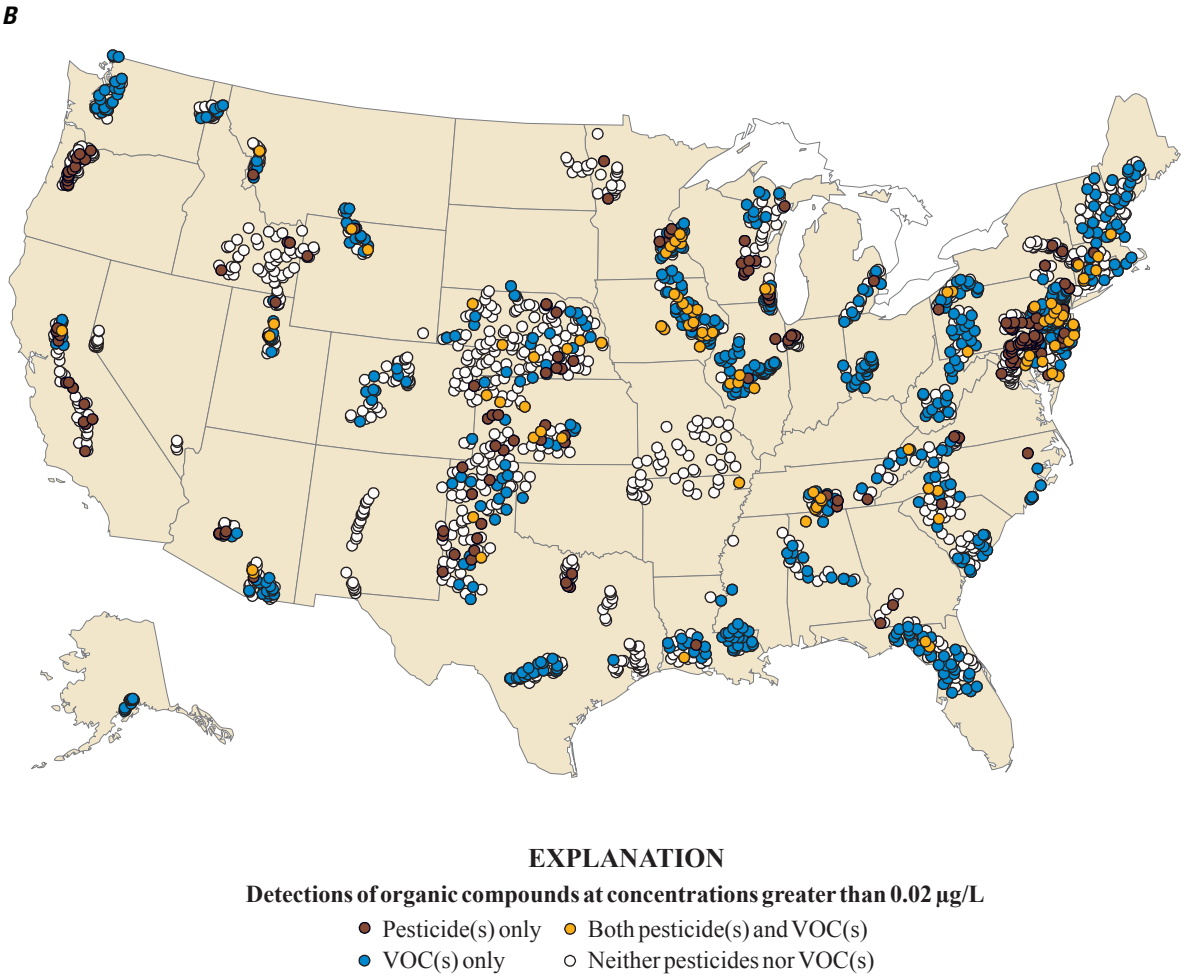


Figure 25B. Geographic distribution of organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, at *(A)* detections above a common reporting level of 0.2 microgram per liter (µg/L), *(B)* detections above a common reporting level of 0.02 µg/L, and *(C)* concentrations greater than human-health benchmarks. VOCs, volatile organic compounds.—Continued

at concentrations greater than one-tenth of benchmarks were significantly higher than concentrations of nitrate in wells with organic compounds at lower concentrations or not detected (0.52 mg/L as N, p value < 0.0001, Mann-Whitney test). The differences in concentrations of nitrate among wells also were apparent when pesticides and VOCs were considered separately (fig. 26). Nitrate concentrations also were higher in all wells in which organic compounds were detected at any concentration (median 0.72 mg/L as N, including those at concentrations greater than one-tenth of benchmarks and below benchmarks) than in wells without detectable organic compounds (median 0.34 mg/L as N). Similar patterns were apparent in the 424 domestic wells sampled for the NAWQA Program in agricultural land-use studies (fig. 1). Nitrate concentrations were higher overall but were significantly greater in wells with organic compounds at concentrations greater than one-tenth of benchmarks (11 mg/L as N) than in wells in which organic compounds were not present at these levels (3.9 mg/L as N). Although nitrate concentrations alone would not be a strong predictor of the presence of organic compounds—only 4.6 percent of wells in aquifer studies with nitrate concentrations greater than 1 mg/L as N had organic compounds at concentrations greater than one-tenth of benchmarks—the tendency for organic compounds to be associated with relatively high concentrations of nitrate suggests that, in some cases, nitrate concentrations may be a useful screening tool for the presence of organic compounds at concentrations potentially of concern for human health.

Atrazine is an agricultural herbicide used primarily on corn and soybeans. It also is used to control vegetation in non-agricultural areas (U.S. Environmental Protection Agency, 1990a; Gilliom and others, 2006). Atrazine was the most

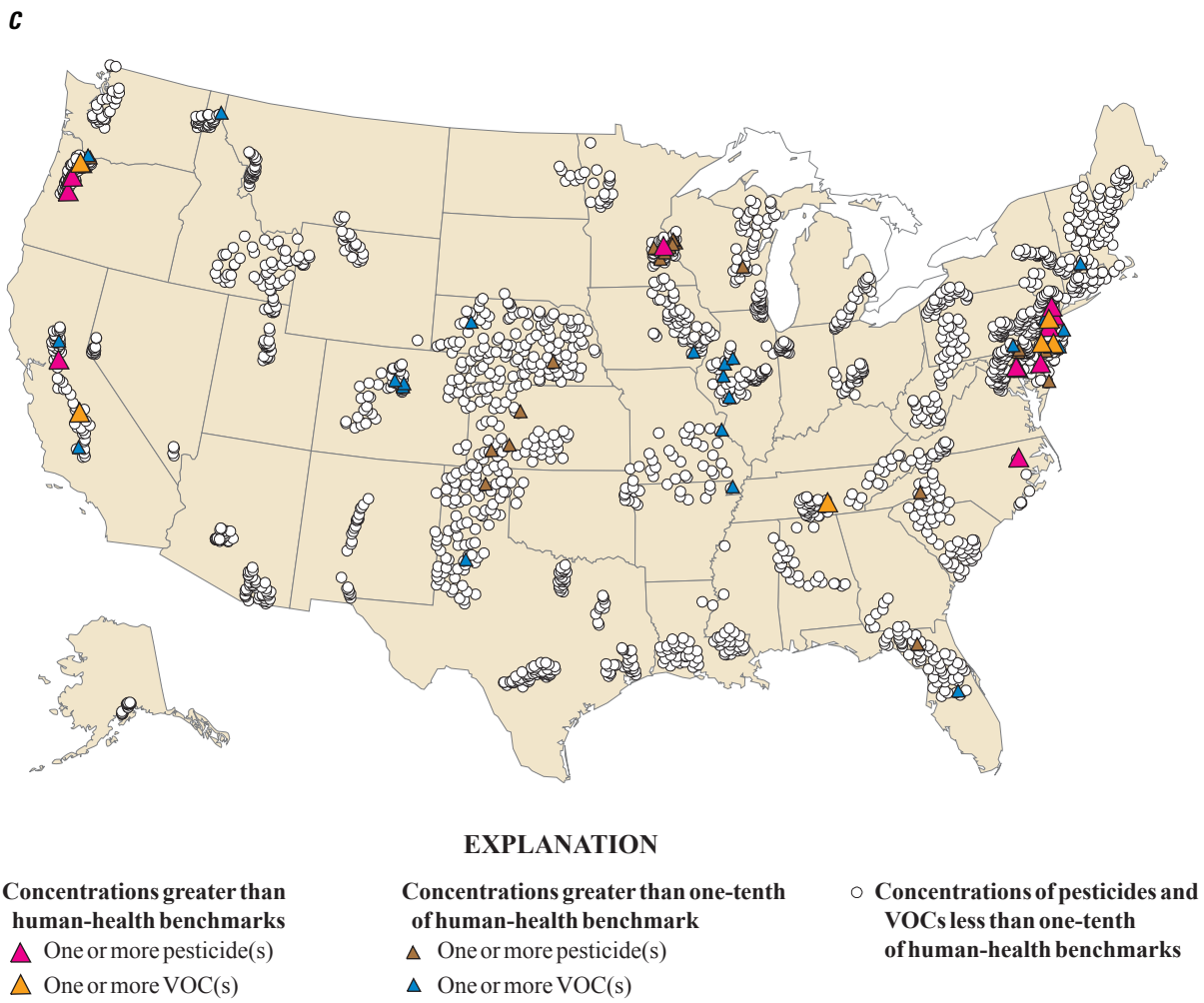


Figure 25C. Geographic distribution of organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, at *(A)* detections above a common reporting level of 0.2 microgram per liter (µg/L), *(B)* detections above a common reporting level of 0.02 µg/L, and *(C)* concentrations greater than human-health benchmarks. VOCs, volatile organic compounds.—Continued

heavily applied agricultural pesticide in the United States in recent years. It was used most intensively in the Midwest but also was used at various rates throughout the eastern half of the United States and in scattered areas of the West (Gilliom and others, 2006). Atrazine is relatively persistent in the environment, compared to other heavily used pesticides, and is mobile in water. Atrazine and its degradate deethylatrazine were the most frequently detected pesticides in the domestic wells sampled in this study, and were the fifth and sixth most frequently detected organic compounds overall (fig. 23). At detection limits as low as 0.003 to 0.004 µg/L, atrazine and deethylatrazine were detected in 15.1 and 17.9 percent of sampled wells, respectively. At higher common reporting levels of 0.02 and 0.2 µg/L, each was detected in about 6 percent (0.02 µg/L) and in about 1 percent (0.2 µg/L) of wells, respectively. Nearly all concentrations (98 percent) were less than 1 µg/L (fig. 22). The USEPA MCL for atrazine is 3 µg/L. No measured concentration of atrazine was greater than 3 µg/L, but concentrations were greater than 0.3 µg/L (one-tenth of the MCL) in 0.85 percent of all sampled wells.

Geographically, atrazine and deethylatrazine were detected in wells throughout the United States (fig. 27), but detections were more frequent in wells in areas of agricultural and urban land use. Wells in predominantly agricultural, urban, or mixed land-use areas (table 8) that were sampled for aquifer studies had detection frequencies for atrazine and deethlyatrazine (9.9 to 26 percent) that were 2 to 4 times higher than detection frequencies (5.2 to 7 percent) for wells in areas of undeveloped land (table 8). In wells sampled for NAWQA studies targeted at agricultural areas (fig. 1, wells not

Table 9. Comparison of concentrations of organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, with human-health benchmarks for drinking water.

[MCLs are U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Levels for public water supplies; HBSLs are Health-Based Screening Levels developed by the U.S. Geological Survey using USEPA toxicity data and methods (Toccalino and Norman, 2006); µg/L, microgram per liter. Only those compounds with concentrations greater than benchmarks or greater than one-tenth of benchmarks are shown]

Organic compound	Human-health benchmark		Wells with concentrations greater than human-health benchmarks or greater than one-tenth of benchmarks			
			Human-health benchmark		One-tenth of human-health benchmark	
	Value (µg/L)	Type	Number of wells	Percent of wells	Number of wells	Percent of wells
Pesticides						
Alachlor	2	MCL	0	0.00	2	0.09
Atrazine	3	MCL	0	0.00	18	0.85
Diazinon	1	HBSL	1	0.05	3	0.14
Dieldrin	[1]0.002	HBSL	9	0.43	9	0.43
Dinoseb	7	MCL	1	0.07	1	0.07
Diuron	[1]2	HBSL	0	0.00	2	0.15
Volatile organic compounds						
Benzene	5	MCL	0	0.00	1	0.05
Chloroform	[2]80	MCL	0	0.00	3	0.15
Dibromochloropropane (DBCP)	0.2	MCL	1	0.05	1	0.05
1,2-Dichloroethane	5	MCL	0	0.00	2	0.10
1,1-Dichloroethene	7	MCL	0	0.00	1	0.05
1,2-Dichloropropane	5	MCL	0	0.00	2	0.10
Ethylene dibromide	0.1	MCL	2	0.10	2	0.10
Methylene chloride	5	MCL	0	0.00	5	0.26
Perchloroethene	5	MCL	1	0.05	10	0.52
Trichloroethene	5	MCL	2	0.10	6	0.31
Vinyl chloride	2	MCL	0	0.00	1	0.05

[1]Value is low end of range, associated with 10^{-6} cancer risk (Toccalino and others, 2006).

[2]MCL is for sum of four trihalomethanes.

shown in fig. 27), atrazine and deethylatrazine were detected even more frequently, in about 50 percent of the sampled wells (Appendix 7B); concentrations of atrazine greater than 0.3 µg/L were present in 9.2 percent of the agricultural land-use wells.

Several studies of pesticides in ground water investigated the distribution of individual pesticides such as atrazine; these studies used data from all well types sampled for the NAWQA Program. The areas where, and rates at which, the compounds were used were found to greatly affect the occurrence and concentration of the compounds (Kolpin and others, 1998; Gilliom and others, 2006). For example, atrazine, metalachlor, and acetochlor were detected most frequently in areas of corn and soybean agriculture; molinate, an insecticide, was detected most frequently in areas of rice agriculture; and 2,4-D and chlorpyrifos were detected most frequently in areas of wheat and alfalfa agriculture. Detection frequencies of individual pesticides also were found to be related to their water solubility, tendency to sorb onto aquifer materials, and time needed for degradation (Kolpin and others, 1998; Barbash and others, 1999, 2001; Gilliom and others, 2006). For example, metolachlor degrades more quickly in soils than atrazine and was detected less frequently in areas of corn and soybean agriculture, although both compounds were used in about the same amounts in these areas. Metolachlor also was detected much less frequently than atrazine in the domestic wells included in the present study (fig. 23 and Appendix 7). A detailed investigation at the national scale found that soil permeability, artificial subsurface drainage (tile drains), and irrigated agriculture

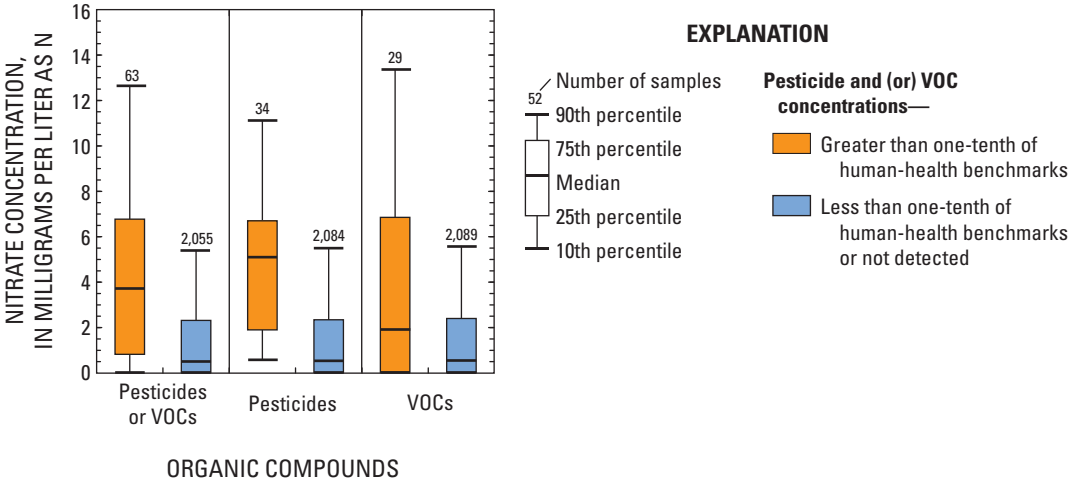


Figure 26. Concentrations of nitrate and organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. VOC, volatile organic compound.

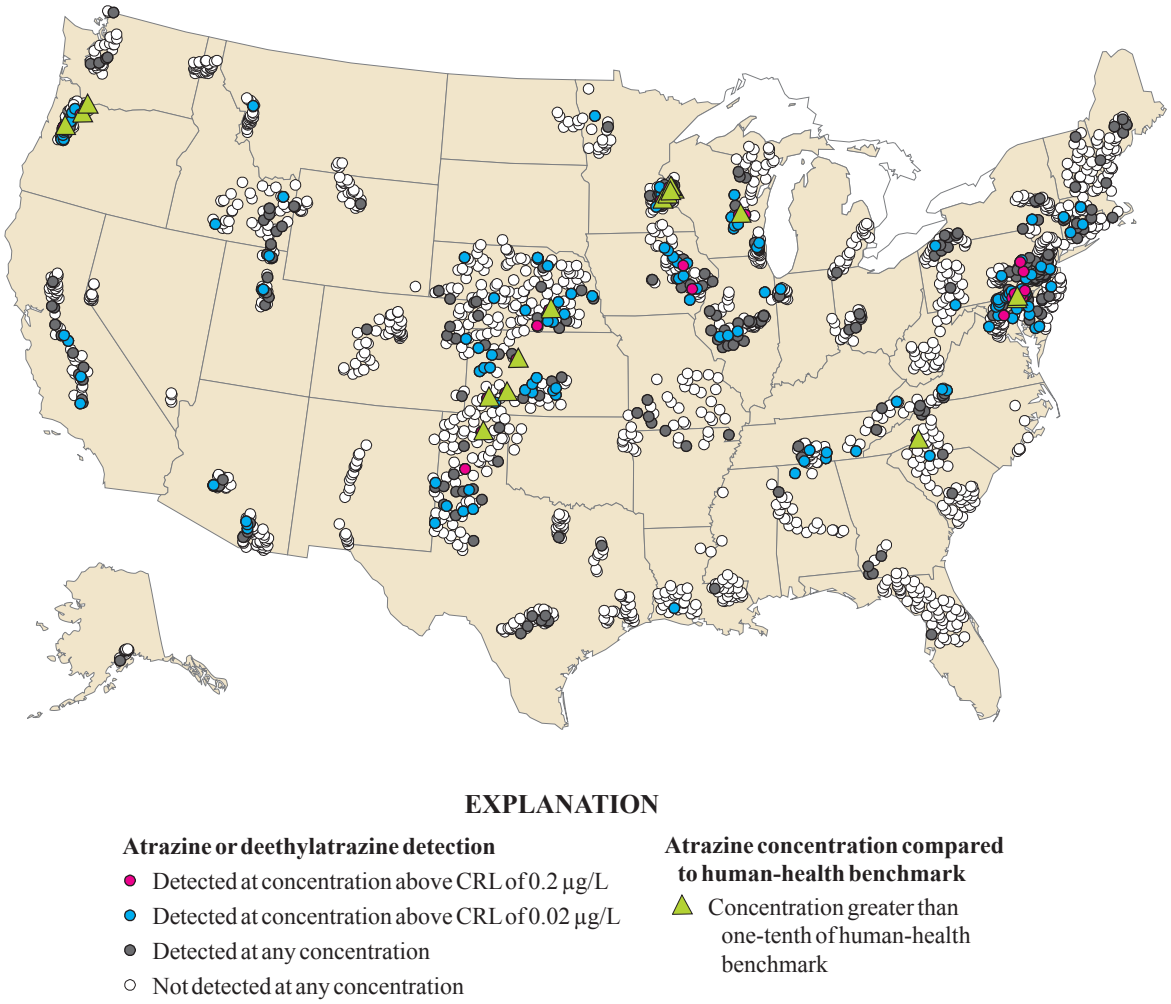


Figure 27. Geographic distribution of atrazine and deethylatrazine in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. CRL, common reporting level; µg/L, microgram per liter.

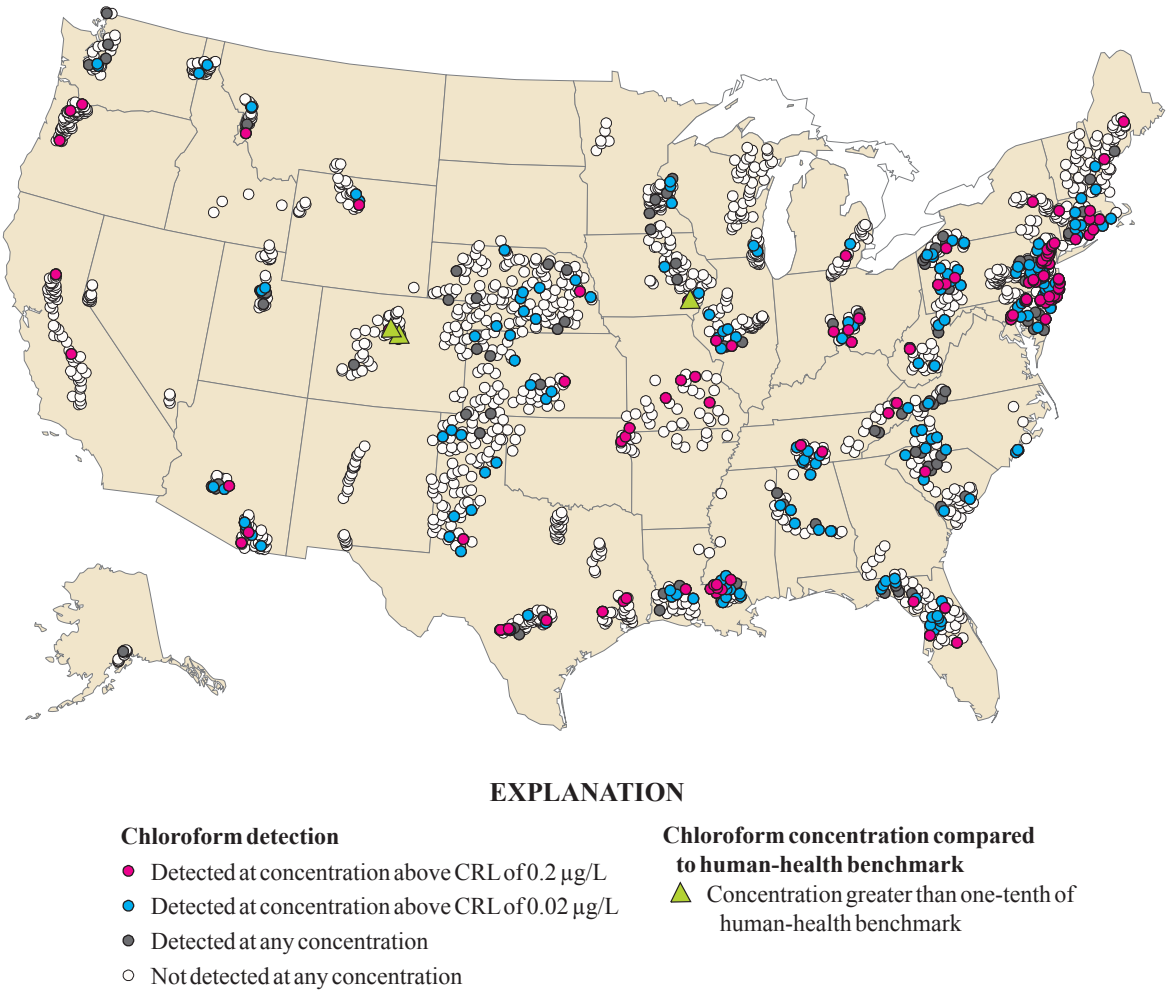


Figure 28. Geographic distribution of chloroform in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. CRL, common reporting level; µg/L, microgram per liter.

were important factors affecting the distribution of atrazine in wells (Kolpin, 1997).

Chloroform was the most frequently detected organic compound in the domestic wells sampled in this study (fig. 23). Chloroform, along with bromodichloromethane, dibromochloromethane, and bromoform, is a byproduct of the disinfection of water with chlorine (Zogorski and others, 2006); chloroform occurs naturally as well. Chlorine and organic material in the water react to form these trihalomethane compounds. Chloroform is used in industry and in the synthesis of other organic compounds. It may be present in ground water as a result of infiltration of treated wastewater or chlorinated, publicly supplied drinking water; shock chlorination of domestic wells with chlorine bleach; the release of chlorine-containing products through septic tanks; or inadvertent spills (Ivahnenko and Zogorski, 2006). Chloroform was detected in about 20 percent of the wells at any concentration and at concentrations greater than a common reporting level of 0.02 µg/L; at concentrations greater than a common reporting level of 0.2 µg/L, it was detected in 5.5 percent of wells. Chloroform concentrations, however, rarely approached levels of concern for human health (fig. 22). Concentrations of chloroform either alone, or combined with concentrations of other trihalomethanes, were greater than one-tenth of the USEPA MCL of 80 µg/L for all trihalomethanes in only three wells (0.15 percent). Geographically, chloroform was detected throughout the United States (fig. 28). The other trihalomethanes—bromodichloromethane, dibromochloromethane, and bromoform—were detected much less frequently and at lower concentrations than chloroform; these were detected in less than 2 percent of wells at any concentration and in less than 0.5 percent of wells at concentrations greater than 0.2 µg/L (Appendix 5). Bromodichloromethane,

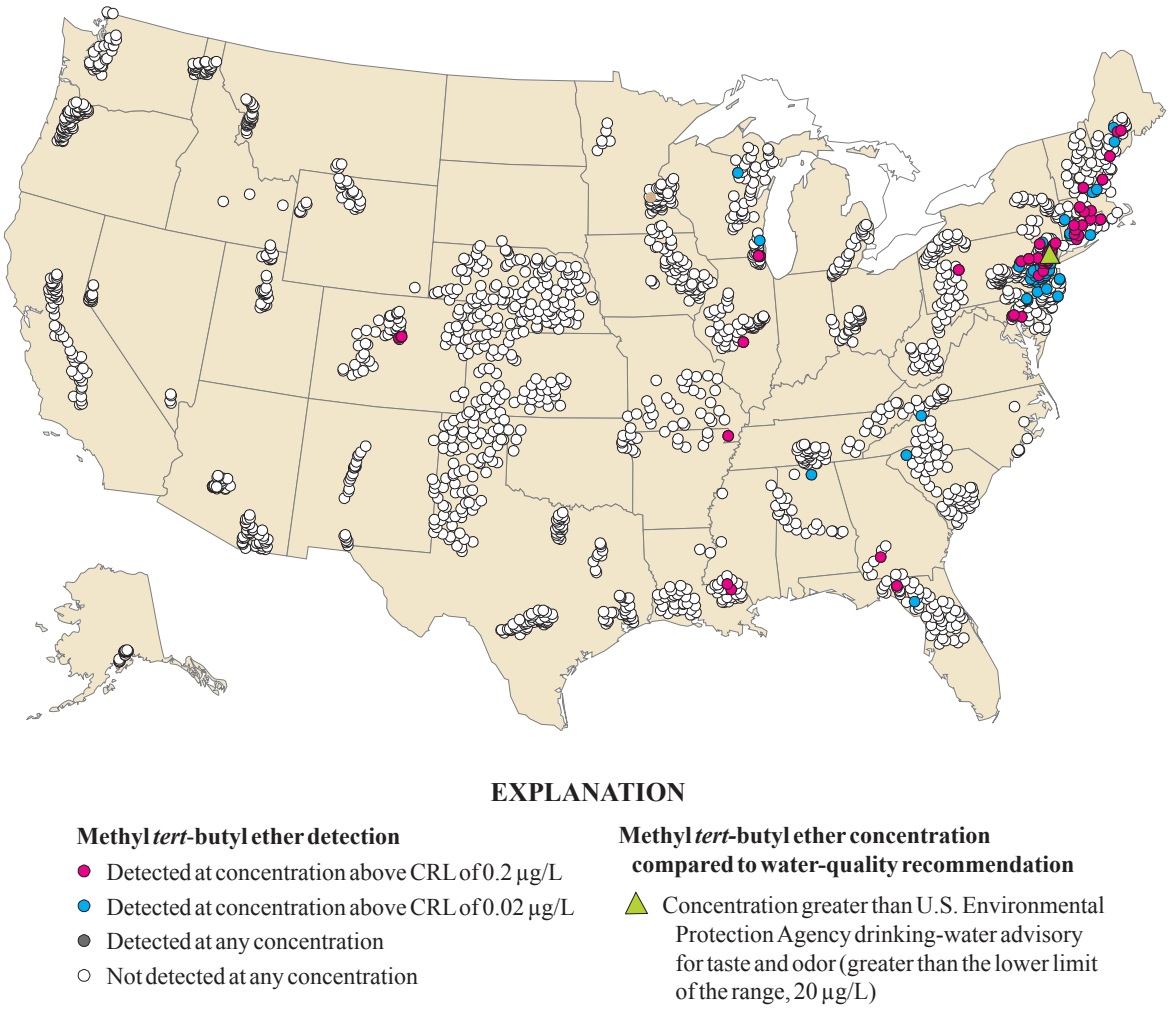


Figure 29. Geographic distribution of methyl *tert*-butyl ether (MTBE) in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. CRL, common reporting level; µg/L, microgram per liter.

dibromochloromethane, and bromoform are formed at lower concentrations than chloroform during water chlorination and are produced in much lower quantities in industry than chloroform (Zogorski and others, 2006).

MTBE is an oxygen-containing compound (oxygenate) that has been added to gasoline to improve combustion, reduce emissions, and increase octane. Oxygenated gasoline was required in the late 1990s in some parts of the United States where air-quality standards were not met; MTBE was the most common oxygenate additive (Moran and others, 2005; Zogorski and others, 2006). MTBE is more soluble, less likely to sorb to aquifer materials, and less readily degraded than most other components of gasoline and, thus, is relatively mobile in ground water. MTBE was detected in about 5 percent of wells at any concentration and at concentrations greater than the common reporting level of 0.02 µg/L; at concentrations greater than 0.2 µg/L, it was detected in 2.7 percent of wells. It was the second most frequently detected organic compound at concentrations greater than 0.2 µg/L (fig. 23). MTBE detections were concentrated in the Northeast and mid-Atlantic regions (fig. 29), areas of dense population and high use of MTBE in gasoline. There is no MCL or HBSL for MTBE, but the USEPA Drinking Water Advisory recommends that concentrations not exceed 20 to 40 µg/L to avoid unpleasant odor or taste (U.S. Environmental Protection Agency, 1997b). Concentrations in only one well were greater than the lower limit of this range (figs. 22 and 29). MTBE was detected much more frequently than other gasoline oxygenates (for example, *tert*-Amyl methyl ether or ethyl *tert*-butyl ether, Appendix 4), which were detected in less than 0.5 percent of wells at all reporting levels (Appendix 7) and were less commonly used in gasoline

(Moran and others, 2005). MTBE also was more frequently detected than any gasoline hydrocarbon, such as benzene, toluene, ethylbenzene, or xylenes ("BTEX" compounds). BTEX compounds were detected in less than 2 percent of wells at all reporting levels (Appendix 7). In studies of MTBE in ground water that included domestic wells and wells of other types sampled for the NAWQA Program, MTBE occurrence was primarily related to population density, MTBE use in gasoline, and recharge; soil permeability, aquifer consolidation, and the number of leaking underground gasoline storage tanks also were related but less strongly than the other three factors (Ayotte and others, 2005; Moran and others, 2005). At a local scale, MTBE occurrence also has been shown to be related to the proximity of gasoline stations (Lince and others, 2001).

Solvents were among the most frequently detected organic compounds in the domestic wells sampled in this study. Solvents have many uses in industry, business, and the home and can enter ground water through accidental spills, improper disposal, wastewater discharge, or septic-tank leachate. Perchloroethene, 1,1,1-trichloroethane, methylene chloride, trichloroethene, and chloromethane were the most frequently detected solvents. These solvents were detected in about 2.5 to 8 percent of wells at any concentration and at concentrations greater than the common reporting level of 0.02 µg/L; at concentrations greater than 0.2 µg/L, they were detected in 1.2 percent of wells or less (fig. 23 and Appendix 7). Detections occurred throughout the United States. Concentrations were greater than MCLs or HBSLs (MCLs of 5 µg/L for perchloroethene and trichloroethene) in only three wells. In 21 wells, or 1 percent of all wells, concentrations were greater than one-tenth of MCLs or HBSLs (table 9 and fig. 22). In an analysis of four of these five solvents in ground water sampled for the NAWQA Program, population density and dissolved oxygen concentrations were important factors related to their occurrence. Dissolved oxygen concentrations were relevant because the compounds can be degraded under anoxic conditions. Other variables that were less strongly associated with the occurrence of the four solvents were the sand content of the soil in the area surrounding the well, the depth to the top of the screened interval, and the number of hazardous waste sites or septic tanks near the well (Moran and others, 2007).

Fecal Indicator Bacteria

Fecal indicator bacteria live in the intestines of warm-blooded animals; their presence in water can signal fecal or sewage contamination (World Health Organization, 2004). These bacteria typically are not harmful but are more easily monitored than the pathogenic bacteria or viruses that also can occur in feces and may cause illness. Fecal indicator bacteria may be introduced into domestic wells from surface sources near the wellhead, especially if the well is not sealed or its casing is not intact. Indicator bacteria also may be transported through the subsurface from sources such as septic tanks or recharge contaminated with livestock wastes.

Fecal indictor bacteria measured in the domestic wells sampled in this study were total coliform bacteria and *Escherichia coli* (*E. coli*). Coliform bacteria are a broad group that can live in water and soils and may be present in the environment from sources other than fecal or sewage contamination. *E. coli* is a member of the total coliform group of bacteria that is almost always found only in feces, and consequently is a specific indicator of fecal or sewage contamination (World Health Organization, 2004; Embrey and Runkle, 2006). *E. coli* is the dominant species of the fecal coliform group. Federal and many state drinking-water standards use total coliform bacteria and fecal coliform bacteria and (or) *E. coli* bacteria as indicators of microbiological water quality. USEPA drinking-water standards for public-supply systems require sampling for total coliform bacteria at frequencies that differ with the size of the system. No more than 5 percent of samples per month may have detections of total coliform bacteria (U.S. Environmental Protection Agency, 2006a). Repeat sampling and analysis for fecal coliform or *E. coli* are required when total coliform bacteria are detected; no fecal coliform or *E. coli* bacteria are allowed under the USEPA MCL.

Total coliform bacteria were measured in samples from 397 wells, and *E. coli* were measured in samples from 378 wells in aquifer studies (table 6); the wells were completed in 15 principal aquifers (Appendix 5–1). Fecal indicator bacteria are measured as the number of colony-forming units in 100-milliliter water samples. A complete description of the microbiological sampling program and results for NAWQA ground-water studies, including the data used in the present study, was provided by Embrey and Runkle (2006). Total coliform and *E. coli* bacteria also were measured in samples from 86 and 55 wells, respectively, in agricultural land-use studies; these wells were located in two carbonate-rock aquifers in the Appalachian region (Appendix 5–2).

Total coliform bacteria were detected in 33.5 percent of the domestic wells sampled wells in aquifer studies, and *E. coli* bacteria were detected in 7.9 percent of the wells. Geographically, indicator bacteria were detected in wells from each of the principal aquifers from which wells were sampled for bacteria (figs. 30 and 31). Detections were more frequent in samples from the carbonate- and crystalline-rock aquifers than in those from other aquifers (fig. 31), consistent with findings of Embrey and Runkle (2006) for all well types. Total coliform bacteria were detected in more than one-half of the sampled wells in several aquifers, including the Central Valley basin-fill aquifer, the North Atlantic coastal plain aquifer, the Valley and Ridge sandstone aquifer, and the Piedmont crystalline-rock aquifer. Wells in which total coliform and *E. coli* bacteria were detected tended to have open intervals that were closer to land surface than the open intervals of wells in which the bacteria were not detected (Mann Whitney test, p values equal to 0.010 and 0.005); wells with detections of total coliform bacteria also were older and had higher percentages of agricultural land in surrounding areas (p values

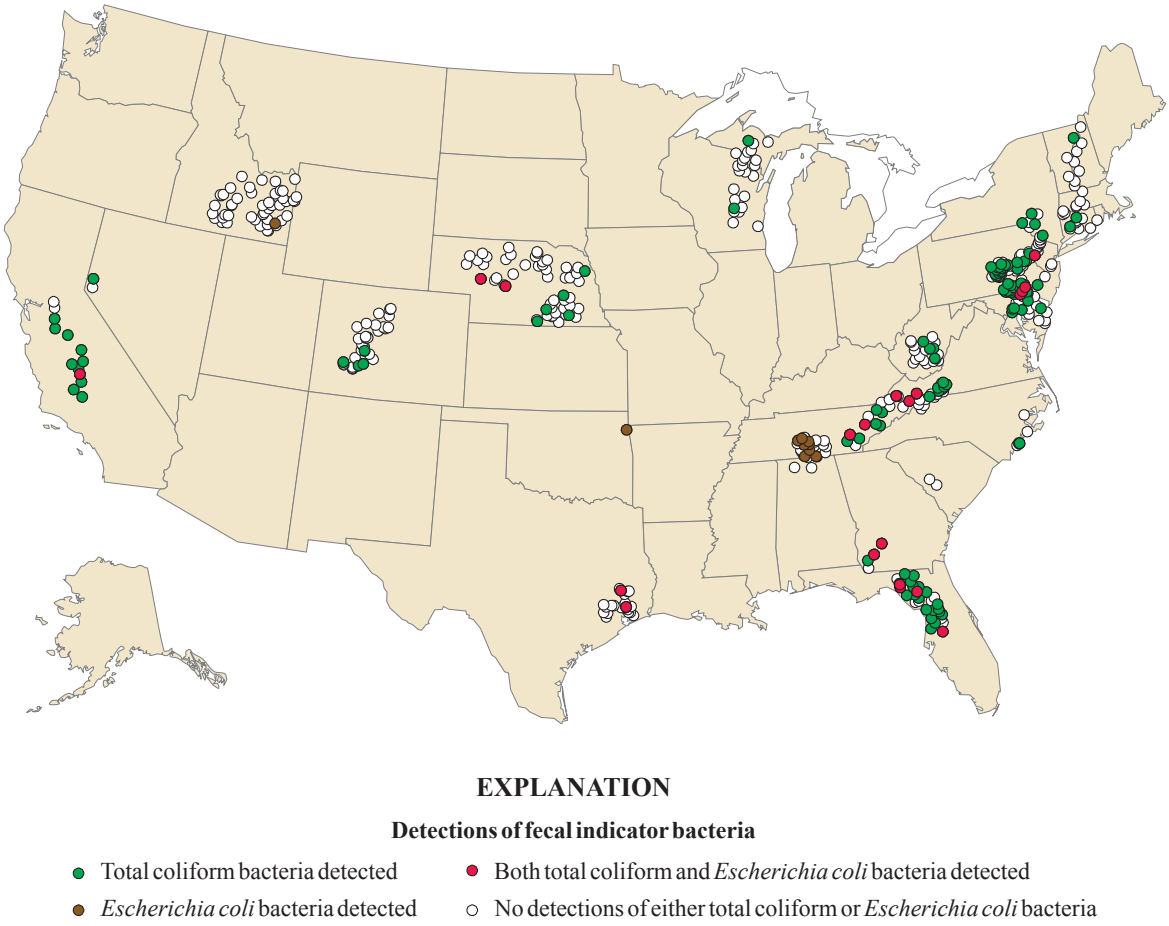


Figure 30. Geographic distribution of fecal indicator bacteria detected in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004.

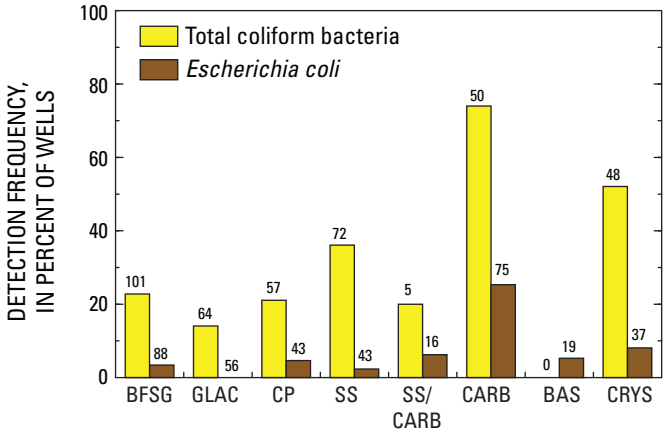


Figure 31. Fecal indicator bacteria detected in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004, by aquifer rock type. BFSG, basin-fill and other non-glacial sand and gravel aquifers; GLAC, glacial sand and gravel aquifers; CP, coastal plain aquifers in semi-consolidated sand; SS, sandstone aquifers; SS/CARB, sandstone/carbonate-rock aquifers; CARB, carbonate-rock aquifers; BAS, basaltic-rock aquifers; CRYS, crystalline-rock aquifers. Numbers above bars are numbers of samples.

Table 10. Number and percentage of domestic wells, in a subset of 1,389 domestic wells from the NAWQA Program in aquifer studies, 1991–2004, containing one or more contaminants at concentrations greater than a human-health benchmark or greater than one-tenth of a benchmark.

[MCLs are U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Levels for public water supplies and include action levels for copper and lead; HBSLs are Health-Based Screening Levels developed by the U.S. Geological Survey using USEPA toxicity data and methods (Toccalino and Norman, 2006). Numbers for MCLs, proposed MCLs, and HBSLs do not add up to totals because some wells have concentrations greater than more than one type of benchmark. Data are from 1,389 domestic wells in which major ions, trace elements, nitrate, and organic compounds were measured. pCi/L, picocuries per liter; --, not determined]

Human-health benchmark	Wells with concentrations greater than human-health benchmarks or greater than one-tenth of benchmarks			
	Human-health benchmark		One-tenth of human-health benchmark	
	Number of wells	Percentage of wells	Number of wells	Percentage of wells
MCLs	184	13.2	837	60.3
Proposed MCL				
Higher value of 4,000 pCi/L for radon	59	4.2	--	--
Lower value of 300 pCi/L for radon	902	64.9	--	--
HBSLs	113	8.14	632	45.5
All human-health benchmarks (MCLs, proposed MCLs[1], and HBSLs)	314	22.6	1,304	93.9

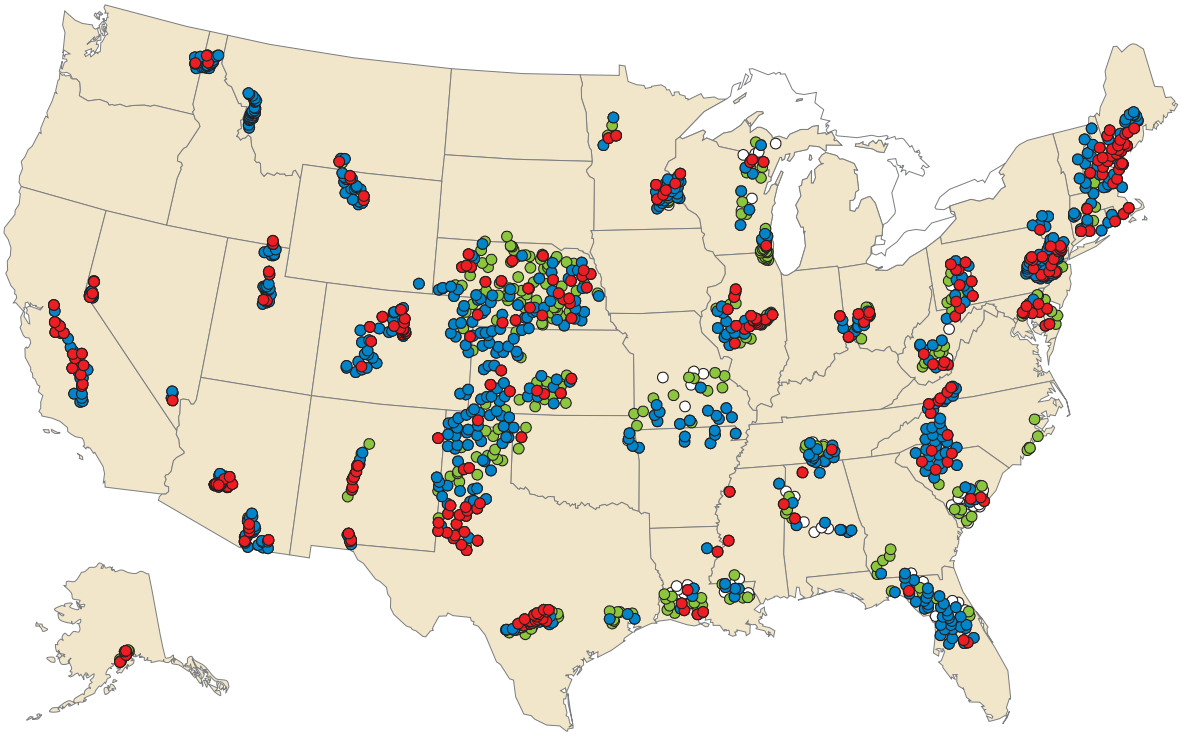
[1]Including radon relative to 4,000 pCi/L for concentrations greater than benchmarks and radon relative to 300 pCi/L for concentrations greater than one-tenth of benchmarks.

less than 0.0001). The effects of land use also were apparent in the detection frequencies of total coliform and *E. coli* bacteria in wells included in the NAWQA agricultural land-use studies, which at 74.4 and 47.3 percent of sampled wells (Appendix 5–2), respectively, were higher than detection frequencies in the wells sampled as part of aquifer studies.

Summary Comparison of Contaminant Concentrations to Human-Health Benchmarks

Concentrations of nearly all contaminants in water from domestic wells sampled in this study, when considered individually, were less than available MCLs and HBSLs in at least 90 percent of wells. Contaminants that occurred most frequently (in more than 1 percent of wells) at concentrations greater than MCLs or HBSLs were: radon (in 64.6 and 4.36 percent of wells for the lower and higher proposed MCLs of 300 and 4,000 pCi/L, respectively); nitrate (4.44 percent, MCL of 10 mg/L as N); the trace elements arsenic (6.75 percent, MCL of 10 µg/L), boron (1.30 percent, HBSL of 1,000 µg/L), strontium (7.32 percent, HBSL of 4,000 µg/L), manganese (5.22 percent, HBSL of 300 µg/L) and uranium (1.74 percent, MCL of 30 µg/L); fluoride (1.16 percent, MCL of 4 µg/L), gross alpha- (uncorrected) and beta-particle radioactivity (5.29 and 1.87 percent; MCL of 15 pCi/L corrected for radon and uranium and screening level MCL of 50 pCi/L, respectively) (tables 3, 5, and 7). The fecal indicator bacteria, total coliform bacteria and *E. coli*, were detected in 33.5 and 7.9 percent of wells, respectively (table 6). Anthropogenic organic compounds were frequently detected, but were present at concentrations greater than MCLs or HBSLs in only 0.8 percent of wells for all compounds (0.3 percent of wells for MCLs and 0.5 percent of wells for HBSLs). Thus, with the exception of nitrate and fecal indicator bacteria, the contaminants that occurred most frequently at concentrations greater than human-health benchmarks in the sampled domestic wells were naturally occurring.

Collectively, at least one contaminant was present at concentrations greater than MCLs or HBSLs in 22.6 percent of wells, using the higher proposed MCL for radon (table 10). In 19.2 percent of wells, these contaminants were naturally occurring. Relative to specific types of benchmarks, concentrations of at least one contaminant were greater than an MCL (using action levels for copper and lead) or an HBSL in 13.2 and 8.14 percent of wells, respectively (table 10). Nearly all wells (93.9 percent) had at least one contaminant at concentrations greater than one-tenth of benchmarks (using the lower proposed MCL for radon; table 10). These results were based



EXPLANATION

Concentrations of contaminants compared to human-health benchmarks

- At least one contaminant > a human-health benchmark, using 4,000 pCi/L for the radon benchmark
- At least one contaminant > a human-health benchmark, using 300 pCi/L for the radon benchmark
- At least one contaminant > one-tenth of a human-health benchmark
- No contaminant > one-tenth of a human-health benchmark

Figure 32. Geographic distribution of wells with at least one contaminant at concentrations greater than or greater than one-tenth of human-health benchmarks in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. Data are for 1,389 wells in which major ions, trace elements, nutrients, radon, and organic compounds were measured. Human-health benchmarks are given in Appendix 4. >, greater than; pCi/L, picocuries per liter.

on a subset of 1,389 wells from 25 principal aquifers in 45 states in which samples were analyzed for major ions, trace elements, nutrients, radon, and organic compounds (fig. 32). (The entire data set of 2,167 wells could not be used for this analysis primarily because trace elements were measured in only about two-thirds of the wells.) Fecal indicator bacteria, gross alpha- and beta-particle radioactivity, radium, and rarely detected pesticides measured by high-performance liquid chromatography/mass spectrometry (HPLC) were excluded from this comparison because they were analyzed in samples from a limited numbers of wells. Fluoride was excluded from the determination of wells with at least one contaminant at concentrations greater than one-tenth of benchmarks because a fluoride concentration equal to one-tenth of the MCL (0.4 mg/L) is less than the range of concentrations in drinking water recommended for the prevention of tooth decay (U.S. Department of Health and Human Services, 1991; Institute of Medicine, 1997; U.S. Centers for Disease Control and Prevention, Fluoride Recommendations Work Group, 2001). Given the relatively frequent occurrence of fecal indicator bacteria and the benchmark of no bacteria detections, the actual number of wells with concentrations of any contaminant greater than a benchmark likely would have been higher than the percentage values given in table 10 if fecal indicator bacteria and the other excluded contaminants had been included in the summary analysis. Organic compounds for which no

human-health benchmarks were available were detected in many other wells also but typically at concentrations orders of magnitude below the MCLs or HBSLs.

Properties or contaminants affecting the aesthetic or other non-health quality of water were more frequently outside recommended ranges than were contaminants of potential health concern. These properties and contaminants included pH (16.3 percent of wells), chloride (2.13 percent of wells), fluoride (4.04 percent of wells), iron (19.1 percent of wells), manganese (21.3 percent of wells), and total dissolved solids (14.8 percent of wells). About 62 percent of all the sampled wells, mostly in central United States, had water that generally is considered to be "hard." Collectively, about half (48 percent) of the 1,389 wells in which co-occurrence was assessed had one or more property or contaminant at levels outside the recommended ranges for aesthetic or other non-health quality. Undesirable effects of elevated concentrations of these properties and contaminants include scale deposition or corrosion of pipes and plumbing fixtures, staining of laundry or plumbing fixtures, unpleasant water color or taste, and teeth staining. The water samples were collected prior to any in-home treatment systems, however, that may have been in place in some homes to treat these properties and contaminants.

Co-occurrence of Contaminants as Mixtures

Contaminants generally do not occur in isolation in ground water but usually co-occur with other contaminants as mixtures. Analysis of individual contaminants, as presented above, is essential for identifying those of potential concern for human health and for assessing where and why they occur. However, little is known about the potential health effects of most mixtures of contaminants in drinking water. Mixtures of multiple contaminants—even at concentrations below benchmarks—may present potential concerns for human health and warrant investigation.

Contaminants often co-occur as mixtures in domestic wells because well water itself is a mixture of ground water from multiple sources, and each source may be affected by different and multiple contaminants. Sources of water may include recharge from precipitation or irrigation in different types of land use, infiltration of surface water, or inflow from adjacent aquifers. Along the flow paths by which ground water reaches a well, naturally occurring contaminants, such as trace elements, may be contributed by the various minerals that compose the aquifer sediments and rocks. Anthropogenic contaminants may be introduced from a variety of sources, such as wastewater disposal, recharge in agricultural or urban areas, or spills of gasoline or other chemicals. The composition of contaminant mixtures that are present in domestic wells depends on the unique sources and flow paths that affect each well.

Approach for Assessment of Mixtures

Because of the uncertainties about the health effects of contaminant mixtures in drinking water and the potential that some mixtures could have greater effects than the effects of their individual components, the co-occurrences of contaminants that occur individually at concentrations above or approaching their respective human-health benchmarks could be of potential concern for human health. For example, health effects may be additive for contaminants that act by similar mechanisms, and some combinations of contaminants may synergistically interact, resulting in greater than additive effects. However, with few exceptions (for example, the triazine herbicides, as discussed below), there are no benchmarks for mixtures as such. The co-occurrence of multiple contaminants with individual concentrations at greater than one-tenth of benchmarks, thus, was used as a simple indicator to identify mixtures of potential concern. This analysis necessarily included only those contaminants with health benchmarks. In addition, the analysis was expanded to include all detections of anthropogenic organic contaminants because some do not have human-health benchmarks. This expanded approach provides a perspective on the patterns in co-occurrences that may be important as more is learned about the sources and the potential health effects of contaminant mixtures.

The overall occurrence of mixtures was assessed by determining the frequency and geographic distribution of mixtures of various levels of complexity, as represented by the number of co-occurring contaminants. This approach provides a perspective on general patterns of co-occurrence of contaminants in domestic wells.

The composition of mixtures, in terms of specific contaminants, was assessed by evaluating the occurrence of unique mixtures of two or more contaminants. Unique mixtures were determined using the methods of Squillace and others (2002) and J.C. Scott (U.S. Geological Survey, written commun., 2008). Unique mixtures are specific combinations of any two, three, or more contaminants, regardless of the presence of additional contaminants. A single sample can contain many unique mixtures, each of which may pose different health effects. For example, a mixture of three contaminants in a sample, contaminants A, B, and C, contains the unique mixtures AB, AC, BC, and ABC (three unique two-compound mixtures and one three-compound mixture). Each of these unique combinations of contaminants may have different health effects. Evaluation of frequently occurring unique mixtures, particularly of contaminants at individual concentrations that approach or exceed their respective human-health benchmarks, can support prioritization of certain unique mixtures for investigation of potential health effects. Few unique mixtures have been investigated in terms of potential health effects relative to the large number of mixtures to which people may be exposed (National Research Council, 1989; Carpenter and others, 2002).

The occurrence and composition of contaminant mixtures was assessed for the 1,389 domestic wells from aquifer studies in which major ions, trace elements, nutrients, radon, and organic compounds were measured. (Fecal indicator bacteria, gross alpha- and beta-particle radioactivity, radium, and rarely detected pesticides measured by HPLC were not included because they were measured in too few wells, as described previously.) Because the two proposed MCLs for radon differ by an order of magnitude and thus produce substantially different results when compared to concentrations, co-occurrence was evaluated using both low and high benchmark values for radon: radon concentrations were compared to the higher proposed MCL of 4,000 pCi/L for mixtures of contaminants that exceed human-health benchmarks and to the lower proposed MCL of 300 pCi/L for mixtures of contaminants at concentrations greater than one-tenth of benchmarks. Fluoride was excluded from the determination of wells with at least one contaminant at concentrations greater than one-tenth of benchmarks, because fluoride at this level (0.4 mg/L) is less than the range of concentrations in drinking water recommended to prevent tooth decay.

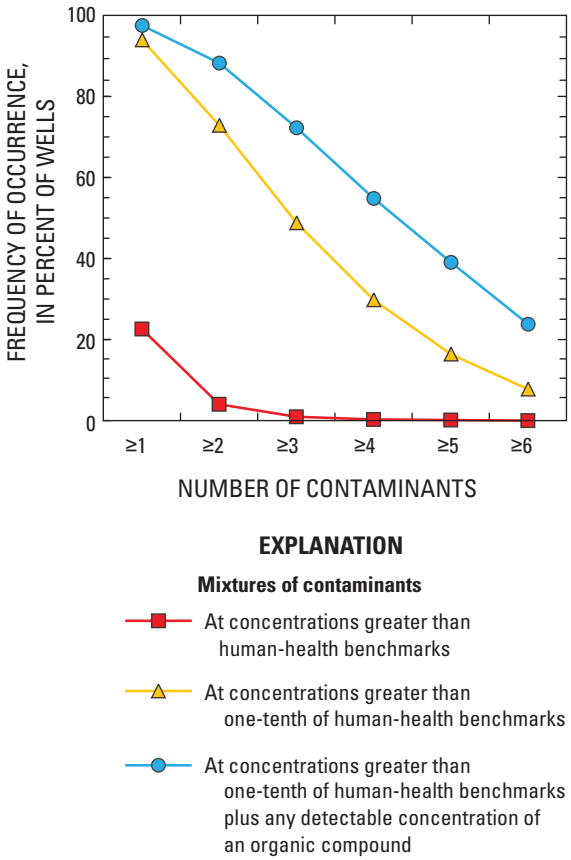


Figure 33. Frequency of occurrence of contaminants in mixtures in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. Data are from 1,389 wells in which major ions, trace elements, nitrate, radon, and organic compounds were measured. Criterion for radon in mixtures of contaminants at concentrations greater than human-health benchmarks is 4,000 picocuries per liter (pCi/L) and criterion for contaminants at concentrations greater than one-tenth of benchmarks is 300 pCi/L. ≥, greater than or equal to.

Occurrence and Distribution of Mixtures

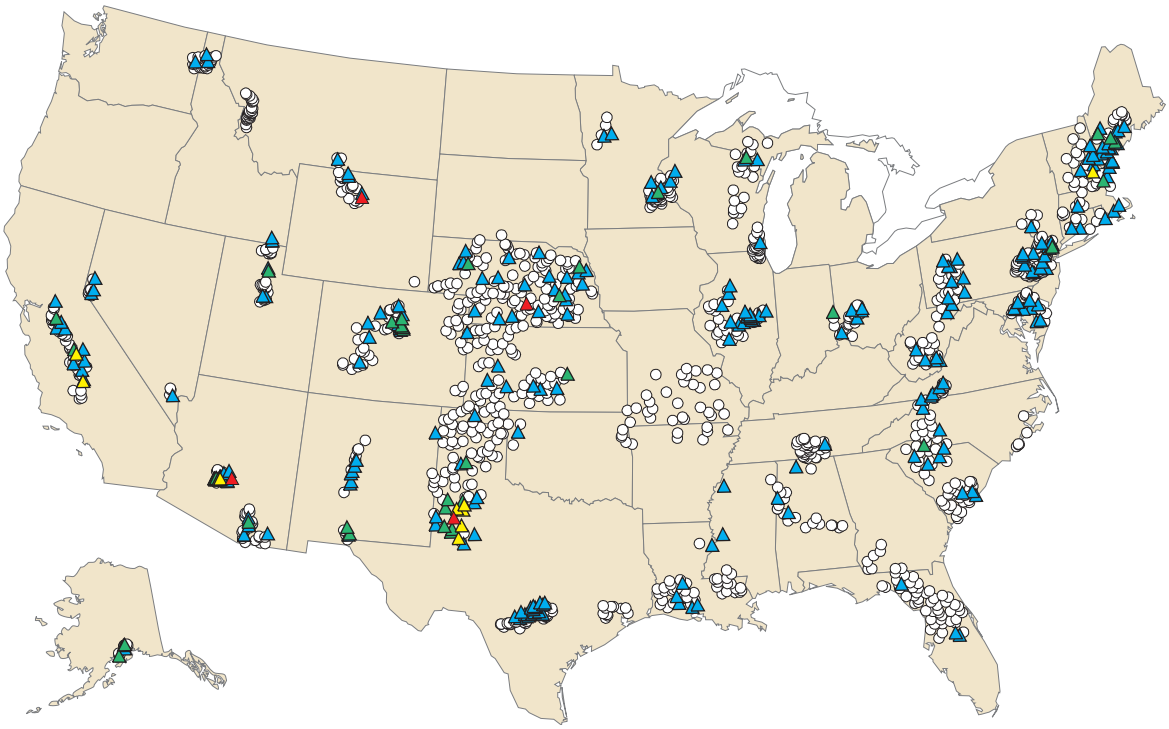
Samples from 72.8 percent of domestic wells contained two or more contaminants with concentrations greater than one-tenth of benchmarks, but only 4.03 percent of the sampled wells had two or more of these contaminants at concentrations greater than human-health benchmarks (fig. 33). With the inclusion of all organic contaminant detections in the analysis, mixtures were present in 88.9 percent of the sampled wells. Mixtures of contaminants at concentrations greater than one-tenth of benchmarks occurred in most of the principal aquifers sampled. The more complex mixtures (those with the largest numbers of contaminants), however, were most common in several aquifers in the western and south-central United States, including the Basin and Range, Central Valley, and High Plains basin-fill aquifers and the Lower Tertiary/Upper Cretaceous sandstone aquifers (fig. 34). Mixtures of two contaminants at concentrations greater than benchmarks, although much less frequent, were similarly distributed.

Overall, complex mixtures were most common in wells with the highest concentrations of total dissolved solids (fig. 35). This reflects the finding that the components of these mixtures were naturally occurring trace elements and other inorganic contaminants. These contaminants largely originate from soil and aquifer minerals, and their concentrations in ground water are increased by such factors as longer residence times, greater degrees of geochemical weathering, or evaporative concentration—factors that result in relatively high dissolved solids overall.

Composition of Mixtures

There were almost 5,000 unique mixtures of contaminants at concentrations greater than one-tenth of their benchmarks, but most (72 percent) were present in only one well. About 40 of these mixtures, however, were found in 5 percent or more of wells. The compositions of these relatively frequent combinations of contaminants are listed in table 11. Two-thirds of these mixtures were composed of two or more of only six contaminants—all inorganic and, except for nitrate, primarily from natural sources. These contaminants

A



EXPLANATION

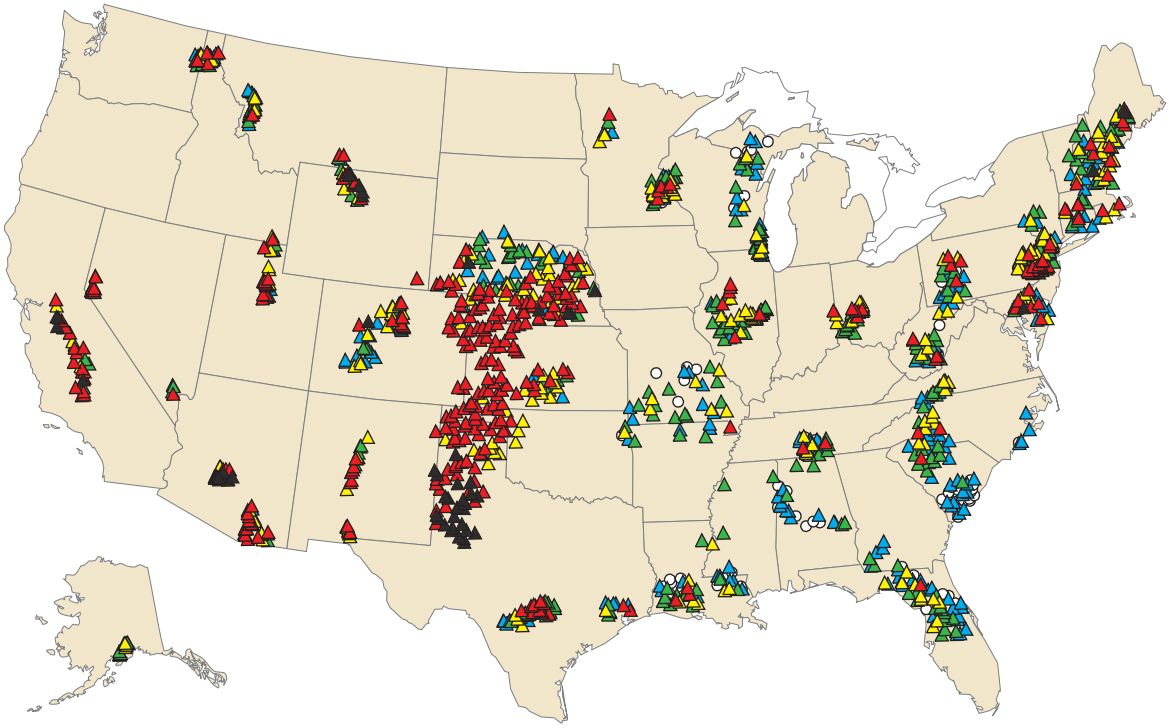
Number of contaminants for which concentrations were greater than human-health benchmarks

▲ >6 ▲ 3 ▲ 1

▲ 4 to 6 ▲ 2 ○ None

Figure 34A. Geographic distribution of wells with multiple contaminants *(A)* at concentrations greater than the human-health benchmarks and *(B)* at concentrations greater than one-tenth of human-health benchmarks in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. Data are from 1,389 wells in which major ions, trace elements, nutrients, radon, and organic compounds were measured. Human-health benchmarks are given in Appendix 4; criterion for radon is 4,000 picocuries per liter (pCi/L) for concentrations greater than human-health benchmarks and 300 pCi/L for concentrations greater than one-tenth of human-health benchmarks. >, greater than.

B



EXPLANATION

Number of contaminants for which concentrations were greater than one-tenth of human-health benchmarks

▲ >6 ▲ 3 ▲ 1
▲ 4 to 6 ▲ 2 ○ None

Figure 34B. Geographic distribution of wells with multiple contaminants *(A)* at concentrations greater than the human-health benchmarks and *(B)* at concentrations greater than one-tenth of human-health benchmarks in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004. Data are from 1,389 wells in which major ions, trace elements, nutrients, radon, and organic compounds were measured. Human-health benchmarks are given in Appendix 4; criterion for radon is 4,000 picocuries per liter (pCi/L) for concentrations greater than human-health benchmarks and 300 pCi/L for concentrations greater than one-tenth of human-health benchmarks. >, greater than.—Continued

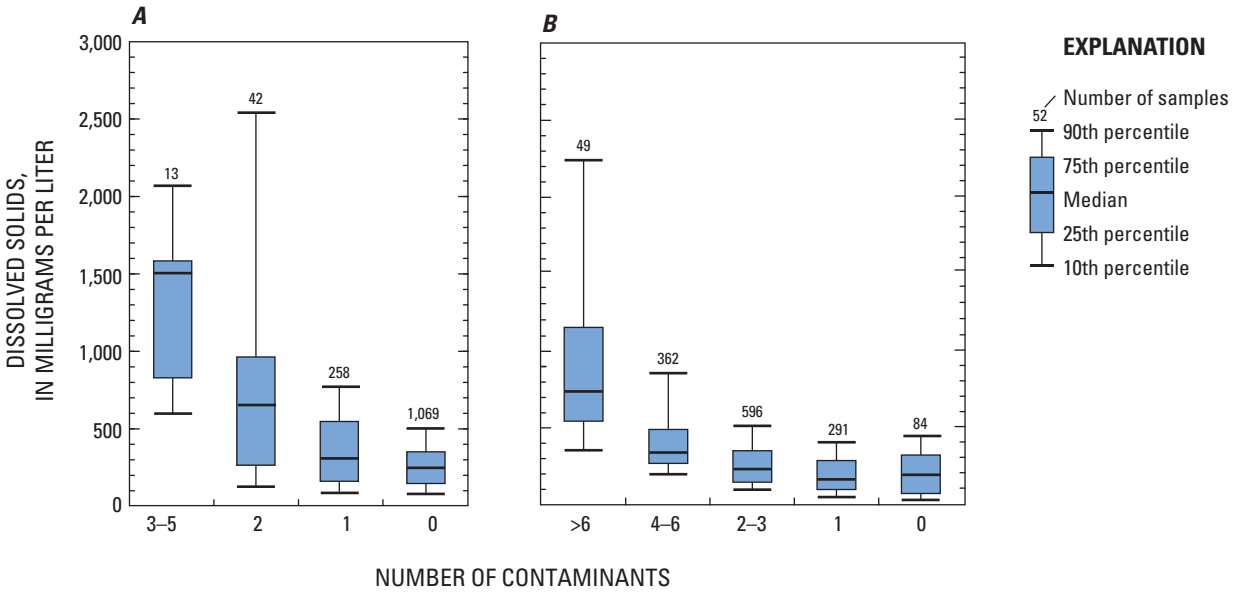


Figure 35. Dissolved solids concentrations in relation to the numbers of contaminants present at *(A)* concentrations greater than human-health benchmarks and *(B)* concentrations greater than one-tenth of human-health benchmarks in samples collected from domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004. Data are from 1,389 wells in which major ions, trace elements, nutrients, radon, and organic compounds were measured. >, greater than.

were nitrate, arsenic, radon, uranium, and to a lesser extent, molybdenum and manganese. Mixtures of two or more of these six contaminants with concentrations greater than one-tenth of benchmarks were present in as many as 32 percent of the wells (table 11). These contaminants also occurred in mixtures at concentrations greater than benchmarks but never in more than 1 percent of the wells. (Not shown in table 11 is the mixture of arsenic and fluoride at concentrations greater than MCLs, in 1 percent of wells.)

Mixtures containing nitrate or arsenic were among the most frequently occurring unique mixtures of contaminants. For example, mixtures of uranium with either nitrate or arsenic at concentrations greater than one-tenth of benchmarks were found in about 20 percent of wells, and mixtures of uranium with either nitrate or arsenic at concentrations greater than benchmarks were found in 0.29 to 0.58 percent of wells. Nitrate and arsenic were frequent components of mixtures defined relative to human-health benchmarks because of their broad distribution and relatively high frequency of occurrence at concentrations greater than benchmarks (figs. 15 and 18; tables 5 and 7). Radon was the most frequent component of unique mixtures of contaminants with concentrations greater than one-tenth of benchmarks, because of its widespread and frequent occurrence at concentrations greater than the criterion for radon used to define these mixtures (the lower proposed MCL of 300 pCi/L). Radon occurred less frequently as a component of mixtures at concentrations greater than benchmarks, because occurrences of radon at levels greater than its higher proposed MCL of 4,000 pCi/L were strongly regional and not associated with ground water containing high concentrations of dissolved solids.

Mixtures that contained organic compounds at concentrations greater than benchmarks or with concentrations greater than one-tenth of benchmarks were rare. The frequency of occurrence of any such mixture was less than 0.01 percent for mixtures of contaminants at concentrations greater than benchmarks, and the frequency was only 0.79 percent for mixtures of contaminants with concentrations greater than one-tenth of benchmarks. This resulted because concentrations of organic compounds seldom approached or exceeded benchmarks; also, some organic compounds were excluded when mixtures were defined relative to benchmarks because they did not have benchmarks. In contrast, eight mixtures of naturally occurring contaminants at concentrations greater than one-tenth of benchmarks and organic contaminants at any concentration were among the most frequently occurring, being present in more than 10 percent of wells (table 12). These mixtures included two- and three-component mixtures of chloroform, atrazine, or deethylatrazine in combination with either radon or nitrate. Co-occurrences of nitrate with the frequently

Table 11. Composition and frequency of occurrence of unique mixtures of contaminants individually at concentrations of potential concern for human health in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004.

[Data are for 1,389 wells in which major ions, trace elements, nitrate, radon, and organic compounds were measured. Criterion for radon in mixtures of contaminants at concentrations greater than human-health benchmarks is 4,000 picocuries per liter (pCi/L), and criterion for contaminants at concentrations greater than one-tenth of benchmarks is 300 pCi/L. All unique mixtures of contaminants with concentrations greater than one-tenth of benchmarks that occur in 5 percent or more of wells are listed.]

Contaminants in the most frequently occurring unique mixtures					Percentage of wells in which unique mixture occurs	
					Mixtures of contaminants with concentrations greater than one-tenth of human-health benchmarks	Mixtures of contaminants at concentrations greater than human-health benchmarks
Nitrate	Radon				32.4	0.07
Arsenic	Radon				29.9	0.07
Nitrate	Arsenic				24.4	0.22
Uranium	Radon				21.0	0.50
Arsenic	Uranium				20.8	0.29
Nitrate	Uranium				19.4	0.58
Nitrate	Arsenic	Radon			17.6	0.00
Nitrate	Arsenic	Uranium			16.4	0.14
Arsenic	Uranium	Radon			15.9	0.00
Nitrate	Uranium	Radon			15.2	0.00
Arsenic	Molybdenum				13.1	0.22
Nitrate	Arsenic	Uranium	Radon		12.3	0.00
Radon	Molybdenum				12.0	0.00
Manganese	Radon				10.8	0.07
Uranium	Molybdenum				10.6	0.07
Arsenic	Molybdenum	Radon			9.50	0.00
Nitrate	Molybdenum				9.29	0.14
Arsenic	Molybdenum	Uranium			8.93	0.07
Arsenic	Manganese				8.78	0.58
Uranium	Molybdenum	Radon			8.42	0.00
Radon	Strontium				8.28	0.00
Nitrate	Arsenic	Molybdenum			7.92	0.07
Nitrate	Uranium	Molybdenum			7.92	0.07
Nitrate	Molybdenum	Radon			7.27	0.00
Arsenic	Strontium				7.20	0.50
Arsenic	Molybdenum	Uranium	Radon		6.98	0.00
Nitrate	Arsenic	Molybdenum	Uranium		6.91	0.07
Arsenic	Barium				6.77	0.00
Nitrate	Strontium				6.48	0.58
Nitrate	Molybdenum	Uranium	Radon		6.26	0.00
Nitrate	Arsenic	Molybdenum	Radon		6.12	0.00
Arsenic	Strontium	Radon			5.90	0.00
Arsenic	Selenium				5.69	0.00
Radon	Barium				5.62	0.00
Radon	Lead				5.62	0.00
Nitrate	Selenium				5.47	0.07
Uranium	Strontium				5.47	0.14
Nitrate	Arsenic	Molybdenum	Uranium	Radon	5.33	0.00
Nitrate	Barium				5.33	0.00
Nitrate	Strontium	Radon			5.33	0.00
Nitrate	Arsenic	Selenium			5.26	0.00
Nitrate	Arsenic	Strontium			5.18	0.14
Uranium	Selenium				5.11	0.00

Table 12. Composition and frequency of occurrence of unique mixtures of contaminants individually at concentrations of potential concern for human health and any detectable concentration for organic compounds in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004.

[Data are for 1,389 wells in which major ions, trace elements, nitrate, radon, and organic compounds were measured. Criterion for radon is 300 picocuries per liter. All unique mixtures of contaminants with concentrations greater than one-tenth of benchmarks and detectable organic compounds that occur in 10 percent or more of wells are listed.]

Contaminants in the most frequently occurring unique mixtures			Percentage of wells in which unique mixture occurs
			Mixtures of contaminants with concentrations greater than one-tenth of benchmarks for all naturally occurring inorganic constituents and any detectable concentration for organic compounds
Radon	Chloroform		14.9
Nitrate	Deethylatrazine		14.3
Radon	Deethylatrazine		13.0
Atrazine	Deethylatrazine		12.3
Nitrate	Atrazine		11.3
Nitrate	Chloroform		11.3
Nitrate	Radon	Deethylatrazine	10.5
Nitrate	Atrazine	Deethylatrazine	10.4

occurring pesticide atrazine and (or) deethylatrazine, its degradation product, likely reflect the proximity of sources of these contaminants, such as fertilizer or manure with pesticide use in agricultural areas. Co-occurrences of radon and these pesticides likely reflect the ubiquitous distribution of radon at concentrations greater than the lower proposed MCL of 300 pCi/L. No mixture containing only organic compounds was present in more than 10 percent of wells except for the combination of atrazine and deethylatrazine, which had an occurrence frequency of 12.3 percent. The common presence of the degradate deethylatrazine with atrazine (in 84 percent of wells with atrazine detections) is consistent with previous findings on the prevalence of degradates of some pesticides in ground water (Gilliom and others, 2006).

Assessing the Potential Significance of Mixtures to Human Health

Depending on the specific compounds, the toxicity of a mixture may result from additive effects of the components, independent effects, antagonistic effects (less than additive), or synergistic effects (greater than additive). Each of these toxicity effects, except for antagonistic, usually results in a toxicity of the mixture that is greater than that of any of its original components (Gilliom and others, 2006). Given the likelihood that many mixtures have combined toxicities greater than those of their individual components, and the paucity of studies that address specific mixtures, the most frequently occurring mixtures and existing knowledge of potential health effects (tables 11 and 12) can be used as a starting point to prioritize unique mixtures for additional study.

A few specific mixtures of organic contaminants have been identified as having the potential to cause health effects because of combined toxicities. Three such mixtures that were found in the domestic wells sampled in this study are mixtures of triazine herbicides, mixtures of triazine herbicides and nitrate, and mixtures of several solvents. Only one of these mixtures, however, has a benchmark value available with which to compare concentrations quantitatively.

The combined concentrations of triazine herbicides, which include atrazine, deethylatrazine, and simazine, are considered additive in their toxic effect on human health by the Agency for Toxic Substances and Disease Registry (2006) and U.S. Environmental Protection Agency (2006b). In domestic wells, atrazine frequently co-occurred with its degradation product deethylatrazine (84 percent of samples with atrazine detections), and simazine (17 percent). All concentrations of total triazines in the 457 wells that had detections of one or more of these herbicides were less than the screening value of 12.5 µg/L, a value developed by USEPA for community public-water systems for the sum of atrazine and its three chlorinated degradates (including deethylatrazine and two others not measured in the present study). The maximum combined concentration was 4.6 µg/L, and the 90th percentile was 0.23 µg/L. Total chlorinated triazine concentrations greater than 12.5 µg/L in public water supplies indicate the need for further analysis and monitoring (U.S. Environmental Protection Agency, 2003b, 2006b).

The co-occurrence of nitrate and atrazine or simazine may be a health concern because atrazine and simazine can react with nitrite, which is formed in the human body from nitrate, to form nitrosamine compounds. The structure of these compounds suggests that they could be carcinogenic, although such effects have not been demonstrated to date (Agency for Toxic Substances and Disease Registry, 2006). For the domestic wells included in the NAWQA Program aquifer studies, the median concentration of nitrate in samples in which atrazine and (or) simazine were detected was 2.9 mg/L as N, greater than background values in many areas of the United States. Two-, three-, and four-component mixtures with nitrate greater than 1.0 mg/L as N and detections of atrazine (11.3 percent of wells; table 12), deethylatrazine (14.3 percent of wells), and (or) simazine also were among the most frequently occurring unique mixtures in wells in the aquifer studies. In domestic wells that were sampled as part of targeted studies of ground-water quality beneath agricultural land, two- and three-component mixtures with nitrate at concentrations greater than 1 mg/L as N and atrazine, deethylatrazine, and (or) simazine were present in 30 to 50 percent of wells; the median nitrate concentration was 7.1 mg/L as N in wells in which triazine herbicides were detected. Although there are no numerical benchmarks available for these mixtures, this co-occurrence of triazine herbicides and elevated nitrate suggests the need for further study, especially in agricultural areas.

Perchloroethene, a commonly detected solvent, frequently occurred with one or more of three other solvents—trichloroethene, 1,1-dichloroethane, and 1,1,1,-trichloroethane—for which the toxic effects are considered additive (Agency for Toxic Substances and Disease Registry, 2004c). Perchloroethene co-occurred with 1,1,1-trichloroethane, its degradation product, most frequently, in 30 percent of samples in which perchloroethene was detected. The combined concentrations of the four solvents were usually low, however. The median value of combined concentrations greater than detection levels was 0.031 µg/L, and the 90th percentile was 0.038, for the 240 wells in which any one of the four solvents was detected. The maximum combined concentration, 29 µg/L, was relatively high, but as with nitrate and triazines, there are currently no benchmark values for these mixtures.

Comparison with Previous Studies of Domestic Well-Water Quality

Results of the present study, which examined a broad suite of contaminants in domestic wells across the United States, are generally consistent with the findings of many regional, statewide, and national studies that investigated various aspects of domestic well water quality or of specific subsets of contaminants in domestic wells. Overall, results of the present study are similar to findings of the USEPA NSA (U.S. Environmental Protection Agency, 1984), which was conducted nearly 30 years ago. The NSA was a survey of water supplies used by about 2,600 rural households, mostly individual domestic wells, that were not regulated by the SDWA; the survey used random sampling and included a broad range (though limited number) of contaminants. Results of the present study also were similar to those compiled in a report on the quality of water from domestic wells in six states by the U.S. General Accounting Office (1997).

The microbiological quality of domestic well water was found to be a common problem in the NSA and the present study, with total coliform bacteria detected in 42.1 percent of domestic wells in the NSA and in 33.5 percent of domestic wells sampled in the present study. Detections of fecal coliform bacteria in 19.8 percent of wells in the NSA were somewhat higher than the detection frequency of 7.9 percent for the fecal indicator bacteria *E. coli*. Detection frequencies for fecal indicator bacteria in the present study are similar to detection frequencies found in a study of randomly selected domestic wells in the Midwest by the CDC (U.S. Centers for Disease Control and Prevention, 1998) for total coliform bacteria (41.3 percent) and *E. coli* (11.1 percent); in the U.S. General Accounting Office (1997) compilation of data for California, Illinois, Nebraska, North Carolina, and Wisconsin for total coliform bacteria (14 to 45 percent); and in several other statewide or regional-scale surveys (Appendix 1). Detections of fecal indicator bacteria in the NSA were more frequent in samples from wells that were dug or augered (rather than drilled using another method), shallow, or in poor condition, or were owned by low-income or low-education households. Well construction also was significant in the CDC study. Similarly in the present study, samples in which total coliform bacteria were detected were from wells that were shallower than wells with no detections of total coliform bacteria; data for the other factors tested in the NSA were not available for the wells in the present study.

The prevalence of common nuisance contaminants, total dissolved solids, iron, and manganese, was similar in the NSA and in the present study. Total dissolved solids were greater than the SMCL of 500 mg/L in 14.7 percent of domestic wells in the NSA and in 14.8 percent of the domestic wells in the present study. Concentrations of iron were greater than the SMCL of 300 µg/L in 29.9 percent of domestic wells in the NSA and in 19.1 percent of wells in the present study; manganese concentrations were greater than the SMCL of 50 µg/L in 20.7 percent of domestic wells in the NSA and in 21.3 percent of the wells of the present study. Elevated concentrations of manganese can be of concern for human health, and manganese was present in concentrations greater than the HBSL in 5.22 percent of the domestic wells sampled in the present study; this aspect of manganese concentrations was not investigated in the NSA. The occurrence of sulfate at concentrations greater than the SMCL of 250 µg/L also was similar in the two studies, 4.1 percent in the NSA and 3.79 in the present study.

Nitrate was one of the contaminants that occurred most frequently in concentrations greater than human-health benchmarks in both the NSA and the present study. Nitrate

concentrations greater than the USEPA MCL of 10 mg/L as N were present in 4.1 percent of domestic wells in the NSA and in 4.36 percent of wells from aquifer studies in the present study. For the present study, the percentage of wells from aquifer studies with concentrations of nitrate greater than the MCL is similar to the range of 2 to 9.4 percent (median value 3.5) reported for a number of statewide or regional voluntary testing programs (programs in Alabama, California, Georgia, Kentucky, Idaho, Indiana, Illinois, Minnesota, New Jersey, Ohio, Pennsylvania, Virginia, and West Virginia, including one statewide mandatory testing program) (see Appendix 1 for references).

In the present study, nitrate concentrations were found to be higher in agricultural areas than in other areas. This finding is consistent with the results of many studies at statewide and regional scales and with the results of other studies by the NAWQA Program. Nitrate concentrations in the present study were greater than 10 mg/L as N in 7.1 percent of wells from aquifer studies with substantial amounts of agricultural land in their immediate vicinities, and concentrations were greater than 10 mg/L as N in 23.4 percent of wells from assessment studies that specifically targeted regional areas of agricultural land use. These relatively large percentages are similar to the percentages of sampled wells with nitrate concentrations greater than the MCL in statewide or regional studies that targeted domestic wells from farming households or near active agriculture across the United States—2 to 32 percent (median value 19 percent) of domestic wells primarily in the Midwest (Illinois, Iowa, Kansas, Minnesota, Missouri, Nebraska, Tennessee, and Wisconsin); 25 percent in the Northwest (Oregon); and 1.7 to 10 percent in the Southeast (North Carolina and Georgia) (see Appendix 1 for references).

Pesticides have been the subject of many previous regional and statewide studies, particularly in the Midwest, and were included to a limited extent in the NSA. In many cases, comparisons among these earlier studies and the present study are complicated by differences in the contaminants analyzed and their detection limits. In the NSA, six organic compounds (all herbicides) were analyzed, and two were detected. The USEPA National Pesticide Study (NPS), conducted in the late 1980s, was more comprehensive and included 127 pesticides, with detection limits that ranged from about 0.1 to 0.7 µg/L for most compounds (the median detection limit was about 0.2 µg/L; U.S. Environmental Protection Agency, 1990a, 1990d). The NPS, which sampled about 730 wells, primarily used random sampling methods, but also some targeted sampling of high pesticide-use areas. In the NPS, the estimated detection frequency for at least one pesticide was 4.2 percent of all domestic wells in the United States and 5.5 percent of domestic wells in vulnerable areas of row-crop agriculture (U.S. Environmental Protection Agency, 1990a). These results are comparable to the finding of the present study of at least one pesticide present in 3.0 percent of the sampled domestic wells at concentrations greater than the common reporting level of 0.2 µg/L. The present study and the NPS also found similar percentages for wells in which pesticides were present at concentrations of concern for human health—0.6 percent (relative to USEPA MCLs or lifetime health advisories) in the NPS study and 0.5 percent (relative to MCLs or HBSLs) in the present study.

Atrazine was the most frequently detected pesticide in the NPS study and in the present study. Detection frequencies were comparable; atrazine was detected in an estimated 0.7 percent of domestic wells nationwide in the NPS (minimum reporting limit of 0.12 µg/L) and in 2.1 percent of domestic wells from aquifer studies at concentrations greater than 0.1 µg/L in the present study. In regional and statewide studies encompassing areas of the United States in which agriculture is dominant, detection frequencies for atrazine were higher than those in domestic wells in the NPS or in wells from aquifer studies used in the present study. In the CDC study in nine Midwestern states, atrazine was detected in 13.6 percent of wells at concentrations greater than a minimum reporting level of 0.05 µg/L (U.S. Centers for Disease Control and Prevention, 1998). In a study that included all counties in the United States in which the pesticide alachlor was sold, atrazine was detected in about 12 percent of wells at concentrations greater than a minimum reporting level of 0.03 µg/L (Holden and others, 1992). In most of the statewide or regional studies in the Midwest described previously for nitrate, atrazine was the most frequently detected pesticide, with detection frequencies ranging from 4 to 23 percent of sampled wells in these studies. Similarly, detection frequencies for atrazine in NAWQA assessment studies that targeted regional agricultural land-use areas—32 and 37 percent of wells with atrazine concentrations greater than 0.02 and 0.01 µg/L, respectively—were considerably higher than the detection frequencies for atrazine in NAWQA domestic wells from aquifer studies, which were not targeted at regional agricultural areas.

The occurrence of selected trace elements and radionuclides in domestic wells also has been studied at regional, statewide, and, to a limited extent, national scales. In the national-scale NSA, trace elements were analyzed, and several, including lead, cadmium, and silver, were found at concentrations greater than reference levels for human health (some of which were the MCLs used in the present study) in relatively large percentages of sampled domestic wells. However, contamination from sampling procedures occurred for some trace elements in that study (U.S. Environmental Protection Agency, 1984). In the present study, concentrations of lead, cadmium, silver, and most other trace elements were found to exceed human-health benchmarks (several of which were lower than the reference levels used in the NSA) in less than 1 percent of the sampled domestic wells. Arsenic was compared to a reference value of 50 µg/L in the NSA, which is greater than the current USEPA MCL. Concentrations of arsenic were greater than the reference value in 0.8 percent of domestic wells in the NSA; this is similar to the value of 0.6 percent of wells with concentrations greater than 50 µg/L for the present study. A number of studies of arsenic, primarily in public water-supply systems, were associated with the

recent reduction in the USEPA MCL for arsenic to 10 µg/L (ISSI Consulting Group and others, 2000; Focazio and others, 2000). Concentrations greater than 10 µg/L were estimated to occur in 7.6 percent of public water-supply systems in the United States (Focazio and others, 2000); this is comparable to the 6.8 percent of domestic wells with arsenic concentrations greater than the MCL in the present study. Similar or, in some cases, larger percentages of wells with arsenic concentrations greater than the MCL have been found for regional or local-scale study areas in other parts of the country (Peters and others, 1999; Riewe and others, 2000; Montgomery and others, 2003; Hagan, 2004; Shiber, 2005; Steinmaus and others, 2005). A nationwide survey of radionuclides in public wells (Longtin, 1988) found concentrations of radium-226 plus radium-228 greater than the USEPA MCL of 5 pCi/L at frequencies (about 1 percent of wells) similar to that in the present study; the frequencies are not nearly as great as those determined for public water supplies by Focazio and others (21 percent; 2001), where sampling was targeted at areas known or suspected to contain radium-rich ground water.

Finally, findings of the present study may be compared to those of the recent national-scale study that used data from all domestic wells in USGS databases for arsenic, radon, uranium, and fluoride, nitrate, and selected organic compounds (Focazio and others, 2006). That study included much of the data used in the present study. Overall in the present study, the frequencies at which arsenic, radon, nitrate, and uranium occurred in the domestic wells at concentrations greater than human-health benchmarks (USEPA MCLs or proposed MCLs) were in most cases slightly lower than the frequencies at which these contaminants were present at concentrations greater than benchmarks in all domestic wells in USGS databases (Focazio and others, 2006). The frequencies for the present study and for Focazio and others (2006) are, respectively: 6.75 and 10.6 percent for arsenic; 64.6 and 75 percent for radon greater than 300 pCi/L; 4.44 and 9.0 percent for radon greater than 4,000 pCi/L; 1.74 and 3.7 percent for uranium; 4.36 and 8.4 percent for nitrate; and 1.16 and 0.81 for fluoride. These differences may result, in part, from the inclusion of wells near contamination sites (for example, landfills or wastewater disposal areas) and, for nitrate, the inclusion of wells from NAWQA agricultural land-use studies in the dataset of all domestic wells in USGS databases that was used in Focazio and others (2006). Differences between the two datasets in sampling densities among geographic areas in the United States also may have affected study results.

Summary and Conclusions

As part of the National Water-Quality Assessment Program (NAWQA) of the U.S. Geological Survey (USGS), water samples collected from 2,167 domestic wells across the United States during 1991–2004 were analyzed for physical properties and the concentrations of as many as 214 chemical contaminants. The wells were located within major hydrogeologic settings in 30 regionally extensive aquifers used for water supply (principal aquifers) in the United States. Water samples were collected prior to any treatment systems that may have been in place, and thus do not represent water consumed by homeowners with in-home treatment. Each well was sampled once during the study period.

The findings of the study are based on a synthesis of data for domestic wells from NAWQA ground-water studies that were parts of integrated assessments of water resources, with study areas that represented typical hydrogeologic settings within the regionally extensive principal aquifers. The studies were not designed as a single, national-scale assessment of domestic well water quality. The wells in the study are clustered geographically and are not a statistically representative sampling of all domestic wells in the United States or within principal aquifers. Within the representative hydrogeologic settings that were studied, however, the wells were randomly selected to represent typical aquifer conditions and were not focused in areas of known contamination. For this reason, and because of the use of consistent sampling and analytical methods, the well-documented quality-assurance procedures, and the broad suite of analytes in the data set, the NAWQA data provide a valuable description of domestic well water quality in the Nation.

Concentrations of water-quality contaminants were compared to human-health benchmarks that included U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Levels (MCLs) for public water supplies and USGS Health-Based Screening Levels (HBSLs). No individual water-quality contaminant was present in concentrations greater than the available benchmarks in more than 8 percent of the sampled wells. Collectively, however, 22.6 percent of a subset of 1,389 wells had at least one contaminant at concentrations greater than benchmarks; the subset consisted of wells in which most contaminants were measured. Concentrations of at least one contaminant were greater than an established MCL (using action levels for copper and lead) or HBSL in 13.2 and 8.14 percent of the wells, respectively.

Radon, nitrate, several trace elements, fluoride, gross alpha- and beta-particle radioactivity, and fecal indicator bacteria occurred most frequently at concentrations of potential concern for human health. Radon concentrations were greater than the proposed MCL of 300 picocuries per liter (pCi/L) in 64.6 percent of the wells and greater than the proposed alternative MCL of 4,000 pCi/L in 4.44 percent of wells. Other contaminants that occurred in concentrations greater than MCLs or HBSLs in more than 1 percent of wells were: nitrate, greater than the MCL of 10 micrograms per liter (µg/L) as N in 4.36 percent of wells; arsenic, greater than the MCL of 10 micrograms per liter (µg/L) in 6.75 percent of wells; manganese, greater than the HBSL of 300 µg/L in 5.22 percent of wells; strontium, greater than the HBSL of 4,000 µg/L in 7.32 percent of wells; uranium, greater than the MCL of 30 µg/L in 1.74 percent of wells; and fluoride, greater than the MCL of 4 mg/L in 1.16 percent of wells. Gross

alpha- (uncorrected) and gross beta-particle radioactivity, measured in samples from about 400 wells, were greater than the MCLs in 5.29 and 1.87 percent of wells, respectively. Contaminants other than those listed were present in concentrations less than the available MCLs or HBSLs for at least 99 percent of the sampled wells. Total coliform and *Escherichia coli* bacteria, measured in about 400 wells, were detected in 33.5 and 7.9 percent of wells, respectively. Thus, with the exceptions of nitrate and fecal indicator bacteria, the contaminants that occurred most frequently at concentrations greater than human-health benchmarks were naturally occurring. Collectively, 19.2 percent of wells contained at least one naturally occurring contaminant (radon, a trace element, or fluoride) at a concentration greater than its benchmark.

Anthropogenic organic compounds were frequently detected—with typical analytical detection limits of 0.001 to 0.1 µg/L—but seldom at concentrations greater than human-health benchmarks. The most frequently detected compounds included the pesticide atrazine, its degradate deethylatrazine, and the volatile organic compounds chloroform, methyl *tert*-butyl ether (MTBE), perchloroethene, and dichlorofluoromethane. These compounds were detected in 1 to 5.5 percent of wells at concentrations greater than 0.2 µg/L and in 3.13 to 17.9 percent of wells at concentrations greater than 0.02 µg/L. Only 7 of the 168 measured organic compounds—diazinon, dibromochloroprane, dieldrin, dinoseb, ethylene dibromide, perchloroethene, and trichloroethene—occurred at concentrations greater than MCLs or HBSLs, each in less than 1 percent of wells. Collectively, only 0.80 percent of wells contained an organic compound at concentrations greater than MCLs or HBSLs. Concentrations of any compound greater than 10 percent of MCLs or HBSLs occurred in 2.95 percent of wells.

Values or concentrations of several other properties and contaminants were outside the recommended ranges for drinking water for aesthetic or other non-health purposes. About 16 percent of the sampled wells had pH values less than (14.4 percent) or greater than (1.9 percent) the USEPA recommended range of 6.5 to 8.5. Total dissolved solids were greater than the USEPA Secondary Maximum Contaminant Level (SMCL) of 500 mg/L in 14.8 percent of wells. Iron and manganese concentrations were greater than SMCLs in about 19.1 and 21.3 percent of wells, respectively. Concentrations of fluoride, which can be harmful at high concentrations but prevents tooth decay at low concentrations, were less than those recommended by the U.S. Centers for Disease Control and Prevention in about 90 percent of the sampled wells.

The occurrence and concentrations or values of some contaminants and properties varied regionally and by principal aquifer and therefore may be of greater potential concern for human health or aesthetic water quality in some locations or regions than nationally. For example, radon concentrations were greater than the proposed MCLs in about 30 percent (higher proposed MCL) and about 90 percent (lower proposed MCL) of the wells in crystalline-rock aquifers, which are in the Northeast, the central and southern Appalachians, and Colorado. Nitrate concentrations were more frequently greater than the MCL in areas of agricultural land use (7.1 percent) than in areas of urban (3.1 percent), mixed (3.7 percent), or undeveloped (0.7 percent) land use. Nitrate concentrations were higher in agricultural areas than in other areas, occurring at concentrations greater than the MCL of 10 mg/L as N in 7.1 percent of wells from aquifer studies with substantial amounts of agricultural land in their immediate vicinities, and in 23.4 percent of wells from NAWQA assessment studies that specifically targeted regional areas of agricultural land use.

Contaminant concentrations also were related to geochemical conditions. Arsenic concentrations were inversely related to dissolved oxygen concentrations in several principal aquifers; uranium concentrations were positively correlated with dissolved oxygen concentrations, in addition to showing regional patterns of occurrence. Relatively high concentrations of iron and manganese occurred everywhere but were inversely correlated with dissolved oxygen and (for manganese) pH. Relations of these contaminants with dissolved oxygen and pH result from differences in the solubility of redox-sensitive species. Differences in geochemical conditions, such as redox and pH, can result in spatial variability of contaminant concentrations within aquifers with similar source-rock characteristics.

Mixtures of contaminants were assessed for individual contaminants present at concentrations of potential concern for human health and for organic compounds detected at any concentration in a subset of 1,389 wells. Mixtures of two or more contaminants at concentrations greater than human-health benchmarks occurred in only 4.03 percent of wells, but mixtures of two or more contaminants with concentrations greater than one-tenth of their benchmarks occurred in 72.8 percent of wells. Mixtures with the largest numbers of contaminants were most common in the western and south-central United States in ground water with relatively high concentrations of dissolved solids.

The composition of mixtures was described in terms of unique mixtures, or specific combinations of any two, three, or more contaminants, regardless of the presence of other contaminants. Two-thirds of the unique mixtures of contaminants with concentrations greater than one-tenth of individual benchmarks that occurred in 5 percent or more of wells were made up of two or more of only six contaminants—nitrate, arsenic, radon, uranium, and to a lesser extent, molybdenum and manganese. Organic compounds were rarely components of these unique mixtures, but mixtures of naturally occurring contaminants at concentrations greater than one-tenth of benchmarks and organic compounds detected at any concentration were common, occurring in 88.9 percent of wells. Eight of these mixtures were each present in more than 10 percent of wells and included two- and three-component mixtures of chloroform, atrazine, or deethylatrazine in combination with radon and nitrate.

Several combinations of organic compounds in mixtures with possible health effects were identified in the sampled wells—specifically, atrazine, deethylatrazine, and simazine;

atrazine or simazine with nitrate; and perchloroethene and three other solvents—but combined concentrations were less than available benchmarks, or no benchmarks were available for the mixtures. Atrazine commonly co-occurred with its degradate deethylatrazine (84 percent of atrazine detections) and with simazine (17 percent of atrazine detections), but combined concentrations were all less than the USEPA screening value of 12.5 µg/L for community public water systems for atrazine and its chlorinated degredates. Nitrate (at concentrations greater than 1 mg/L as N) co-occurred with atrazine, deethylatrazine, and (or) simazine in as many as 14 percent of all wells from aquifer studies and even more frequently in wells from assessment studies that targeted regional agricultural land-use areas, but there are currently (2009) no benchmarks for these mixtures. Similarly, there are currently no benchmarks available for mixtures of perchlorethene with trichloroethene, 1,1-dichloroethane, or 1,1,1-trichloroethane, which are considered to have additive toxic effects with one another.

Organic compounds typically co-occurred with relatively high concentrations of nitrate, especially for organic compounds at concentrations approaching health benchmark values. Median nitrate concentrations were 2 to 8 times higher in wells that also contained organic compounds detected at any concentration, organic compounds present at concentrations greater than one-tenth of MCLs or HBSLs, or organic compounds present at concentrations greater than MCLs or HBSLs than in wells with no detections of organic compounds or without organic compounds present at these elevated concentrations. Although nitrate concentrations were not a strong predictor of organic compound occurrence, the small but significantly higher likelihood that organic compounds might be present at concentrations approaching health benchmarks when nitrate concentrations were high suggests that elevated nitrate concentrations could be a useful screening tool, in some cases, for the occurrence of organic compounds at concentrations of potential health concern.

Results of this study are similar to findings of a USEPA statistical sampling of domestic wells in rural areas, the National Statistical Assessment of Rural Water Conditions (NSA), that was conducted nearly 30 years ago and was mandated by the Safe Drinking Water Act of 1975. In both studies, the microbial quality of domestic well water was found to be a common problem, and nitrate was one of the most common contaminants to occur in concentrations greater than human-health benchmarks. Detection frequencies for total coliform and nitrate concentrations greater than the MCL were similar in the two studies. The frequencies at which concentrations of dissolved solids, iron, manganese, and sulfate were greater than SMCLs in the present study were similar to those for domestic wells in the NSA study. Several trace elements were found to be potentially of concern nationally and regionally in the present study, but unlike findings of the NSA study, the present study found that most trace elements were not a substantial concern for human health at the national scale. The present study also differed from the NSA study in its comprehensive approach and use of low-detection limits for organic compounds, which identified the widespread presence of anthropogenic organic compounds in domestic well water, although nearly always at concentrations less than human-health benchmarks.

The present study provides the most comprehensive national analysis to date of the quality of water from domestic wells and provides a foundation for improving our understanding and management of this critical source of drinking water. Information about the distribution of naturally occurring contaminants in domestic wells among principal aquifers and geographically can help determine the appropriate levels of monitoring in aquifers and areas of the most concern for specific contaminants. Information about the distribution of contaminants that originate from anthropogenic sources similarly can be used in monitoring, education, and protection programs in vulnerable areas. For example, the findings on nitrate and bacteria indicate that domestic wells in or adjacent to areas of agricultural and urban land use, or completed in aquifers that allow rapid infiltration, may require special consideration. Information from the present study can be used to inform homeowners and those concerned with public health about the potential risks to domestic-well water quality that are associated with some current or past land uses or with natural sources. The persistent nature of some contaminants and relatively slow movement of ground water, which may be affected by past land uses, make understanding of these risks of particular concern for residents and water managers in areas where land use is changing.

Mixtures of contaminants at concentrations approaching human-health benchmarks and of organic compounds at detectable concentrations were prevalent in the domestic wells, suggesting a need for further investigation of mixtures in drinking water. Existing standards and other human-health benchmarks for drinking water were developed for individual chemicals and may not address all potential effects of drinking-water contaminants, because exposure is often to mixtures of multiple contaminants. Additional research is needed regarding the possible toxicities of mixtures to humans, including mixtures with degradation products. A total of 43 unique mixtures were identified of contaminants with concentrations greater than one-tenth of individual human-health benchmarks in more than 5 percent of the domestic wells sampled in this study. Such information on the occurrences and characteristics of mixtures can be used to aid in prioritizing toxicity assessments.

The occurrence of anthropogenic organic compounds is widespread in principal aquifers, although at concentrations well below human-health benchmarks. The widespread occurrence demonstrates that all aquifers require some level of consideration to prevent or mitigate contamination. Long-term, consistent data are essential for assessing trends in domestic-well water quality, particularly in response to changes in chemical use, well use, and management practices, because of the slow rate of ground-water flow and the time

lag between the adoption of management practices and improvement in water quality.

Acknowledgments

The author thanks the USGS personnel providing guidance to this study: Marion Berndt, Gregory Delzer, Neil Dubrovsky, Michael Focazio, Robert Gilliom, Pixie Hamilton, Wayne Lapham, Jeffrey Martin, Thomas Nolan, Gary Rowe, Paul Stackelberg, Patty Toccalino, Kelly Warner, William Wilber, and Michael Yurewicz. The author also thanks USGS colleagues Jonathan Scott, for conducting the analyses of unique multi-component combinations of nitrate and organic compounds; Zoltan Szabo, for radium data and assistance with interpretation of data for radium and other radionuclides; Sandra Embrey, for microbiological data; and Stacey Archfield, for assistance with statistical methods and analysis.

References

Aeolion, C.M., and Conte, B.C., 2004, Susceptibility of residential wells to VOC and nitrate contamination: Environmental Science & Technology, v. 38, no. 6, p. 1648–1653.

Agency for Toxic Substances and Disease Registry, 2004a, Toxicological profile for strontium: U.S. Department of Health and Human Services, Public Health Service, accessed November 12, 2008, at http://www.atsdr.cdc.gov/toxprofiles/tp159.html.

Agency for Toxic Substances and Disease Registry, 2004b, Guidance manual for the assessment of joint toxic action of chemical mixtures: U.S. Department of Health and Human Services, Public Health Service, May 2004, 103 p., accessed January 25, 2007, at http://www.atsdr.cdc.gov/interaction profiles/IP-ga/ipga.pdf.

Agency for Toxic Substances and Disease Registry, 2004c, Interaction profile for 1,1,1-trichloroethane, 1,1-dichloroethane, trichloroethylene, and tetrachloroethylene: U.S. Department of Health and Human Services, Public Health Service, May 2004, 103 p., accessed January 17, 2007, at http://www.atsdr.cdc.gov/interaction profiles/IP-vocs/ip02.pdf.

Agency for Toxic Substances and Disease Registry, 2006, Interaction profile for atrazine, deethylatrazine, diazinon, nitrate, and simazine: U.S. Department of Health and Human Services, Public Health Service, August 2006, 68 p., accessed January 17, 2007, at http://www.atsdr.cdc.gov/interaction profiles/IP-10/ip10.pdf.

Agency for Toxic Substances and Disease Registry, 2008, Public health statement, manganese: U.S. Department of Health and Human Services, Public Health Service, September 2008, accessed November 12, 2008, at http://www.atsdr.cdc.gov/toxprofiles/tp151-c1-b.pdf.

American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1992, Standard Methods for the Examination of Water and Wastewater (18th ed.): Washington, D.C., American Public Health Association, variously paginated.

American Society for Testing Materials, 1996, Annual book of ASTM standards, section 11, Water and Environmental Technology: v. 11.02, D5072-92, p. 674–676.

Apodaca, L.E., and Bails, J.B., 2000, Water quality in alluvial aquifers of the Southern Rocky Mountains Physiographic Province, Upper Colorado River Basin, Colorado, 1997: U.S. Geological Survey Water-Resources Investigations Report 99–4222, 68 p.

Apodaca, L.E., Mueller, D.K., and Koterba, M.T., 2006, Review of trace element blank and replicate data collected in ground and surface water for the National Water-Quality Assessment Program, 1991–2002: U.S. Geological Survey Scientific Investigations Report 2006–5093, 32 p.

Argonne National Laboratory, 2005, Basic concepts for mixtures risk assessment: Argonne, Ill., Agronne National Laboratory, Environmental Science Division, Human Health Fact Sheet, August 2005, 2 p., accessed January 17, 2007, at http://www.ead.anl.gov/pub/doc/zmix-concepts.pdf.

Ayotte, J.D., Argue, D.M., and McGarry, F.J., 2005, Methyl *tert*-butyl ether occurrence and related factors in public and private wells in southeast New Hampshire: Environmental Science & Technology, v. 39, no. 1, p. 9–15.

Ayotte, J.D., Flanagan, S.M., and Morrow, W.S., 2007, Occurrence of uranium and ^{222}Radon in glacial and bedrock aquifers in the northern United States, 1993–2003: U.S. Geological Survey Scientific Investigations Report 2007–5037, 85 p.

Ayotte, J.D., Montgomery, D.L., Flanagan, S.M., and Robinson, K.W., 2003, Arsenic in groundwater in eastern New England: occurrence, controls, and human health implications: Environmental Science & Technology, v. 37, no. 10, p. 2075–2083.

Baker, D.B., Wallrabenstein, L.K., Richards, R.P., and Creamer, N.L., 1989, Nitrate and pesticides in private wells of Ohio—A state atlas: Tiffin, Ohio, Heidelberg College, The Water Quality Laboratory, June 1989, 304 p.

Barbash, J.E., Thelin, G.P., Kolpin, D.W., and Gilliom, R.J., 1999, Distribution of major herbicides in ground water of the United States: U.S. Geological Survey Water-Resources Investigations Report 98–4245, 58 p.

Barbash, J.E., Thelin, G.P., Kolpin, D.W., and Gilliom, R.J., 2001, Major herbicides in ground water—Results from the National Water-Quality Assessment: Journal of Environmental Quality, v. 30, p. 831–845.

Barber, L.B., Thurman, E.M., Schroeder, M.P., and LeBlanc, D.R., 1988, Long-term fate of organic micropollutants in sewage-contaminated groundwater: Environmental Science & Technology, v. 22, p. 205–211.

Bartos, T.T., Eddy-Miller, C.A., Norris, J.R., Gamper, M.E., and Hallberg, L.L., 2005, Water-quality characteristics of Quaternary unconsolidated-deposit aquifers and Lower Tertiary aquifers of the Bighorn Basin, Wyoming and Montana, 1999–2001: U.S. Geological Survey Scientific Investigations Report 2004–5252, 155 p.

Bauder, J.W., Sinclair, K.N., and Lund, R.E., 1993, Physiographic and land use characteristics associated with nitrate-nitrogen in Montana groundwater: Journal of Environmental Quality, v. 22, no. 2, p. 255–262.

Bauder, J.W., White, B.A., and Inskeep, W.P., 1991, Montana extension initiative focuses on private well quality: Journal of Soil and Water Conservation, v. 46, no. 1, p. 69–74.

Becker, M.F., Bruce, B.W., Pope, L.M., and Andrews, W.J., 2002, Ground-water quality in the central High Plains Aquifer, Colorado, Kansas, New Mexico, Oklahoma, and Texas, 1999: U.S. Geological Survey Water-Resources Investigations Report 02–4112, 64 p.

Bell, R.W., and Williamson, A.K., 2006, Data delivery and mapping over the web, National Water-Quality Assessment Data Warehouse: U.S. Geological Survey Fact Sheet 2006–3101, 6 p.

Bexfield, L.M., and Anderholm, S.K., 1997, Water-quality assessment of the Rio Grande Valley, Colorado, New Mexico, and Texas—Ground-water quality in the Rio Grande flood plain, Cochiti Lake, New Mexico, to El Paso, Texas, 1995: U.S. Geological Survey Water-Resources Investigations Report 96–4249, 93 p.

Bexfield, L.M., and Plummer, L.N., 2003, Occurrence of arsenic in ground water of the Middle Rio Grande Basin, central New Mexico, *in* Welch, A.H., and Stollenwerk, K.G., eds., Arsenic in Ground Water: Boston, Mass., Kluwer Academic Publishers, p. 295–327.

Blackburn, B.G., Craun, G.F., Yoder, J.S., Hill, Vincent, Calderon, R.L., Chen, Nora, Lee, S.H., Levy, D.A., and Beach, M.J., 2004, Surveillance for waterborne-disease outbreaks associated with drinking water—United States, 2001–2002: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, Morbidity and Mortality Weekly Report, v. 53, no. SS-8, p. 23–45.

Borchardt, M.A., Bertz, P.D., Spencer, S.K., and Battigelli, D.A., 2003, Incidence of enteric viruses in groundwater from household wells in Wisconsin: Applied and Environmental Microbiology, v. 69, no. 2, p. 1172–1180.

Bourne, A.C., 2001, Assessing the contamination risk of private well water supplies in Virginia: Blacksburg, Va., Virginia Polytechnic Institute and State University, M.S. Thesis, 141 p.

Brenton, R.W., and Arnett, T.L., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of dissolved organic carbon by UV-promoted persulfate oxidation and infrared spectrometry: U.S. Geological Survey Open-File Report 92–480, 12 p.

Brook, J.V., Rheineck, Bruce, Postle, Jeff, Allen, Paula, Zogbaum, Randy, Funk, Justin, Strohl, Derek, and Baldock, Jon, 2002, Agricultural chemicals in Wisconsin groundwater: Madison, Wis., Wisconsin Department of Agriculture, Trade, and Consumer Protection, Water Quality Section, 18 p.

Bruce, B.W., Gurdak, J.J., and McMahon, P.B., 2007, Receptors—Quality of the used resource in the High Plains Aquifer, *in* McMahon, P.B., Dennehy, K.J., Bruce, B.W., Gurdak, J.J., and Qi, S.L., Water-quality assessment of the High Plains Aquifer, 1999–2004: U.S. Geological Survey Professional Paper 1749, chap. 3, p. 74–104.

Bruce, B.W., and McMahon, P.B., 1998, Shallow groundwater quality of selected land-use/aquifer settings in the South Platte River Basin, Colorado and Nebraska, 1993–95: U.S. Geological Survey Water-Resources Investigations Report 97–4229, 48 p.

Brutsaert, W.F., Norton, S.A., Hess, C.T., and Williams, J.S., 1981, Geologic and hydrologic factors controlling radon-222 in ground water in Maine: Ground Water, v. 19, p. 407–471.

Carey, D.I., Dinger, J.S., Davidson, O.B., Sergeant, R.E., Taraba, J.L., Ilvento, T.W., Coleman, Steve, Boone, Rayetta, and Knoth, L.M., 1993, Quality of private ground-water supplies in Kentucky: Lexingon, Ky., Kentucky Geological Survey Information Circular 44, 155 p.

Carmichael, J.K., and Bennett, M.W., 1993, Reconnaissance of quality of water from farmstead wells in Tennessee, 1989–90: U.S. Geological Survey Water-Resources Investigations Report 92–4186, 43 p.

Carpenter, D.O., Arcaro, Kathleen, and Spink, D.C., 2002, Understanding the human-health effects of chemical mixtures: Environmental Health Perspectives, v. 110 supplement, p. 25–42.

Chapelle, F.H., and McMahon, P.B., 1991, Geochemistry of dissolved inorganic carbon in a Coastal Plain aquifer. 1. Sulfate from confining beds as an oxidant in microbial CO_2 production: Journal of Hydrology, v. 127, p. 1865–1874.

Childress, C.J.O., Foreman, W.T., Connor, B.F., and Maloney, T.J., 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: U.S. Geological Survey Open-File Report 99–193, 19 p.

Coes, A.L., Gellenbeck, D.J., Towne, D.C., and Freark, M.C., 2000, Ground-water quality in the Upper Santa Cruz Basin, Arizona, 1998: U.S. Geological Survey Water-Resources Investigations Report 00–4117, 55 p.

Conine, S., Cox, D., Mitchell, K., Kuyper, C., and Bragg, J., 1989, Bacteriological quality of private water wells in Clark County, Arkansas: 1989, Proceedings of the Arkansas Academy of Science, v. 43, p. 19–20.

Connor, B.F., Rose, D.L., Noriega, M.C., Murtagh, L.K., and Abney, S.R., 1998, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of 87 volatile organic compounds in water by gas chromatography/mass spectrometry, including detections less than reporting limits: U.S. Geological Survey Open-File Report 97–829, 78 p.

Cowdery, T.K., 1998, Ground-water quality in the Red River of the North Basin, Minnesota and North Dakota, 1991–95: U.S. Geological Survey Water-Resources Investigations Report 98–4175, 15 p.

Eaton, D.L., and Klaassen, C.D., 2001, Principles of toxicology, *in* Klaasen, C.D., ed., Casarett and Doull's Toxicology: The Basic Science of Poisons (6th ed.): New York, McGraw-Hill, p. 1236.

Edmonds, R.J., and Gellenbeck, D.J., 2002, Ground-water quality in the West Salt River Valley, Arizona, 1996–98—Relations to hydrogeology, water use, and land use: U.S. Geological Survey Water-Resources Investigations Report 01–4126, 60 p.

Embrey, S.S., and Runkle, D.L., 2006, Microbial quality of the Nation's ground-water resources, 1993–2004: U.S. Geological Survey Scientific Investigations Report 2006–5290, 34 p.

Erickson, M.L., and Barnes, R.J., 2005, Glacial sediment causing regional-scale elevated arsenic in drinking water: Ground Water, v. 43, no. 6, p. 796–805.

Faires, L.M., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of metals in water by inductively coupled plasma-mass spectrometry: U.S. Geological Survey Open-File Report 92–634, 28 p.

Field, R.W., and Kross, B.C., 1996, Intercomparison of waterborne radon-222 collection methods—Professional vs. homeowner collection: Ground Water Monitoring & Remediation, v. 16, p. 106–112.

Field, R.W., and Kross, B.C., 1998, Iowa survey of waterborne ^{222}Rn concentrations in private wells: Health Physics, v. 74, no. 2, p. 249–252.

Fishman, M.J., ed., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of inorganic and organic constituents in water and fluvial sediments: U.S. Geological Survey Open-File Report 98–125, 217 p.

Fishman, M.J., and Friedman, L.C., 1989, Methods for determination of inorganic and organic constituents in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.

Florida Department of Health, 2006, Drinking water toxics program: Tallahassee, Fla., Florida Department of Health, Division of Environmental Health, accessed August 24, 2006, at http://www.doh.state.fl.us/environment/water/pdfs/brochure_toxics.pdf.

Focazio, M.J., Szabo, Zoltan, Kraemer, T.F., Mullin, A.H., Barringer, T.H., and DePaul, V.T., 2001, Occurrence of selected radionuclides in ground water used for drinking water in the United States—A reconnaissance survey, 1998: U.S. Geological Survey Water-Resources Investigations Report 00–4273, 40 p.

Focazio, M.J., Tipton, Deporah, Shapiro, S.D., and Geiger, L.H., 2006, The chemical quality of self-supplied domestic well water in the United States: Ground Water Monitoring & Remediation, v. 26, no. 3, p. 1–13.

Focazio, M.J., Welch, A.H., Watkins, S.A., Helsel, D.R., and Horn, M.A., 2000, A retrospective analysis on the occurrence of arsenic in ground-water resources of the United States and limitations in drinking-water-supply characterization: U.S. Geological Survey Water-Resources Investigations Report 99–4279, 22 p.

Fong, A.L., Andrews, W.J., and Stark, J.R., 1998, Water-quality assessment of part of the Upper Mississippi River Basin, Minnesota and Wisconsin—Ground-water quality in the Prairie du Chien-Jordan Aquifer, 1996: U.S. Geological Survey Water-Resources Investigations Report 98–4248, 45 p.

Furlong, E.T., Anderson, B.D., Werner, S.L., Soliven, P.P., Coffey, L.J., and Burkhardt, M.R., 2001, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of pesticides in water by graphitized carbon-based solid-phase extraction and high-performance liquid chromatography/mass spectrometry: U.S. Geological Survey Water-Resources Investigations Report 01–4134, 73 p.

Gabarino, J.R., 1999, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of dissolved arsenic, boron, lithium, selenium, strontium, thallium, and vanadium using inductively coupled plasma-mass spectrometry: U.S. Geological Survey Open-File Report 99–093, 31 p.

Gilliom, R.J., Alley, W.M., and Gurtz, M.E., 1995, Design of the National Water-Quality Assessment Program—Occurrence and distribution of water-quality conditions: U.S. Geological Survey Circular 1112, 33 p.

Gilliom, R.J., Barbash, J.E., Crawford, C.G., Hamilton, P.A., Martin, J.D., Nakagaki, Naomi, Nowell, L.H., Scott, J.C., Stackelberg, P.E., Thelin, G.P., and Wolock, D.M., 2006, Pesticides in the Nation's streams and ground water, 1992–2001: U.S. Geological Survey Circular 1291, 172 p., available at http://ca.water.usgs.gov/pnsp/pubs/circ1291.

Gilliom, R.J., Hamilton, P.A., and Miller, T.L., 2001, The National Water-Quality Assessment Program—Entering a new decade of investigations: U.S. Geological Survey Fact Sheet 071–01, 6 p., accessed October 11, 2006, at http://pubs.usgs.gov/fs/fs-071-01/pdf/fs07101.pdf.

Glass, R.L., 2001, Ground-water quality in Cook Inlet Basin, Alaska, 1999: U.S. Geological Survey Water-Resources Investigations Report 01–4208, 58 p.

Goetsch, W.D., McKenna, D.P., and Bicki, T.J., 1992, Statewide survey for agricultural chemicals in rural, private water-supply wells in Illinois: Springfield, Ill., Illinois Department of Agriculture.

Goodenkauf, Owen, and Atkinson, J.C., 1986, Occurrence of volatile organic chemicals in Nebraska ground water: Ground Water, v. 24, no. 2, p. 231–233.

Gosselin, D.C., Headrick, Jacqueline, Chen, X.H., Summerside, Scott, Tremblay, Rod, and Bottger, Kurt, 1996, Domestic well-water quality in rural Nebraska: Lincoln, Nebr., University of Nebraska, Institute of Agriculture and Natural Resources, Conservation and Survey Division, and Nebraska Department of Health, April 1996, variously paginated.

Gosselin, D.C., Headrick, Jacqueline, Haravey, F.E., Tremblay, Rod, and McFarland, Kimberly, 1999, Fluoride in Nebraska's ground water: Ground Water Monitoring & Remediation, v. 19, p. 87–95.

Gosselin, D.C., Headrick, Jacqueline, Tremblay, Rod, Chen, X.H., and Summerside, Scott, 1997, Domestic well water quality in rural Nebraska: Focus on nitrate-nitrogen, pesticides, and coliform bacteria: Ground Water Monitoring & Remediation, v. 17, p. 77–87.

Gotkowitz, M.G., Schreiber, M.E., and Simo, J.A., 2004, Effects of water use on arsenic release to well water in a confined aquifer: Ground Water, v. 42, no. 4, p. 568–575.

Hagan, E.F., 2004, State ambient ground water quality monitoring program, Arsenic speciation results (2002 & 2003): Idaho Department of Water Resources, Ground water quality technical brief, September 2004, 13 p., accessed September 14, 2006, at http://www.idwr.state.id.us/hydrologic/info/pubs/gwq/Arsenic_Technical_Brief_final.pdf.

Hallberg, G.R., Woida, K., Libra, R.D., Rex, K.D., Sesker, K.D., Kross, B.C., Seigley, L.S., Nations, B.K., Quade, D.J., Bruner, D.R., Nicholson, H.F., Johnson, J.K., and Cherryholmes, K.L., 1992, The Iowa state-wide rural well-water survey—Site and well characteristics and water quality: Iowa City, Iowa, Iowa Department of Water Resources, Technical Information Series 23, 43 p., accessed August 24, 2006, at http://www.igsb.uiowa.edu/gspubs/pdf/TIS-23.pdf.

Hamilton, P.A., Miller, T.L., and Myers, D.N., 2004, Water quality in the Nation's streams and aquifers—Overview of selected findings, 1991–2001: U.S. Geological Survey Circular 1265, 20 p., available at http://pubs.usgs.gov/circ/2004/1265/pdf/circular1265.pdf.

Hamlin, S.N., Belitz, Kenneth, Kraja, Sarah, and Dawson, Barbara, 2002, Ground-water quality in the Santa Ana Watershed, California—Overview and data summary: U.S. Geological Survey Water-Resources Investigations Report 02–4243, 137 p.

Helsel, D.R., 2005a, Insider censoring—Distortion of data with nondetects: Human and Ecological Risk Assessment, v. 11, p. 1127–1137.

Helsel, D.R., 2005b, Nondetects and Data Analysis: Hoboken, N.J., Wiley-Interscience, 250 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Hess, C.T., Michel, J., Horton, T.R., Prichard, H.M., and Coniglio, W.A., 1985, The occurrence of radioactivity in public water supplies in the United States: Health Physics, v. 48, no. 5, p. 553–586.

Holden, L.R., Graham, J.A., Whitmore, R.W., Alexander, W.J., Pratt, R.W., Liddle, S.K., and Piper, L.L., 1992, Results of a national alachlor well water survey: Environmental Science & Technology, v. 26, p. 935–943.

Hopke, P.K., Borak, T.B., Doull, J., Cleaver, J.E., Eckerman, K.F., Gundersen, L.C.S., Harley, N.H., Hess, C.T., Kinner, N.E., Kopecky, K.J., McKone, T.E., Sextro, R.G., and Simon, S.L., 2000, Health risks due to radon in drinking water: Environmental Science & Technology, v. 34, no. 6, p. 921–926.

Hutson, S.S., Barber, N.L., Kenney, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A., 2004, Estimated use of water in the United States in 2000: U.S. Geological Survey Circular 1268, 46 p.

Inkpen, E.L., Tesoriero, A.J., Ebbert, J.C., Silva, S.R., and Sandstrom, M.W., 2000, Ground-water quality in regional, agricultural, and urban settings in the Puget Sound Basin, Washington and British Columbia, 1996–1998: U.S. Geological Survey Water-Resources Investigations Report 00–4100, 66 p.

Institute of Medicine, 1997, Dietary Reference Intakes for Calcium, Phosphorus, Magnesium, Vitamin D, and Fluoride: Washington, D.C., National Academy Press, 432 p.

Iowa Department of Natural Resources, 2004, Iowa community private well study: Iowa City, Iowa, Iowa Department of Natural Resources, Geological Survey, Water Fact Sheet 2004–4, accessed October 4, 2006, at http://www.cheec.uiowa.edu/private_well/priv_well.pdf.

ISSI Consulting Group, The Cadmus Group, Inc., and ICF Consulting, 2000, Arsenic occurrence in public-drinking water supplies: Washington, D.C., U.S. Environmental Protection Agency, Office of Water, EPA-815-R-00-023, 156 p.

Ivahnenko, Tamara, and Zogorski, J.S., 2006, Sources and occurrence of chloroform and other trihalomethanes in drinking-water supply wells in the United States: 1986–2001: U.S. Geological Survey Scientific Investigations Report 5006–5015, 13 p.

Jurgens, B.C., Burow, K.R., Dalgish, B.A., and Shelton, J.L., 2008, Hydrogeology, water chemistry, and factors affecting the transport of contaminants in the zone of contribution of a public-supply well in Modesto, Eastern San Joaquin Valley, California: U.S. Geological Survey Scientific Investigations Report 2008–5156, 78 p.

Kelly, W.R., Holm, T.R., Wilson, S.D., and Roadcap, G.S., 2005, Arsenic in glacial aquifers—Sources and geochemical controls: Ground Water, v. 43, no. 4, p. 500–510.

Klaseus, T.G., Buzicky, G.C., and Schneider, E.C., 1988, Pesticides and groundwater—Surveys of selected Minnesota wells: Minneapolis, Minn., Minnesota Department of Health and Minnesota Department of Agriculture, 95 p., accessed September 25, 2006, at http://www.co.stearns.mn.us/documents/ground21.pdf.

Kolker, Allan, Haack, S.K., Cannon, W.F., Westjohn, D.B., Kim, M.J., Nriagu, Jerome, and Woodruff, L.G., 2003, Arsenic in southeastern Michigan, *in* Welch, A.H., and Stollenwerk, K.G., eds., Arsenic in Ground Water: Boston, Mass., Kluwer Academic Publishers, p. 281–294.

Kolpin, D.W., 1997, Agricultural chemicals in groundwater of the Midwestern United States—Relations to land use: Journal of Environmental Quality, v. 26, no. 4, p. 1025–1037.

Kolpin, D.W., Barbash, J.E., and Gilliom, R.J., 1998, Occurrence of pesticides in shallow groundwater of the United States—Initial results from the National Water-Quality Assessment: Environmental Science & Technology, v. 32, p. 558–566.

Kolpin, D.W., Burkart, M.R., and Thurman, E.M., 1994, Herbicides and nitrate in near-surface aquifers in the mid-continental United States, 1991: U.S. Geological Survey Water-Supply Paper 2413, 34 p.

Koterba, M.T., 1998, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program—Collection, documentation, and compilation of required site, well, subsurface, and landscape data for wells: U.S. Geological Survey Water-Resources Investigations Report 98–4107, 91 p.

Koterba, M.T., Wilde, F.D., and Lapham, W.W., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program—Collection and documentation of water-quality samples and related data: U.S. Geological Survey Open-File Report 99–399, 113 p.

Lapham, W.W., Hamilton, P.A., and Myers, D.N., 2005, National Water-Quality Asssessment Program—Cycle II, Regional assessments of aquifers: U.S. Geological Survey Fact Sheet 2005–3013, 4 p., accessed October 11, 2006, at http://pubs.usgs.gov/fs/2005/3013/pdf/PASforWeb.pdf.

Lapham, W.W., Wilde, F.D., and Koterba, M.T., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program—Selection, installation, and documentation of wells, and collection of related data: U.S. Geological Survey Open-File Report 95–398, 69 p.

Lapham, W.W., Wilde, F.D., and Koterba, M.T., 1997, Guidelines and standard procedures for studies of ground-water quality—Selection and installation of wells, and supporting documentation: U.S. Geological Survey Water-Resources Investigations Report 96–4233, 110 p.

Lawrence, Errol, Poeter, Eileen, and Wanty, Richard, 1991, Geohydrologic, geochemical, and geologic controls on the occurrence of radon in ground water near Conifer, Colorado, U.S.A.: Journal of Hydrology, v. 127, p. 367–386.

Lee, Lopaka, 2005, The NADA package—Nondetects and data analysis for environmental data, v. 1.2–1: accessed September 2005, at http://www.stats.bris.ac.uk/R/doc/packages/NADA.pdf.

LeGrand, H.E., 1987, Radon and radium emanations from fractured crystalline rocks—A conceptual hydrogeological model: Ground Water, v. 25, no. 1, p. 59–69.

LeMasters, Gary, and Doyle, D.J., 1989, Grade A dairy farm well water quality survey: Madison, Wis., Wisconsin Department of Agriculture, Trade, and Consumer Protection and Wisconsin Agricultural Statistics Service, April 1989, 36 p.

Liang, J.L., Dziuban, E.J., Craun, G.F., Hill, Vincent, Moore, M.R., Gelting, R.J., Calderon, R.L., Beach, M.J., and Roy, S.L., 2006, Surveillance for waterborne-disease outbreaks associated with drinking water and water not intended for drinking—United States, 2003–2004: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, Morbidity and Mortality Weekly Report, v. 55, no. SS-12, p. 31–58.

Lince, D.P., Wilson, L.R., Carlson, G.A., and Bucciferro, Anthony, 2001, Effects of gasoline formulation on methyl *tert*-butyl ether (MTBE) contamination in private wells near gasoline stations: Environmental Science & Technology, v. 35, no. 6, p. 1050–1053.

Liu, Aiguo, Ming, Jinghua, and Ankumah, R.O., 2005, Nitrate contamination in private wells in rural Alabama, United States: Science of the Total Environment, v. 346, p. 112–120.

Longtin, J.P., 1988, Occurrence of radon, radium, and uranium in groundwater: Journal of the American Water Works Association, v. 80, p. 84–93.

Loomis, D.P., 1987, Radon-222 concentration and aquifer lithology in North Carolina: Ground Water Monitoring Review: v. 7, no. 2, p. 33–39.

Louisiana Department of Environmental Quality, 2003, Baseline monitoring program, Fiscal years 2001–2003 (July 2000 through June 2003): Environmental Technology Division of the Louisiana Department of Environmental Quality, Triennial summary report, 2003, 29 p.

Ludtke, A.S., and Woodworth, M.T., 1997, USGS inorganic blind sample program (IBSP) monitoring and evaluating laboratory analytical quality: U.S. Geological Survey Fact Sheet FS-136-97.

Maas, R.P., Kucken, D.J., Patch, S.C., Peek, B.T., and Van Engelen, D.L., 1995, Pesticides in eastern North Carolina rural supply wells—Land use factors and persistence: Journal of Environmental Quality, v. 24, no. 3, p. 426–431.

Mahler, R.L., and Loeffelman, K.A., 1999, Idaho wellhead sampling program, Nitrate sampling, Cumulative results, 1990–99: Moscow, Idaho, University of Idaho, Soil Science Divisions, WQ-39, accessed August 24, 2006, at http://www.uidaho.edu/wq/wqbr/wqbr39.html.

Maine Department of Human Services, 1998, The presence of MTBE and other gasoline compounds in Maine's drinking water—A preliminary report: Augusta, Maine, Maine Department of Human Services, Bureau of Health, October 13, 1998, 24 p.

Mallatt, M., Moore, E., Lutz, E., Yoder, K., and Oldham, J.M., 2003, Natural fluoride concentrations of private wells in Indiana: Proceedings, 32nd Annual Meeting and Exhibition of the American Association for Dental Research: San Antonio, Tex., March 12–15, 2003, accessed September 12, 2006, at http://iadr.confex.com/iadr/2003/SanAnton/techprogram/abstract_27977.htm

Martin, J.D., 1999a, Summary and evaluation of pesticides in field blanks collected for the National Water-Quality Assessment Program, 1992–95: U.S. Geological Survey Open-File Report 98–412, 102 p.

Martin, J.D., 1999b, Quality of pesticides for environmental water samples collected for the National Water-Quality Assessment Program, 1992–96, and examples of the use of quality-control information in water-quality assessments: accessed November 2, 2006, at http://ca.water.usgs.gov/pnsp/rep/qcsummary.

Martin, J.D., 2002, Variability of pesticide detections and concentrations in field replicate water samples collected for the National Water-Quality Assessment Program, 1992–97: U.S. Geological Survey Water-Resources Investigations Report 01–4178, 84 p.

Maupin, M.A., and Barber, N.L., 2005, Estimated withdrawals from principal aquifers in the United States, 2000: U.S. Geological Survey Circular 1279, 46 p.

Mays, C.W., Rowland, R.E., and Steyney, A.F., 1985, Cancer risk from the lifetime intake of Ra and U isotopes: Health Physics, v. 48, p. 635–647.

McLain, Betty, 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of chromium in water by graphite furnace atomic absorption spectrophotometry: U.S. Geological Survey Open-File Report 93–449, 16 p.

McMahon, P.B., and Chapelle, F.H., 2008, Redox processes and water quality of selected principal aquifer systems: Ground Water, v. 46, p. 259–271.

Mehnert, Edward, Schock, S.C., Barnhardt, M.L., Caughey, M.E., Chou, S.F.J., Dey, W.S., Dreher, G.B., and Ray, Chittaranjan, 1995, The occurrence of agricultural chemicals in Illinois' rural, private wells—Results from the pilot study: Ground Water Monitoring & Remediation, v. 15, p. 142–149.

Menheer, M.A., and Brigham, M.E., 1997, Ground-water sampling methods and quality-control data for the Red River of the North Basin, Minnesota, North Dakota, and South Dakota, 1993–95: U.S. Geological Survey Water-Resources Investigations Report 96–4317, 34 p.

Milby-Dawson, B.J., 2001, Ground-water quality in the southeastern Sacramento Valley Aquifer, California, 1996: U.S. Geological Survey Water-Resources Investigations Report 01–4125, 24 p.

Miller, J.A., ed., 2000, Ground water atlas of the United States: Reston, Va., U.S. Geological Survey, variously paginated.

Mitchell, T.J., and Harding, A.K., 1996, Who is drinking nitrate in their well water?—A study conducted in rural northeastern Oregon: Journal of Environmental Health, v. 58, p. 14–19.

Montgomery, D.L., Ayotte, J.D., Carroll, P.R., and Hamlin, Patricia, 2003, Arsenic concentrations in private bedrock wells in southeastern New Hampshire: U.S. Geological Survey Fact Sheet FS-051-03, 4 p.

Moran, M.J., Zogorski, J.S., and Rowe, B.L., 2006, Approach to an assessment of volatile organic compounds in the Nation's ground water and drinking-water supply wells: U.S. Geological Survey Open-File Report 2005–1452, 36 p.

Moran, M.J., Zogorski, J.S., and Squillace, P.J., 2005, MTBE and gasoline hydrocarbons in ground water of the United States: Ground Water, v. 43, no. 4, p. 615–627.

Moran, M.J., Zogorski, J.S., and Squillace, P.J., 2007, Chlorinated solvents in groundwater of the United States: Environmental Science & Technology, v. 41, no. 4, p. 74–81.

Mueller, D.K., and Titus, C.J., 2005, Quality of nutrient data from streams and ground water sampled during water years 1992–2001: U.S. Geological Survey Scientific Investigations Report 2005–5106, 27 p.

Nakagaki, Naomi, and Wolock, D.M., 2005, Estimation of agricultural pesticide use in drainage basins using land cover maps and county pesticide data: U.S. Geological Survey Open-File Report 2005–1188, 46 p., accessed November 2005, at http://pubs.usgs.gov/of/2005/1188.

National Atmospheric Deposition Program, 2005, 2000 Isopleth Maps, accessed October 5, 2005, at http://nadp.sws.uiuc.edu/isopleths/maps2000.

National Ground Water Association, 2006, Getting your water tested: Dublin, Ohio, National Ground Water Association, accessed February 17, 2006, at http://www.wellowner.org/awaterquality/testing.shmtl.

National Research Council, 1989, Risk assessment of mixtures of systemic toxicants in drinking water: Washington, D.C., National Academy of Sciences, National Research Council, Drinking Water and Health, v. 9, p. 121–132.

National Research Council, 2001, Arsenic in Drinking Water, 2001 Update: Washington, D.C., National Academy Press, 225 p.

Neely, K.W., 2005, Nitrate overview for the statewide ambient ground water quality monitoring program, 1990–2003: Idaho Department of Water Resources, Ground water quality technical brief, January 7, 2005, 12 p., accessed August 24, 2006, at http://www.idwr.state.id.us/hydrologic/info/pubs/gwq/Nitrate_Report_2005.pdf

New Jersey Department of Environmental Protection, 2008, New Jersey Private Well Testing Act Program—Well test results for September 2002–April 2007: Trenton, N.J., New Jersey Department of Environmental Protection, 64 p., accessed September 18, 2008, at http://www.nj.gov/dep/pwta.

New Mexico Department of Health, 1998, Executive summary—Well-water quality assessment for southern New Mexico: Las Cruces, N.M., New Mexico Department of Health, Border Health Council, accessed October 4, 2006, at http://www.mnsu.edu/~bho/bhc/h20-nm.html.

Nolan, B.T., 1999, Nitrate behavior in ground waters of the southeastern United States: Journal of Environmental Quality, v. 28, no. 5, p. 1518–1527.

Nolan, B.T., 2001, Relating nitrogen sources and aquifer susceptibility to nitrate in the shallow ground waters of the United States: Ground Water, v. 39, no. 2, p. 290–299.

Nolan, B.T., and Hitt, K.J., 2003, Nutrients in shallow ground waters beneath relatively undeveloped areas in the conterminous United States: U.S. Geological Survey Water-Resources Investigations Report 02–4289, 17 p.

Nolan, B.T., and Hitt, K.J., 2006, Vulnerability of shallow groundwater and drinking-water wells to nitrate in the United States: Environmental Science & Technology, v. 40, no. 24, p. 7834–7840.

Nolan, B.T., Hitt, K.J., and Ruddy, B.C., 2002, Probability of nitrate contamination of recently recharged groundwaters in the conterminous United States: Environmental Science & Technology, v. 36, no. 10, p. 2138–2145.

Nolan, B.T., and Ruddy, B.C., 1996, Nitrate in ground waters of the United States—assessing the risk: U.S. Geological Survey Fact Sheet FS-092-96, 4 p.

Nolan, B.T., and Stoner, J.D., 2000, Nutrients in groundwaters of the conterminous United States, 1992–1995: Environmental Science & Technology, v. 34, no. 7, p. 1156–1165.

North Carolina Department of Health and Human Services, 2003, Contamination of private drinking well water by nitrates: North Carolina Department of Health and Human Services, Public Health, accessed August 31, 2006, at http://www.epi.state.nc.us/epi/meri/ilocontamination.html.

Oregon Department of Human Services, 2003, Domestic well testing program: Portland, Oreg., accessed September 28, 2006, at http://Oregon.gov/DHS/ph/dwp/docs/dwtrules.pdf.

Otton, J.K., Gundersen, L.C.S., and Schumann, R.R., 1993, The geology of radon: U.S. Geological Survey General Interest Publication, 29 p.

Patton, C.J., and Truitt, E.P., 2000, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of ammonium plus organic nitrogen by a Kjeldahl digestion method and an automated photometric finish that includes digest cleanup by gas diffusion: U.S. Geological Survey Open-File Report 00–170, 31 p.

Peters, S.C., Blum, J.D., Klaue, Bjoern, and Karagas, M.R., 1999, Arsenic in New Hampshire drinking water: Environmental Science & Technology, v. 33, no. 9, p. 1328–1333.

Pirkey, K.D., and Glodt, S.R., 1998, Quality control at the U.S. Geological Survey National Water Quality Laboratory: U.S. Geological Survey Fact Sheet FS-026-98.

Plummer, L.N., Busenberg, Eurybiades, Eberts, S.M., Bexfield, L.M., Brown, C.J., Fahlquist, L.S., Katz, B.G., and Landon, M.K., 2008, Low-level detections of halogenated volatile organic compounds in groundwater—Use in vulnerability assessments: Journal of Hydrologic Engineering, v. 13, no. 11, p. 1049–1068.

Poff, J.A., and Ross, B.B., 2000, A confidence report for Virginia's groundwater: Blacksburg, Va., Virginia Water Resources Research Center Special Report, 65 p.

Pope, L.M., Bruce, B.W., and Hansen, C.V., 2001, Groundwater quality in the Quaternary deposits of the central High Plains Aquifer, south-central Kansas, 1999: U.S. Geological Survey Water-Resources Investigations Report 00–4259, 44 p.

Price, C.V., Nakagaki, N., Hitt, K.J., and Clawges, R.M., 2007, Enhanced historical land-use and land-cover data sets of the U.S. Geological Survey: U.S. Geological Survey Data Series 240 [digital data], at http://pubs.usgs.gov/ds/2006/240.

Ray, Chittaranjan, and Schock, S.C., 1996, Comparability of large-scale studies of agricultural contamination of rural private wells: Ground Water Monitoring & Remediation, v. 16, p. 92–102.

Reutter, D.C., and Dunn, D.D., 2000, Water-quality assessment of the Trinity River Basin, Texas—Ground-water quality of the Trinity, Carrizo-Wilcox, and Gulf Coast Aquifers, February–August 1994: U.S. Geological Survey Water-Resources Investigations Report 99–4233, 56 p.

Richards, R.P., Baker, D.B., Creamer, N.L., Kramer, J.W., Ewing, D.E., Merryfield, B.J., and Wallrabenstein, L.K., 1996, Well water quality, well vulnerability, and agricultural contamination in the Midwestern United States: Journal of Environmental Quality, v. 25, p. 389–402.

Riding, Rich, and Quilter, M.C., 2004, 2004 State of Utah ground-water program: Utah Department of Food and Agriculture, 15 p., accessed September 7, 2006, at http://www.ag.state.ut.us/conservation/gw_report.pdf.

Riewe, Tom, Weissbach, Annette, Heinen, Liz, and Stoll, Rick, 2000, Naturally occurring arsenic in well water in Wisconsin: Water Well Journal, June 2000, accessed September 11, 2006, at http://www.dnr.state.wi.us/org/water/dwg/arsenic/NOA_In_WI.pdf.

Robinson, J.L., 2003, Comparison between agricultural and urban ground-water quality in the Mobile River Basin, 1999–2001: U.S. Geological Survey Water-Resources Investigations Report 03–4182, 37 p.

Rose, D.L., and Schroeder, M.P., 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: U.S. Geological Survey Open-File Report 94–708, 26 p.

Rowe, B.L., Delzer, G.C., Bender, D.A., and Zogorski, J.S., 2005, Volatile organic compound matrix spike recoveries for ground- and surface-water samples, 1997–2001: U.S. Geological Survey Scientific Investigations Report 2005–5225, 51 p.

Ruddy, B.C., Lorenz, D.L., and Mueller, D.K., 2006, County-level estimates of nutrient inputs to the land surface of the conterminous United States, 1982–2001: U.S. Geological Survey Scientific Investigations Report 2006–5102, 17 p.

Ryker, Sarah, 2001, Mapping arsenic in groundwater: Geotimes, November 2001, accessed December 2005, at http://www.agiweb.org/geotimes/nov01/feature_Asmap.html.

SAS Institute, 1998, StatView Reference (2d ed.): Cary, N.C., Sas Institute, Inc., 528 p.

Savoca, M.E., Sadorf, E.M., and Akers, K.K., 1999, Groundwater quality in the eastern part of the Silurian-Devonian and Upper Carbonate Aquifers in the Eastern Iowa Basins, Iowa and Minnesota, 1996: U.S. Geological Survey Water-Resources Investigations Report 98–4224, 31 p.

Schock, S.C., Mehnert, Edward, Caughey, M.E., Dreher, G.B., Dey, W.S., Wilson, Steven, Ray, Chittaranjan, Chou, S.F.J., Valkenburg, John, Gosar, J.M., Karny, J.R., Barnhardt, M.L., Black, W.F., Brown, M.R., and Garcia, V.J., 1992, Pilot study—Agricultural chemicals in rural, private wells in Illinois: Illinois State Geological Survey and Illinois State Water Survey Cooperative Report 14, 80 p., accessed September 12, 2006, at http://www.sus.uiuc.edu/pubdoc/coop/SWSCoop_14.pdf.

Schreiber, M.E., Gotkowitz, M.B., Simo, J.A., and Freiberg, P.G., 2003, Mechanisms of arsenic release to water from naturally occurring sources, eastern Wisconsin, in Welch, A.H., and Stollenwerk, K.G., eds., Arsenic in Ground Water—Occurrence and geochemistry: Boston, Mass., Kluwer Academic Publishers, chap. 9, p. 259–280.

Schwartz, G.E., and Alexander, R.B., 1995, Soils data for the conterminous United States derived from the NRCS State Soil Geographic (STATSGO) Data Base: Reston, Va., U.S. Geological Survey, accessed November 13, 2008, at http://water.usgs.gov/GIS/metadata/usgswrd/XML/ussoils.xml.

Scott, J.C., 1990, Computerized stratified random site-selection approaches for design of a ground-water-quality sampling network: U.S. Geological Survey Water-Resources Investigations Report 90–4101, 109 p.

Senior, L.A., 1998, Radon-222 in the ground water of Chester County, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 98–4169, 79 p.

Shapiro, S.D., Busenberg, Eurybiades, Focazio, M.J., and Plummer, L.N., 2004, Historical trends in occurrence and atmospheric inputs of halogenated volatile organic compounds in untreated ground water used as a source of drinking water: Science of the Total Environment, v. 321, p. 201–271.

Shiber, J.G., 2005, Arsenic in domestic well water and health in central Appalachia, USA: Water, Air, and Soil Pollution, v. 160, p. 327–341.

Sievers, D.M., and Fulhage, C.D., 1992, Nitrate in rural wells of Missouri: Transactions of the American Society of Agricultural Engineers, v. 35, no. 5, p. 1633–1637.

Sloto, R.A., and Senior, L.A., 1998, Radon in the ground water of Chester County, Pennsylvania: U.S. Geological Survey Fact Sheet 120–98, 4 p.

Solley, W.B., Pierce, R.R., and Perlman, H.A., 1998, Estimated use of water in the United States in 1995: U.S. Geological Survey Circular 1200, 71 p., data accessed February 2006, at http://water.usgs.gov/watuse.

Sonan, Leticia, Vendrell, Paul, and Hitchcock, Rick, 2005, Water quality in Georgia's private drinking water wells: Proceedings, Georgia Water Resources Conference, accessed August 24, 2006, at http://gwri.ce.gatech.edu/GAConf/News/GAConfNews.php.

Spruill, T.B., 1983, Statistical summaries of selected chemical constituents in Kansas ground-water supplies, 1976–1981: U.S. Geological Survey Open-File Report 83–263, 29 p.

Squillace, P.J., Scott, J.C., Moran, M.J., Nolan, B.T., and Kolpin, D.W., 2002, VOCs, pesticides, nitrate, and their mixtures in groundwater used for drinking water in the United States: Environmental Science & Technology, v. 36, no. 9, p. 1923–1930.

Stanley, D.L., Boozer, T.M., and Schroder, L.J., 1998, Summary of the U.S. Geological Survey National Field Quality Assurance Program from 1979 through 1997: U.S. Geological Survey Open-File Report 98–392, 15 p.

State Water Resources Control Board, 2005, Volunteer domestic well assessment project, El Dorado County Data Summary Report: Sacramento, Calif., California Environmental Protection Agency, State Water Resources Control Board, 23 p.

Steichen, James, Koelliker, James, Grosh, Doris, Heiman, Alan, Yearout, Robert, and Robins, Victor, 1988, Contamination of farmstead wells by pesticides, volatile organics, and inorganic chemicals in Kansas: Ground Water Monitoring & Remediation, v. 8, no. 3, p. 153–160.

Steinmaus, C.M., Yuan, Yan, and Smith, A.H., 2004, The temporal stability of arsenic concentrations in well water in western Nevada: Environmental Research, v. 99, p. 164–168.

Stuart, M.A., Rich, F.J., and Bishop, G.A., 1995, Survey of nitrate contamination in shallow domestic drinking water wells of the Inner Coastal Plain of Georgia: Ground Water, v. 33, no. 2, p. 284–290.

Suffolk County Department of Health Services, 1998, Water quality monitoring program to detect pesticide contamination in groundwaters of Nassau and Suffolk Counties, N.Y., 1997 PRL Annual Report—Appendix J: Suffolk County Department of Health Services, Division of Environmental Quality, Bureau of Groundwater Resources, Interim Report, June 1998, accessed September 5, 2006, at http://www.dec.state.ny.us/website/dshm/prl/scdoh.htm.

Swartz, G.E., and Alexander, R.A., 1995, Soils data for the conterminous United States derived from the NRCS State Soil Geographic (STATSGO) data base: U.S. Geological Survey Open-File Report 95–449 [digital data], accessed June 2002, at http://water.usgs.gov/lookup/getspatial?ussoils.

Swistock, B.R., Sharpe, W.E., and Robillard, P.D., 1993, A survey of lead, nitrate, and radon contamination of private individual water systems in Pennsylvania: Journal of Environmental Health, v. 55, no. 5, p. 6–12.

Sworobuk, J.E., Law, C.B., and Bissonnette, G.K., 1987, Assessment of the bacteriological quality of rural groundwater supplies in northern West Virginia: Water, Air, and Soil Pollution, v. 36, no. 1–2, p. 163–170.

Szabo, Zoltan, DePaul, V.T., Kraemer, T.F., and Parsa, Bahman, 2005, Occurrence of radium-224 and comparison to that of radium-226 and radium-228 in water from the unconfined Kirkwood-Cohansey aquifer system, southern New Jersey: U.S. Geological Survey Scientific Investigations Report 2004–5224, 92 p.

Szabo, Zoltan, Pucci, A.A., Jr., and Feigenson, M.D., 1997, Sr-isotopic evidence for leakage of pore water from clay-silt confining units to the Atlantic City 800-foot sand, Atlantic City, New Jersey, *in* Miller, K.G., and Snyder, S.W., eds., Proceedings of the Ocean Drilling Program, Scientific Results, v. 150X, p. 343–354.

Szabo, Zoltan, and Zapecza, O.S., 1991, Geologic and geochemical factors controlling uranium, radium-226, and radon-222 in ground water, Newark Basin, New Jersey, *in* Gunderson, L.C.S., and Wanty, R.B., eds., Field studies of radon in rocks, soils, and water: U.S. Geological Survey Bulletin 1971, p. 243–265.

Taglioli, B.L., Delzer, G.C., and Zogorski, J.S., 2000, Study design and analytical results used to evaluate carry-over contamination by volatile organic compounds in surface- and ground-water sampling procedures: U.S. Geological Survey Open-File Report 00–384, 36 p.

Thomas, M.A., 2007, The association of arsenic with redox conditions, depth, and ground-water age in the glacial system of the northern United States: U.S. Geological Survey Scientific Investigations Report 2007–5036, 26 p.

Toccalino, P.L., 2007, Development and application of health-based screening levels for use in water-quality assessments: U.S. Geological Survey Scientific Investigations Report 2007–5106, 12 p.

Toccalino, P.L., and Norman, J.E., 2006, Health-based screening levels to evaluate U.S. Geological Survey ground water quality data: Risk Analysis, v. 26, no. 5, p. 1339–1348.

Toccalino, P.L., Norman, J.E., Booth, N.L., and Zogorski, J.S., 2006, Health-based screening levels—A tool for evaluating what water-quality data may mean to human health: U.S. Geological Survey, National Water-Quality Assessment Program, accessed May 2007, at http://water.usgs.gov/nawqa/HBSL.

Toccalino, P.L., Nowell, Lisa, Wilber, William, Zogorski, John, Donahue, Joyce, Eiden, Catherine, Krietzman, Sandra, and Post, Gloria, 2003, Development of health-based screening levels for use in state- or local-scale water-quality assessments: U.S. Geological Survey Water-Resources Investigations Report 03–4054, 22 p.

Toccalino, P.L., Zogorski, J.S., and Norman, J.E., 2005, Health-based screening levels and their application to water-quality data: U.S. Geological Survey Fact Sheet 2005–3059, 2 p.

Townsend, M.A., Young, D.P., and Healy, J., 1998, Results of agrichemical survey of ground water in Kansas, 1993–1994: Lawrence, Kans., Kansas Geological Survey Open-File Report 98–22, 46 p.

Troiano, John, Weaver, Don, Marade, Joe, Spurlock, Frank, Pepple, Mark, Nordmark, Craig, and Bartkowiak, Donna, 2001, Summary of well water sampling in California to detect pesticide residues resulting from nonpoint source applications: Journal of Environmental Quality, v. 30, p. 448–459.

Tuthill, Anna, Meikle, D.B., and Alavanja, M.C.R., 1998, Coliform bacteria and nitrate contamination of wells in major soils of Frederick, Maryland: Journal of Environmental Health, v. 60, p. 16–20.

U.S. Centers for Disease Control and Prevention, 1998, A survey of the quality of water drawn from domestic wells in nine midwest states: U.S. Centers for Disease Control and Prevention, National Center for Environmental Health, accessed October 6, 1999, at http://www.cdc.gov/nceh/programs/emergenc/WellWater/MidwestWell.htm.

U.S. Centers for Disease Control and Prevention, 2003, Private well resources: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, accessed September 27, 2006, at http://www.cdc.gov/ncidod/dpd/healthywater/privatewell.htm.

U.S. Centers for Disease Control and Prevention, Fluoride Recommendations Work Group, 2001, Recommendations for using fluoride to prevent and control dental caries in the United States: Morbidity and Mortality Weekly Report, 50(RR14), August 17, 2001, p. 1–42.

U.S. Department of Agriculture, Natural Resources Conservation Service, 1994, State Soil Geographic (STATSGO) data base for the United States and Puerto Rico [digital data on CDROM]: Ft. Worth, Tex., U.S. Department of Agriculture.

U.S. Department of Health and Human Services, 1991, Review of fluoride—Benefits and risks: U.S. Department of Health and Human Services, Public Health Service, February 1991, variously paginated, accessed September 11, 2008, at http://www.health.gov/environment/ReviewofFluoride/default.htm.

U.S. Environmental Protection Agency, 1980, Prescribed procedures for measurement of radioactivity in drinking water: U.S. Environmental Protection Agency, Environmental Monitoring and Support Laboratory, Office of Research and Development, EPA 600-4-80-032, August 1980, 133 p.

U.S. Environmental Protection Agency, 1984, National statistical assessment of rural water conditions—Technical summary: Washington, D.C., U.S. Environmental Protection Agency, Office of Drinking Water, EPA570/9-84-004, 111 p.

U.S. Environmental Protection Agency, 1990a, National Pesticide Survey—Summary results of EPA's national survey of pesticides in drinking water wells: Washington, D.C., U.S. Environmental Protection Agency, Office of Water and Office of Pesticides and Toxic Substances, EPA 570/9-90-NPS5, 17 p., accessed October 3, 2006, at http://nepis.epa.gov/pubtitleOSWER.htm.

U.S. Environmental Protection Agency, 1990b, National Pesticide Survey—Project summary: Washington, D.C., U.S. Environmental Protection Agency, Office of Water and Office of Pesticides and Toxic Substances, EPA 570/9-90-NPS6, 11 p., accessed October 3, 2006, at http://nepis.epa.gov/pubtitleOSWER.htm.

U.S. Environmental Protection Agency, 1990c, National Pesticide Survey—Survey design: Washington, D.C., U.S. Environmental Protection Agency, Office of Water and Office of Pesticides and Toxic Substances, EPA 570/9-90-NPS1, 7 p., accessed October 3, 2006, at http://nepis.epa.gov/pubtitleOSWER.htm.

U.S. Environmental Protection Agency, 1990d, National Pesticide Survey—Survey analytes: Washington, D.C., U.S. Environmental Protection Agency, Office of Water and Office of Pesticides and Toxic Substances, EPA 570/9-90-NPS2, variously paginated, accessed October 3, 2006, at http://nepis.epa.gov/pubtitleOSWER.htm.

U.S. Environmental Protection Agency, 1992, National Pesticide Survey—Update and summary of Phase II results: Washington, D.C., U.S. Environmental Protection Agency, Office of Water and Office of Pesticides and Toxic Substances, EPA 570/9-91-021, 6 p., accessed October 3, 2006, at http://nepis.epa.gov/pubtitleOSWER.htm.

U.S. Environmental Protection Agency, 1997a, Reporting requirements for risk/benefit information: Federal Register, v. 62, no. 182, pp. 49, 369–49, 395.

U.S. Environmental Protection Agency, 1997b, Drinking water advisory—Consumer acceptability advice and health effects analysis on methyl tertiary-butyl ether (MtBE): Washington, D.C., U.S. Environmental Protection Agency, Office of Water, EPA 822-F-97-009, 42 p., accessed September 15, 2008, at http://www.epa.gov/waterscience/criteria/drinking/mtbe.pdf.

U.S. Environmental Protection Agency, 1999, Proposed radon in drinking water rule: Washington, D.C., U.S. Environmental Protection Agency, Office of Water, EPA 815-F-99-006, 6 p., accessed October 26, 2005, at http://www.epa.gov/safewater/radon/proposal.html.

U.S. Environmental Protection Agency, 2000a, National Water Quality Inventory, 1998 Report to Congress—Ground Water and Drinking Water Chapters: Washington, D.C., U.S. Environmental Protection Agency, Office of Water, EPA 816-R-00-013, 99 p., accessed September 28, 2006, at http://www.epa.gov/ogwde/protect/98_305b_all.pdf.

U.S. Environmental Protection Agency, 2000b, Radionuclides notice of data availability—Technical support document: Washington, D.C., U.S. Environmental Protection Agency, Office of Water, accessed December 28, 2006, at http://www.epa.gov/safewater/radionuclides/pdfs/regulation_radionuclides_rulemaking_techsupportdoc.pdf.

U.S. Environmental Protection Agency, 2001a, Factoids—Drinking water and ground water statistics for 2000: Washington, D.C., U.S. Environmental Protection Agency, Office of Water, EPA 816-K-01-004, 10 p., accessed September 28, 2006, at http://www.epa.gov/safewater/data/pdsfs/data_factoids_2000.pdf.

U.S. Environmental Protection Agency, 2001b, Radionuclides rule—A quick reference guide: Washington, D.C., U.S. Environmental Protection Agency, Office of Water, EPA 816-F-01-003, 2 p., accessed December 28, 2006, at http://www.epa.gov/safewater/radionuclides/pdfs/qrg_radionuclides.pdf.

U.S. Environmental Protection Agency, 2001c, Supplementary guidance for conducting health risk assessment of chemical mixtures: Washington, D.C., U.S. Environmental Protection Agency, Risk Assessment Forum, EPA 630-R-00-002, variously paginated., accessed January 17, 2007, at http://www.epa.gov/ncea/raf/pds/chem_mix_08_2001.pdf.

U.S. Environmental Protection Agency, 2002a, Drinking water from household wells: Washington, D.C., U.S. Environmental Protection Agency, Office of Water, EPA 816-K-02-003, 19 p., accessed September 28, 2006, at http://www.epa.gov/safewater/privatewells/household_wells.pdf.

U.S. Environmental Protection Agency, 2002b, Method 1103.1—*Escherichia coli (E. coli)* in water by membrane filtration using membrane-thermotolerant *E. coli* agar (MTec): U.S. Environmental Protection Agency, Office of Water, September 2002, EPA 821-R-02-020, 17 p.

U.S. Environmental Protection Agency, 2002c, Method 1604—Total coliforms and *Escherichia coli* in water by membrane filtration using a simultaneous detection technique (MI Medium): U.S. Environmental Protection Agency, Office of Water, September 2002, EPA 821-R-02-024, 18 p.

U.S. Environmental Protection Agency, 2003a, Announcement of regulatory determinations for priority contaminants on the drinking water contaminant candidate list: Washington, D.C., Federal Register, v. 68, no. 138, p. 42898–42905, accessed September 17, 2008, at http://edocket.access.gpo.gov/2003/pdf/03-18151.pdf.

U.S. Environmental Protection Agency, 2003b, Interim reregistration eligibility decision for atrazine: Washington, D.C., U.S. Environmental Protection Agency, Office of Pesticide Programs case no. 0062, 304 p., http://www.epa.gov/oppsrrd1/REDs/atrazine_ired.pdf.

U.S. Environmental Protection Agency, 2006a, 2006 Edition of the drinking water standards and health advisories: Washington, D.C., U.S. Environmental Protection Agency, Office of Water, EPA 822-R-06-013, 18 p.

U.S. Environmental Protection Agency, 2006b, Triazine cumulative risk assessment: Washington, D.C., U.S. Environmental Protection Agency, Office of Pesticide Programs, Health Effects Division, March 28, 2006, 67 p., http://www.epa.gov/oppsrrd1/REDs/triazine_cumulative_risk.pdf.

U.S. Environmental Protection Agency, 2008a, Drinking water—Regulatory determinations regarding contaminants on the second drinking water contaminant candidate list: Washington, D.C., Federal Register, v. 73, no. 147, p. 44251–44261, accessed September 17, 2008, at http://www.epa.gov/fedrgstr/EPA-WATER/2008/July/Day-30/w17463.pdf.

U.S. Environmental Protection Agency, 2008b, Regulatory determinations support document for selected contaminants from the second drinking water contaminant candidate list (CCL 2), Chapter 3—Boron: Washington, D.C., U.S. Environmental Protection Agency, Office of Ground Water and Drinking Water, EPA Report 815-R-08-012, 4 p., accessed September 17, 2008, at http://www.epa.gov/safewater/ccl/pdfs/reg_determine2/report_ccl2-reg2_supportdocument_full.pdf.

U.S. General Accounting Office, 1997, Drinking Water—Information on the quality of water found at community water systems and private wells: Washington, D.C., U.S. General Accounting Office, Resources, Community, and Economic Development Division, GAO/RCED-97-123, 47 p.

U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1–A9, accessed October 17, 2006, at http://water.usgs.gov/owq/FieldManual.

U.S. Geological Survey, 1997, NWIS—New remark code (V) for water-quality data: Office of Water Quality Technical Memorandum 97.08, accessed November 6, 2006, at http://water.usgs.gov/admin/ memo/QW/qw97.08.html.

U.S. Geological Survey, 1998, Changes in reporting levels and data qualifiers for selected pesticides and degradation products in schedules 2050 and 2051: National Water Quality Laboratory Technical Memorandum 98.03A, accessed November 6, 2006, at http://nwql.usgs.gov/Public/tech_memos/nwql.98-03A.html.

U.S. Geological Survey, 1999, The quality of our Nation's waters—Nutrients and pesticides: U.S. Geological Survey Circular 1225, 82 p., available at http://pubs.usgs.gov/circ/circ1225.

U.S. Geological Survey, 2003a, Principal aquifers, *in* National Atlas of the United States of America, 1 sheet, 1:5,000,000 scale, available at http://www.nationalatlas.gov/wallmaps.html.

U.S. Geological Survey, 2003b, Principal aquifers of the 48 conterminous United States, Hawaii, Puerto Rico, and the U.S. Virgin Islands: U.S. Geological Survey, Madison, Wisc., 1:2,500,000 scale, accessed September 12, 2006, at http://nationalatlas.gov/metadata/aquifrp025.faq.html.

U.S. Geological Survey, 2006a, Ground-water monitoring for pesticides in Wyoming: U.S. Geological Survey, Wyoming Water Science Center, accessed September 7, 2006, at http://wy.water.usgs.gov/projects/pesticide.

U.S. Geological Survey, 2006b, National Field Quality Assurance Program: U.S. Geological Survey, accessed November 1, 2006, at http://nfqa.cr.usgs.gov.

U.S. Geological Survey, 2006c, Organic Blind Sample Project: U.S. Geological Survey, accessed November 1, 2006, at http://bqs.usgs.gov/OBSP/index.html.

U.S. Senate, 2002, Title XIV of the public health service act, Safety of public water systems (Safe Drinking Water Act), Part A—Definitions (as amended through P.L. 107–377): Updated December 2002, accessed July 23, 2008, at http://epw.senate.gov/sdwa.pdf.

Veterans Benefits Administration, 2005, Lender's handbook, VA pamphlet 26-7, revised: Washington, D.C., U.S. Department of Veterans Affairs, Veterans Benefits Administration, variously paginated.

Vogelmann, J.E., Howard, S.M., Yang, L., Larson, C.R., Wylie, B.K., and VanDriel, N., 2001, Completion of the 1990s national land cover dataset for the conterminous United States from Landsat Thematic Mapper data and ancillary data sources: Photogrammetric Engineering and Remote Sensing, v. 67, p. 650–662.

Wanty, R.B., and Nordstrom, D.K., 1993, Natural radionuclides, *in* Alley, W.M., ed., Regional Ground-Water Quality: New York, Van Nostrand Reinhold, p. 423–441.

Wanty, R.B., Lawrence, E.P., and Gundersen, L.C.S., 1992, A theoretical model for the flux of radon-222 from rock to ground water, *in* Gates, A., and Gundersen, L.C.S., eds. Geological Society of America Special Paper 271, p. 73–78.

Warner, K.L., and Arnold, T.L., 2006, Framework for regional synthesis of water-quality data for the glacial aquifer system in the United States: U.S. Geological Survey Scientific Investigations Report 2005–5223, 6 p.

Welch, A.H., Szabo, Zoltan, Parkhurst, D.L., van Metre, P.C., and Mullin, A.H., 1995, Gross-beta activity in ground water: natural sources and artifacts of sampling and laboratory analysis: Applied Geochemistry, v. 10, p. 491–503.

Welch, A.H., Westjohn, D.B., Helsel, D.R., and Wanty, R.B., 2000, Arsenic in ground water of the United States: occurrence and geochemistry: Ground Water, v. 38, no. 4, p. 589–604.

Werner, S.L., Burkhardt, M.R., and DeRusseau, S.N., 1996, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of pesticides in water by Carbopak-B solid-phase extraction and high-performance liquid chromatography: U.S. Geological Survey Open-File Report 96–216, 42 p.

Wolock, D.M., 1997, STATSGO soil characteristics for the conterminous United States: U.S. Geological Survey Open-File Report 97–656 [digital data], accessed February 2004, at http://water.usgs.gov/lookup/getspatial?muid.

Wood, W.W., Kraemer, T.F., and Shapiro, Allen, 2004, Radon (^{222}Rn) in ground water of fractured rocks: a diffusion/ion exchange model: Ground Water, v. 42, no. 4, p. 552–567.

World Health Organization, 2004, Guidelines for Drinking-Water Quality (3d ed.), Volume 1, Recommendations: Geneva, Switzerland, World Health Organization, 515 p.

Zapecza, O.S., and Szabo, Zoltan, 1986, Natural radioactivity in ground water—a review: U.S. Geological Survey Water-Supply Paper 2325, p. 50–57.

Zaugg, S.D., Sandstrom, M.W., Smith, S.G., and Fehlberg, K.M., 1995, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of pesticides in water by C-18 solid-phase extraction and capillary-column gas chromatography/mass spectrometry with selected-ion monitoring: U.S. Geological Survey Open-File Report 95–181, 60 p.

Zogorski, J.S., Carter, J.M., Ivahnenko, Tamara, Lapham, W.W., Moran, M.J., Rowe, B.L., Squillace, P.J., and Toccalino, P.L., 2006, Volatile organic compounds in the Nation's ground water and drinking-water supply wells: U.S. Geological Survey Circular 1292, 101 p., available at http://water.usgs.gov/nawqa/vocs/national_assessment.

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix 1. Summary of selected studies on domestic well water quality in the United States

Table

1–1. Summary of selected studies on domestic well water quality in the United States 84

Table 1–1. Summary of selected studies on domestic well water quality in the United States.

[**Geographic scale:** Number in parentheses is number of states or counties in study area. U.S., United States. **Targeted contaminants:** Bact, fecal indicator bacteria; compounds. **Study findings: Percentage of wells with concentrations greater than USEPA MCLs:** Value for total coliform bacteria is any detection, MCL for maximum contaminant level; mg/L, milligram per liter; µg/L, microgram per liter; CDC, U.S. Centers for Disease Control and Prevention; USGS, U.S. Geological

State	Geographic scale	Targeted contaminants	Sampling design	Target population or area(s)
Multiple states	National	Bact, NO_3, Majors, TE, Rad, Pest	Random stratified	Rural households
	National	NO_3, Pest	Random and random stratified	Rural households
	Multiple states	Pest	Random stratifed	Counties where alachlor was sold
	Multiple states (12) in the midwestern U.S.	NO_3, Pest	Non-random	Agriculturual areas and shallow aquifers
	Multiple states (6)	All available data	Compilation of existing data	--
	Multiple states (5) in the midwestern U.S.	NO_3, Pest	Voluntary testing	--
	Multiple states (9) in the midwestern U.S.	Bact, NO_3, Pest	Random and random stratified	--
	Multiple states (4) in the southeastern U.S.	As	Voluntary testing	--
	National	NO_3, Majors, TE, Pest, VOCs, Rn, Rad	Non-random	--
Alabama	Statewide	NO_3	Voluntary testing	--
	County	Bact	Non-random	--
California	County	Bact, NO_3, TE, VOCs, Rad	Voluntary testing	Specific focus areas
Georgia	Multiple counties (61)	NO_3, Majors	Non-random	Counties with intensive agriculture
	Statewide	Bact, NO_3	Voluntary testing	--
Idaho	Statewide	NO_3	Unknown	--
	Statewide	As	Stratified random	--
	Statewide	NO_3	Stratified random	--
Illinois	Multiple counties (5)	NO_3, Pest	Stratified random	Agricultural areas with various aquifer depths
	Multiple counties (74)	NO_3, Pest	Random	--
	Statewide	F	Voluntary testing	--
Iowa	Statewide	Bact, NO_3, Majors, Pest	Stratified random	Rural households
	Statewide	Rn	Random	
	Statewide	Bact, NO_3, Pest, As	Random	Wells serving multiple households
Kansas	Statewide	NO_3, Majors, Rad	Non-random	--
	Multiple counties (49)	NO_3, Majors, TE, Pest, VOCs	Non-random	Farm households
	Multiple counties (33)	NO_3, Pest	Non-random	Agricultural areas with shallow water table and permeable sediments
Kentucky	Statewide	NO_3, Pest	Voluntary testing	--
Lousiana	Statewide	NO_3, Majors, TE, Pest, VOCs, others	Non-random stratified	--

NO_3, nitrate; Majors, major ions; TE, trace elements; Rn, radon; Rad, radioactivity or radionuclides other than radon; Pest, pesticides; VOCs, volatile organic nitrate is 10 mg/L as N, and MCL for arsenic is 10 µg/L; numbers have been rounded to two significant digits. USEPA, U.S. Environmental Protection Agency; MCL, Survey; Coop. Ext., University Cooperative Extension Program; --, not available or not applicable; ~, approximately]

Number of wells	Agency or agency type	Study findings: Percentage of wells with concentrations greater than USEPA MCLs			Reference
		Total coliform bacteria	Nitrate	Arsenic	
1,057	USEPA	42	4.1	--	U.S. Environmental Protection Agency (1984)
734	USEPA	--	2.4	--	U.S. Environmental Protection Agency (1990a, 1990b, 1992)
1,430	Industry	--	4.9	--	Holden and others (1992)
303	USGS	--	6.0	--	Kolpin and others (1994)
--	U.S. General Accounting Office	14–46	3.2–28.2	--	U.S. General Accounting Office (1997)
34,759	University	--	3.4	--	Richards and others (1996)
5,520	CDC	41	13	--	U.S. Centers for Disease Control and Prevention (1998)
[1]179	University	--	--	6.0	Shiber (2005)
~2,000–15,000	USGS	--	8.4	11	Focazio and others (2006)
1,021	Coop. Ext.	--	1.0–2.0	--	Liu and others (2005)
50	University	78	8.0	--	Conine and others (1989)
398	State	28	1.8	3.8	State Water Resources Control Board (2005)
2,588	State and University	--	1.7	--	Stuart and others (1995)
[2]1,413	Coop. Ext.	41	3.6	--	Sonan and others (2005)
2,524	University and other	--	6.0	--	Mahler and Loeffelman (1999)
[3]~1,900	State and USGS	--	5.0	~15	Hagan (2004)
[4]1,868	State and USGS	--	5.0	--	Neely (2005)
240	State	--	18	--	Schock and others (1992); Mehnert and others (1995)
337	State	--	11	--	Goetsch and others (1992) in Ray and Schock (1996)
8,519	State	--		--	Mallatt and others (2003)
686	State and University	45	18	--	Hallberg and others (1992)
352	University	--		--	Field and Kross (1998) and Field (1996)
103	University and USGS	30	23	2.9	Iowa Department of Natural Resources (2004)
[5]766	USGS and State	--	14	--	Spruill (1983)
103	University	--	28	--	Steichen and others (1988)
78	State	--	32	--	Townsend and others (1998)
4,859	Coop. Ext., State, and other	--	4.6	--	Carey and others (1993)
[6]194	State	--	0	1.0	Louisiana Department of Environmental Quality (2003)

Table 1–1. Summary of selected studies on domestic well water quality in the United States.—Continued

[**Geographic scale:** Number in parentheses is number of states or counties in study area. U.S., United States. **Targeted contaminants:** Bact, fecal indicator bacteria; compounds. **Study findings: Percentage of wells with concentrations greater than USEPA MCLs:** Value for total coliform bacteria is any detection, MCL for maximum contaminant level; mg/L, milligram per liter; µg/L, microgram per liter; CDC, U.S. Centers for Disease Control and Prevention; USGS, U.S. Geological

State	Geographic scale	Targeted contaminants	Sampling design	Target population or area(s)
Maine	Statewide	VOCs	Random	--
Maryland	County	Bact, NO_3	Required testing	--
Minnesota	Statewide	NO_3, Pest	Non-random	Agricultural areas with shallow water table and susceptible aquifers
Missouri	Multiple counties (~17)	NO_3	Non-random stratifed	Agricultural areas with various soil and aquifer types
Montana	Multiple counties (38)	Bact, NO_3	Voluntary testing	--
Nebraska	Statewide	VOCs	Non-random	Wells near waste-disposal sites
	Statewide	Bact, NO_3, F, Pest	Stratified random	--
New Hampshire	Statewide	As	Random	--
	Multiple counties (3)	As	Stratified random	Bedrock wells
New Jersey	Statewide	Bact, NO_3, TE, VOCs	Required testing	--
New Mexico	Multiple counties (4)	Bact, NO_3, F, As, others	Non-random	Wells near potential sources, high population areas, and in vulnerable aquifers
New York	Multiple counties (2)	Pest	Non-random	Wells near potential sources and other wells
North Carolina	Multiple counties (12)	NO_3, Pest	Non-random	Wells near row-crop farming
	Statewide	NO_3	Voluntary testing	Wells near intensive livestock operations
Ohio	Statewide	NO_3, Pest	Voluntary testing	--
Oregon	Multiple counties (2)	NO_3	Non-random	Intensive agricultural areas
Pennsylvania	County	Rn	Non-random	--
	Statewide	NO_3, Rn, Pb	Unknown	--
South Carolina	Multiple counties (21)	NO_3, VOCs	Non-random	Wells near toxic release sites
Tennesee	Statewide	Bact, NO_3, others	Non-random	Farm households
Utah	Statewide	Bact, NO_3, Pest	Voluntary testing	--
Virginia	Multiple counties (65)	Bact, NO_3	Voluntary testing	--
West Virginia	County	Bact	Random	Rural households
Wisconsin	Statewide	NO_3, Pest	Stratified random	Dairy farm households
	Statewide	NO_3, Pest	Stratified random	--
	Statewide	Bact, NO_3, others	Non-random	Wells near areas of septage disposal or densely located septic tanks
Wyoming	Statewide	Pest	Unknown	--

[1] Number is for bacteria samples only.
[2] 88 percent from domestic wells.
[3] 67 percent from domestic wells.
[4] About 2/3 from domestic wells.
[5] Percent of samples from domestic wells unspecified.
[6] 22 percent from domestic wells.
[7] Number of samples was 3,342.
[8] Not all wells were sampled for arsenic.
[9] At least 30 percent from domestic wells.

NO_3, nitrate; Majors, major ions; TE, trace elements; Rn, radon; Rad, radioactivity or radionuclides other than radon; Pest, pesticides; VOCs, volatile organic nitrate is 10 mg/L as N, and MCL for arsenic is 10 µg/L; numbers have been rounded to two significant digits. USEPA, U.S. Environmental Protection Agency; MCL, Survey; Coop. Ext., University Cooperative Extension Program; --, not available or not applicable; ~, approximately]

Number of wells	Agency or agency type	Study findings: Percentage of wells with concentrations greater than USEPA MCLs			Reference
		Total coliform bacteria	Nitrate	Arsenic	
946	State	--	--	--	Maine Department of Human Services (1998)
832	County	36	--	--	Tuthill and others (1998)
100	State	--	23	--	Klaseus and others (1988)
226	Coop. Ext.	--	19	--	Sievers and Fulhage (1992)
1,300	Coop. Ext.	40	[7]5.3	--	Bauder and others (1991) and Bauder (1993)
63	State	--		--	Goodenkauf and Atkinson (1986)
1,808	University and State	13	19	--	Gosselin and others (1996, 1997, 1999)
992	University	--		13	Peters and others (1999)
353	USGS, USEPA and State	--		19	Montgomery and others (2003)
51,028	State	--	2.7	[8]2.8	New Jersey Department of Environmental Protection (2008)
99	Regional	19	19	1	New Mexico Department of Health (1998)
1,111	County	--	--	--	Suffolk County Department of Health Services (1998)
171	University	--	5.8	--	Maas and others (1995)
1,595	State	--	10	--	North Carolina Department of Health and Human Services (2003)
14,478	University	--	2.7	--	Baker and others (1989)
89	University and State	--	25	--	Mitchell and Harding (1996)
534	USGS and State	--	--	--	Sloto and Senior (1998)
~1,600	Coop. Ext.	--	9.0	--	Swistock and others (1993)
70	University	--	0.0	--	Aelion and Conte (2004)
150	USGS and State	--	2.0	--	Carmichael and Bennett (1993)
445	State	33	--	--	Riding and Quilter (2004) and others
9,697	Coop. Ext.	40	1.9	--	Boune (2001); Poff and Ross (2000)
[9]155	University	68	--	--	Sworobuk and others (1987)
534	State	--	10	--	LeMasters and Doyle (1989)
336	State	--	14	--	Brook and others (2002)
50	University	28	8.0	--	Borchardt and others (2003)
286	USGS and State	--	--	--	U.S. Geological Survey (2006a)

References Cited

Aeolion, C.M., and Conte, B.C., 2004, Susceptibility of residential wells to VOC and nitrate contamination: Environmental Science & Technology, v. 38, no. 6, p. 1648–1653.

Baker, D.B., Wallrabenstein, L.K., Richards, R.P., and Creamer, N.L., 1989, Nitrate and pesticides in private wells of Ohio—A state atlas: Tiffin, Ohio, Heidelberg College, The Water Quality Laboratory, June 1989, 304 p.

Bauder, J.W., Sinclair, K.N., and Lund, R.E., 1993, Physiographic and land use characteristics associated with nitrate-nitrogen in Montana groundwater: Journal of Environmental Quality, v. 22, no. 2, p. 255–262.

Bauder, J.W., White, B.A., and Inskeep, W.P., 1991, Montana extension initiative focuses on private well quality: Journal of Soil and Water Conservation, v. 46, no. 1, p. 69–74.

Borchardt, M.A., Bertz, P.D., Spencer, S.K., and Battigelli, D.A., 2003, Incidence of enteric viruses in groundwater from household wells in Wisconsin: Applied and Environmental Microbiology, v. 69, no. 2, p. 1172–1180.

Bourne, A.C., 2001, Assessing the contamination risk of private well water supplies in Virginia: Blacksburg, Va., Virginia Polytechnic Institute and State University, M.S. Thesis, 141 p.

Brook, J.V., Rheineck, Bruce, Postle, Jeff, Allen, Paula, Zogbaum, Randy, Funk, Justin, Strohl, Derek, and Baldock, Jon, 2002, Agricultural chemicals in Wisconsin groundwater: Madison, Wis., Wisconsin Department of Agriculture, Trade, and Consumer Protection, Water Quality Section, 18 p.

Carey, D.I., Dinger, J.S., Davidson, O.B., Sergeant, R.E., Taraba, J.L., Ilvento, T.W., Coleman, Steve, Boone, Rayetta, and Knoth, L.M., 1993, Quality of private ground-water supplies in Kentucky: Lexington, Ky., Kentucky Geological Survey Information Circular 44, 155 p.

Carmichael, J.K., and Bennett, M.W., 1993, Reconnaissance of quality of water from farmstead wells in Tennessee, 1989–90: U.S. Geological Survey Water-Resources Investigations Report 92–4186, 43 p.

Conine, S., Cox, D., Mitchell, K., Kuyper, C., and Bragg, J., 1989, Bacteriological quality of private water wells in Clark County, Arkansas: 1989, Proceedings of the Arkansas Academy of Science, v. 43, p. 19–20.

Field, R.W., and Kross, B.C., 1996, Intercomparison of waterborne radon-222 collection methods—Professional vs. homeowner collection: Ground Water Monitoring and Remediation, v. 16, p. 106–112.

Field, R.W., and Kross, B.C., 1998, Iowa survey of waterborne ^{222}Rn concentrations in private wells: Health Physics, v. 74, no. 2, p. 249–252.

Focazio, M.J., Tipton, Deporah, Shapiro, S.D., and Geiger, L.H., 2006, The chemical quality of self-supplied domestic well water in the United States: Ground Water Monitoring & Remediation, v. 26, no. 3, p. 1–13.

Goetsch, W.D., McKenna, D.P., and Bicki, T.J., 1992, Statewide survey for agricultural chemicals in rural, private water-supply wells in Illinois: Springfield, Ill., Illinois Department of Agriculture.

Goodenkauf, Owen, and Atkinson, J.C., 1986, Occurrence of volatile organic chemicals in Nebraska ground water: Ground Water, v. 24, no. 2, p. 231–233.

Gosselin, D.C., Headrick, Jacqueline, Chen, X.H., Summerside, Scott, Tremblay, Rod, and Bottger, Kurt, 1996, Domestic well-water quality in rural Nebraska: Lincoln, Nebr., University of Nebraska, Institute of Agriculture and Natural Resources, Conservation and Survey Division, and Nebraska Department of Health, April 1996, variously paginated.

Gosselin, D.C., Headrick, Jacqueline, Haravey, F.E., Tremblay, Rod, and McFarland, Kimberly, 1999, Fluoride in Nebraska's ground water: Ground Water Monitoring & Remediation, v. 19, p. 87–95.

Gosselin, D.C., Headrick, Jacqueline, Tremblay, Rod, Chen, X.H., and Summerside, Scott, 1997, Domestic well water quality in rural Nebraska: Focus on nitrate-nitrogen, pesticides, and coliform bacteria: Ground Water Monitoring & Remediation, v. 17, p. 77–87.

Hagan, E.F., 2004, State ambient ground water quality monitoring program, Arsenic speciation results (2002 & 2003): Idaho Department of Water Resources, Ground water quality technical brief, September 2004, 13 p., accessed September 14, 2006, at http://www.idwr.state.id.us/hydrologic/info/pubs/gwq/Arsenic_Technical_Brief_final.pdf.

Hallberg, G.R., Woida, K., Libra, R.D., Rex, K.D., Sesker, K.D., Kross, B.C., Seigley, L.S., Nations, B.K., Quade, D.J., Bruner, D.R., Nicholson, H.F., Johnson, J.K., and Cherryholmes, K.L., 1992, The Iowa statewide rural well-water survey—Site and well characteristics and water quality: Iowa City, Iowa, Iowa Department of Water Resources, Technical Information Series 23, 43 p., accessed August 24, 2006, at http://www.igsb.uiowa.edu/gspubs/pdf/TIS-23.pdf.

Holden, L.R., Graham, J.A., Whitmore, R.W., Alexander, W.J., Pratt, R.W., Liddle, S.K., and Piper, L.L., 1992, Results of a national alachlor well water survey: Environmental Science & Technology, v. 26, p. 935–943.

Iowa Department of Natural Resources, 2004, Iowa community private well study: Iowa City, Iowa, Iowa Department of Natural Resources, Geological Survey, Water Fact Sheet 2004–4, accessed October 4, 2006, at http://www.cheec.uiowa.edu/private_well/priv_well.pdf.

Klaseus, T.G., Buzicky, G.C., and Schneider, E.C., 1988, Pesticides and groundwater—Surveys of selected Minnesota wells: Minneapolis, Minn., Minnesota Department of Health and Minnesota Department of Agriculture, 95 p., accessed September 25, 2006, at http://www.co.stearns.mn.us/documents/ground21.pdf.

Kolpin, D.W., Burkart, M.R., and Thurman, E.M., 1994, Herbicides and nitrate in near-surface aquifers in the midcontinental United States, 1991: U.S. Geological Survey Water-Supply Paper 2413, 34 p.

LeMasters, Gary, and Doyle, D.J., 1989, Grade A dairy farm well water quality survey: Madison, Wis., Wisconsin Department of Agriculture, Trade, and Consumer Protection and Wisconsin Agricultural Statistics Service, April 1989, 36 p.

Liu, Aiguo, Ming, Jinghua, and Ankumah, R.O., 2005, Nitrate contamination in private wells in rural Alabama, United States: Science of the Total Environment, v. 346, p. 112–120.

Louisiana Department of Environmental Quality, 2003, Baseline monitoring program, Fiscal years 2001–2003 (July 2000 through June 2003): Environmental Technology Division of the Louisiana Department of Environmental Quality, Triennial summary report, 2003, 29 p.

Maas, R.P., Kucken, D.J., Patch, S.C., Peek, B.T., and Van Engelen, D.L., 1995, Pesticides in eastern North Carolina rural supply wells—Land use factors and persistence: Journal of Environmental Quality, v. 24, no. 3, p. 426–431.

Mahler, R.L., and Loeffelman, K.A., 1999, Idaho wellhead sampling program, Nitrate sampling, Cumulative results, 1990–99: Moscow, Idaho, University of Idaho, Soil Science Divisions, WQ-39, accessed August 24, 2006, at http://www.uidaho.edu/wq/wqbr/wqbr39.html.

Maine Department of Human Services, 1998, The presence of MTBE and other gasoline compounds in Maine's drinking water—A preliminary report: Augusta, Maine, Maine Department of Human Services, Bureau of Health, October 13, 1998, 24 p.

Mallatt, M., Moore, E., Lutz, E., Yoder, K., and Oldham, J.M., 2003, Natural fluoride concentrations of private wells in Indiana: Proceedings, 32nd Annual Meeting and Exhibition of the American Association for Dental Research, San Antonio, Tex., March 12–15, 2003, accessed September 12, 2006, at http://iadr.confex.com/iadr/2003/SanAnton/techprogram/abstract_27977.htm.

Mehnert, Edward, Schock, S.C., Barnhardt, M.L., Caughey, M.E., Chou, S.F.J., Dey, W.S., Dreher, G.B., and Ray, Chittaranjan, 1995, The occurrence of agricultural chemicals in Illinois' rural, private wells—Results from the pilot study: Ground Water Monitoring & Remediation, v. 15, p. 142–149.

Mitchell, T.J., and Harding, A.K., 1996, Who is drinking nitrate in their well water?: A study conducted in rural northeastern Oregon: Journal of Environmental Health, v. 58, p. 14–19.

Montgomery, D.L., Ayotte, J.D., Carroll, P.R., and Hamlin, Patricia, 2003, Arsenic concentrations in private bedrock wells in southeastern New Hampshire: U.S. Geological Survey Fact Sheet FS–051–03, 4 p.

Neely, K.W., 2005, Nitrate overview for the statewide ambient ground water quality monitoring program, 1990–2003: Idaho Department of Water Resources, Ground water quality technical brief, January 7, 2005, 12 p., accessed August 24, 2006, at http://www.idwr.state.id.us/hydrologic/info/pubs/gwq/Nitrate_Report_2005.pdf

New Jersey Department of Environmental Protection, 2008, New Jersey Private Well Testing Act Program—Well test results for September 2002–April 2007: Trenton, N.J., New Jersey Department of Environmental Protection, 64 p., accessed September 18, 2008, at http://www.nj.gov/dep/pwta.

New Mexico Department of Health, 1998, Executive summary—Well-water quality assessment for southern New Mexico: Las Cruces, N.M., New Mexico Department of Health, Border Health Council, accessed October 4, 2006, at http://www.mnsu.edu/~bho/bhc/h20-nm.html.

North Carolina Department of Health and Human Services, 2003, Contamination of private drinking well water by nitrates: North Carolina Department of Health and Human Services, Public Health, accessed August 31, 2006, at http://www.epi.state.nc.us/epi/meri/ilocontamination.html.

Peters, S.C., Blum, J.D., Klaue, Bjoern, and Karagas, M.R., 1999, Arsenic in New Hampshire drinking water: Environmental Science & Technology, v. 33, no. 9, p. 1328–1333.

Poff, J.A., and Ross, B.B., A confidence report for Virginia's groundwater: Blacksburg, Va., Virginia Water Resources Research Center Special Report, 65 p.

Ray, Chittaranjan, and Schock, S.C., 1996, Comparability of large-scale studies of agricultural contamination of rural private wells: Ground Water Monitoring & Remediation, v. 16, p. 92–102.

Richards, R.P., Baker, D.B., Creamer, N.L., Kramer, J.W., Ewing, D.E., Merryfield, B.J., and Wallrabenstein, L.K., 1996, Well water quality, well vulnerability, and agricultural contamination in the Midwestern United States: Journal of Environmental Quality, v. 25, p. 389–402.

Riding, Rich, and Quilter, M.C., 2004, 2004 State of Utah ground-water program: Utah Department of Food and Agriculture, 15 p., accessed September 7, 2006, at http://www.ag.state.ut.us/conservation/gw_report.pdf.

Schock, S.C., Mehnert, Edward, Caughey, M.E., Dreher, G.B., Dey, W.S., Wilson, Steven, Ray, Chittaranjan, Chou, S.F.J., Valkenburg, John, Gosar, J.M., Karny, J.R., Barnhardt, M.L., Black, W.F., Brown, M.R., and Garcia, V.J., 1992, Pilot study—Agricultural chemicals in rural, private wells in Illinois: Illinois State Geological Survey and Illinois State Water Survey Cooperative Report 14, 80 p., accessed September 12, 2006, at http://www.sus.uiuc.edu/pubdoc/coop/SWSCoop_14.pdf.

Shiber, J.G., 2005, Arsenic in domestic well water and health in central Appalachia, U.S.A.: Water, Air, and Soil Pollution, v. 160, p. 327–341.

Sievers, D.M., and Fulhage, C.D., 1992, Nitrate in rural wells of Missouri: Transactions of the American Society of Agricultural Engineers, v. 35, no. 5, p. 1633–1637.

Sloto, R.A., and Senior, L.A., 1998, Radon in the ground water of Chester County, Pennsylvania: U.S. Geological Survey Fact Sheet 120–98, 4 p.

Sonan, Leticia, Vendrell, Paul, and Hitchcock, Rick, 2005, Water quality in Georgia's private drinking water wells: Proceedings, Georgia Water Resources Conference, accessed August 24, 2006, at http://gwri.ce.gatech.edu/GAConf/News/GAConfNews.php.

Spruill, T.B., 1983, Statistical summaries of selected chemical constituents in Kansas ground-water supplies, 1976–1981: U.S. Geological Survey Open-File Report 83–263, 29 p.

State Water Resources Control Board, 2005, Volunteer domestic well assessment project, El Dorado County Data Summary Report: Sacramento, Calif., California Environmental Protection Agency, State Water Resources Control Board, 23 p.

Steichen, James, Koelliker, James, Grosh, Doris, Heiman, Alan, Yearout, Robert, and Robins, Victor, 1988, Contamination of farmstead wells by pesticides, volatile organics, and inorganic chemicals in Kansas: Ground Water Monitoring & Remediation, v. 8, no. 3, p. 153–160.

Stuart, M.A., Rich, F.J., and Bishop, G.A., 1995, Survey of nitrate contamination in shallow domestic drinking water wells of the Inner Coastal Plain of Georgia: Ground Water, v. 33, no. 2, p. 284–290.

Suffolk County Department of Health Services, 1998, Water quality monitoring program to detect pesticide contamination in groundwaters of Nassau and Suffolk Counties, N.Y., 1997 PRL Annual Report–Appendix J: Suffolk County Department of Health Services, Division of Environmental Quality, Bureau of Groundwater Resources, Interim Report, June 1998, accessed September 5, 2006, at http://www.dec.state.ny.us/website/dshm/prl/scdoh.htm.

Swistock, B.R., Sharpe, W.E., and Robillard, P.D., 1993, A survey of lead, nitrate, and radon contamination of private individual water systems in Pennsylvania: Journal of Environmental Health, v. 55, no. 5, p. 6–12.

Sworobuk, J.E., Law, C.B., and Bissonnette, G.K., 1987, Assessment of the bacteriological quality of rural groundwater supplies in Northern West Virginia: Water, Air, and Soil Pollution, v. 36, no. 1–2, p. 163–170.

Townsend, M.A., Young, D.P., and Healy, J., 1998, Results of agrichemical survey of ground water in Kansas, 1993–1994: Lawrence, Kans., Kansas Geological Survey Open-File Report 98–22, 46 p.

Tuthill, Anna, Meikle, D.B., and Alavanja, M.C.R., 1998, Coliform bacteria and nitrate contamination of wells in major soils of Frederick, Maryland: Journal of Environmental Health, v. 60, p. 16–20.

U.S. Centers for Disease Control and Prevention, 1998, A survey of the quality of water drawn from domestic wells in nine midwest states: U.S. Centers for Disease Control and Prevention, National Center for Environmental Health, accessed October 6, 1999, at http://www.cdc.gov/nceh/programs/emergenc/WellWater/MidwestWell.htm.

U.S. Environmental Protection Agency, 1984, National statistical assessment of rural water conditions—Technical summary: Washington, D.C., U.S. Environmental Protection Agency, Office of Drinking Water, EPA570/9-84-004, 111 p.

U.S. Environmental Protection Agency, 1990a, National Pesticide Survey—Summary results of EPA's national survey of pesticides in drinking water wells: Washington, D.C., U.S. Environmental Protection Agency, Office of Water and Office of Pesticides and Toxic Substances, EPA 570/9-90-NPS5, 17 p., accessed October 3, 2006, at http://nepis.epa.gov/pubtitleOSWER.htm.

U.S. Environmental Protection Agency, 1990b, National Pesticide Survey—Project summary: Washington, D.C., U.S. Environmental Protection Agency, Office of Water and Office of Pesticides and Toxic Substances, EPA 570/9-90-NPS6, 11 p., accessed October 3, 2006, at http://nepis.epa.gov/pubtitleOSWER.htm.

U.S. Environmental Protection Agency, 1992, National Pesticide Survey—Update and summary of Phase II results: Washington, D.C., U.S. Environmental Protection Agency, Office of Water and Office of Pesticides and Toxic Substances, EPA 570/9-91-021, 6 p., accessed October 3, 2006, at http://nepis.epa.gov/pubtitleOSWER.htm.

U.S. General Accounting Office, 1997, Drinking water information on the quality of water found at community water systems and private wells: Washington, D.C., U.S. General Accounting Office, Resources, Community, and Economic Development Division, GAO/RCED-97-123, 47 p.

U.S. Geological Survey, 2006a, Ground-water monitoring for pesticides in Wyoming: U.S. Geological Survey, Wyoming Water Science Center, accessed September 7, 2006, at http://wy.water.usgs.gov/projects/pesticide.

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix 2. Characteristics, principal aquifers, study units, and assessment studies of domestic wells sampled for the NAWQA Program, 1991–2004, by aquifer type

Tables

2–1. Characteristics, principal aquifers, study units, and assessment studies of domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, by aquifer rock type 94
2–2. Characteristics, principal aquifers, study units, and assessment studies of domestic wells sampled for the NAWQA Program in agricultural land-use studies, 1991–2004, by aquifer rock type 99

Table 2–1. Characteristics, principal aquifers, study units, and assessment studies of domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, by aquifer rock type.

[Well and water depths in parentheses are single values only. Numbers of wells for well depth, depth to top of open interval, and depth to water may differ. --, not applicable or not available]

Principal aquifer	NAWQA study unit	Study code	Number of wells	Median well depth, in feet below land surface	Median depth to top of open interval, in feet below land surface	Median depth to water, in feet below land surface	Sampling period
Basin-fill and other non-glacial sand and gravel aquifers (BFSG)							
Basin and Range basin-fill aquifers (BR)	Central Arizona Basins (CAZB)	cazbsus1a	17	377	320	251	1996–97
		cazbsus1b	18	215	217	65	1996–97
		cazbsus2	25	340	230	199	1998
		cazbsus3	17	264	222	107	1996
	Great Salt Lake Basins (GRSL)	grslsus1a	17	238	142	126	1998
		grslsus1b	17	202	180	75	1998
	Nevada Basin and Range (NVBR)	nvbrsus1	4	300	145	--	1995
		nvbrsus2	3	185	120	--	1995
		nvbrsus3	11	125	120	--	1995
Central Valley aquifer system (CV)	Sacramento River Basin (SACR)	sacrsus1	27	155	120	22	1996
	San Joaquin–Tulare Basins (SANJ)	sanjsus1	30	182	133	84	1995, 2002
High Plains aquifer (HP)	High Plains aquifer (HPGW)	hpgwsus1a	74	263	215	158	1999
		hpgwsus1b	46	204	163	137	2001
		hpgwsus1c	104	205	183	83	2002–03
		hpgwsus2	20	74	64	30	1999
		hpgwsus4	27	190	170	89	2003
		hpgwsus5	27	113	100	15	2004
Mississippi River Valley alluvial aquifer (MV)	Mississippi Embayment (MISE)	misesus1	2	70	(30)	(12)	1998
		misesus3	3	130	105	11	1998
Northern Rocky Mountains Intermontane Basins aquifer system (NR)	Northern Rockies Intermontane Basins (NROK)	nroksus1	29	137	130	86	1999
		nroksus2	28	58	50	26	2001
Other stream valley alluvial aquifers (OS)	Central Nebraska Basins (CNBR)	cnbrsus2	9	50	37	8	1997
	Upper Colorado River Basin (UCOL)	ucolsus1	22	60	48	33	1997
		ucolsus2	12	49	43	(5)	1997
	Yellowstone River Basin (YELL)	yellsus1	1	(19)	(6)	(11)	1999
Rio Grande aquifer system (RG)	Rio Grande Valley (RIOG)	riogsus1	25	178	173	12	1995

Table 2–1. Characteristics, principal aquifers, study units, and assessment studies of domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, by aquifer rock type.—Continued

[Well and water depths in parentheses are single values only. Numbers of wells for well depth, depth to top of open interval, and depth to water may differ. --, not applicable or not available]

Principal aquifer	NAWQA study unit	Study code	Number of wells	Median well depth, in feet below land surface	Median depth to top of open interval, in feet below land surface	Median depth to water, in feet below land surface	Sampling period
Basin-fill and other non-glacial sand and gravel aquifers (BFSG)—Continued							
Snake River Plain basin-fill aquifers (SPf)	Upper Snake River Basin (USNK)	usnksus1	9	67	64	--	1994
		usnksus2	19	145	128	17	1995
		usnksus3	6	166	112	7	1996
Willamette Lowland basin-fill aquifers (WL)	Willamette Basin (WILL)	willsus1	69	60	50	16	1993
Glacial sand and gravel aquifers (GLAC)							
Eastern glacial aquifers (Ge)	Allegheny and Monongahela River Basins (ALMN)	almnsus2	30	73	68	--	1996
	Conneticut, Housatonic, and Thames River Basins (CONN)	connsus2	28	113	105	25	2002
	Delaware River Basin (DELR)	delrsus3	12	86	61	21	2001
	Hudson River Basin (HDSN)	hdsnsus1	2	108	--	--	1994
	Long Island–New Jersey Coastal Drainages (LINJ)	linjsus1	1	(152)	(146)	--	1997
Central glacial aquifers (Gc)	Lake Erie-Lake Saint Clair Drainages (LERI)	lerisus1	27	78	74	30	1998
	Lower Illinois River Basin (LIRB)	lirbsus1	26	239	235	--	1996
		lirbsus2	28	50	15	41	1996
	Great and Little Miami River Basins (MIAM)	miamsus1	30	60	60	25	1999
	Upper Illinois River Basin (UIRB)	uirbsus1	27	72	68	22	2001
		uirbsus2	23	45	40	10	2000
	Western Lake Michigan Drainages (WMIC)	wmicsus2	24	82	72	27	2003
West central glacial aquifers (Gwc)	Eastern Iowa Basins (EIWA)	eiwasus2	32	52	51	11	1998
	Red River of the North Basin (REDN)	rednsus1	5	62	56	--	1992, 1995
		rednsus2	15	65	58	7	1993
		rednsus3	3	60	--	(24)	1995
		rednsus5	25	109	111	19	1991–94
Western glacial aquifers (Gw)	Cook Inlet Basin (COOK)	cooksus1a	22	105	98	64	1999
	Puget Sound Basin (PUGT)	pugtsus1	29	68	64	22	1996

Table 2–1. Characteristics, principal aquifers, study units, and assessment studies of domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, by aquifer rock type.—Continued

[Well and water depths in parentheses are single values only. Numbers of wells for well depth, depth to top of open interval, and depth to water may differ. --, not applicable or not available]

Principal aquifer	NAWQA study unit	Study code	Number of wells	Median well depth, in feet below land surface	Median depth to top of open interval, in feet below land surface	Median depth to water, in feet below land surface	Sampling period
Coastal plain aquifers in semi-consolidated sand (CP)							
Coastal lowlands aquifer system (CL)	Acadian–Pontchartrain Drainages (ACAD)	acadsus1	29	140	128	27	2000–01
		acadsus2	27	120	113	(90)	2001
	Trinity River Basin (TRIN)	trinsus3	29	180	155	39	1994, 2002
North Atlantic Coastal Plain aquifer system (NA)	Albemarle–Pamlico Drainage Basin (ALBE)	albesus1	1	(20)	--	(11)	1994
		albesus7	6	90	75	17	2002–2003
	Delmarva Peninsula (DLMV)	dlmvsus1	13	49	40	8	2001
	Long Island–New Jersey Coastal Drainages (LINJ)	linjsus2	30	100	90	5	1998
	Potomac River Basin and Delmarva Peninsula (PODL)	podlsus2	15	81	73	36	2003
Southeastern Coastal Plain aquifer system (SC)	Mobile River Basin (MOBL)	moblsus1	24	144	121	53	1999
	Santee River Basin and Coastal Drainages (SANT)	santsus1	2	125	105	57	1997
Texas coastal uplands aquifer system (TC)	Trinity River Basin (TRIN)	trinsus2	10	102	(20)	25	1994
Sandstone aquifers (SS)							
Cambrian-Ordovician aquifer system (CO)	Upper Mississippi River Basin (UMIS)	umissus3	25	180	126	31	1996
		umissus4	25	200	175	88	1996
	Western Lake Michigan Drainages (WMIC)	wmicsus1	20	128	97	35	1995
Early Mesozoic basin aquifers (EM)	Delaware River Basin (DELR)	delrsus1	25	160	40	25	1999
	Long Island–New Jersey Coastal Drainages (LINJ)	linjsus3	22	193	50	(14)	1998–99
	Potomac River Basin (POTO)	potosus2	22	155	45	29	1994
Lower Tertiary/Upper Cretaceous aquifers (LT)	Red River of the North Basin (REDN)	rednsus5	1	(127)	(123)	(48)	1994
	Yellowstone River Basin (YELL)	yellsus2	23	160	80	27	2000–01

Table 2–1. Characteristics, principal aquifers, study units, and assessment studies of domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, by aquifer rock type.—Continued

[Well and water depths in parentheses are single values only. Numbers of wells for well depth, depth to top of open interval, and depth to water may differ. --, not applicable or not available]

Principal aquifer	NAWQA study unit	Study code	Number of wells	Median well depth, in feet below land surface	Median depth to top of open interval, in feet below land surface	Median depth to water, in feet below land surface	Sampling period
		Sandstone aquifers (SS)—Continued					
Pennsylvanian aquifers (P)	Alleheny and Monongahela River Basin (ALMN)	almnsus1	30	105	21	45	1996
	Kanawha–New River Basins (KANA)	kanasus1	16	92	29	63	1997
Valley and Ridge sandstone and shale aquifers (VRs)	Delaware River Basin (DELR)	delrsus2	27	185	82	41	2000
	Lower Susquehanna River Basin (LSUS)	lsussus1	29	155	60	39	1993
		Sandstone and carbonate-rock aquifers (SS/CARB)					
Edwards-Trinity aquifer system (ET)	South-Central Texas (SCTX)	sctxsus1	21	295	180	130	1996
		sctxsus2	25	400	123	170	1996
		sctxsus3	1	(1,500)	(250)	--	1997
	Trinity River Basin (TRIN)	trinsus1	22	162	125	26	1994
Mississippian aquifers (M)	Kanawha–New River Basins (KANA)	kanasus1	5	205	42	101	1997
	Lake Erie–Lake Saint Clair Drainages (LERI)	lerisus1	1	--	--	--	1998
	Lower Tennessee River Basin (LTEN)	ltensus1	8	86	56	38	1999
		ltensus2	4	99	58	35	2000
		Carbonate-rock aquifers (CARB)					
Floridan aquifer system (F)	Apalachicola–Chattahoochee-Flint River Basin (ACFB)	acfbsus1	7	100	69	34	1995
	Georgia-Florida Coastal Plain (GAFL)	gaflsus2	30	93	65	26	2002–03
		gaflsus3	30	150	95	28	2002
	Santee River Basin and Coastal Drainages (SANT)	santsus2	29	170	90	18	1998
Ordovician aquifers (O)	Lower Tennessee River Basin (LTEN)	ltensus2	21	140	20	21	2000
Ozark Plateaus aquifer system (OP)	Ozark Plateaus (OZRK)	ozrksus2a	33	196	74	54	1993
		ozrksus3a	16	140	77	49	1993
Silurian-Devonian aquifers (SD)	Eastern Iowa Basins (EIWA)	eiwasus1	32	223	150	59	1996
Valley and Ridge carbonate-rock aquifers (VRc)	Kanawha–New River Basins (KANA)	kanasus2	1	(325)	(183)	(157)	1997
	Upper Tennessee River Basin (UTEN)	utensus1	18	245	64	73	1998–99

Table 2–1. Characteristics, principal aquifers, study units, and assessment studies of domestic wells sampled for the NAWQA Program in aquifer studies, 1991–2004, by aquifer rock type.—Continued

[Well and water depths in parentheses are single values only. Numbers of wells for well depth, depth to top of open interval, and depth to water may differ. --, not applicable or not available]

Principal aquifer	NAWQA study unit	Study code	Number of wells	Median well depth, in feet below land surface	Median depth to top of open interval, in feet below land surface	Median depth to water, in feet below land surface	Sampling period
		Basaltic-rock aquifers (BAS)					
Snake River Plain basaltic-rock aquifers (SPb)	Upper Snake River Basin (USNK)	usnksus1	14	280	117	183	1992–95
		usnksus2	5	210	50	--	1995
		Crystalline-rock aquifers (CRYS)					
New England crystalline-rock aquifers (NEx)	Connecticut, Housatonic, and Thames River Basins (CONN)	connsus1	27	225	35	18	1995
	Long Island–New Jersey Coastal Drainages (LINJ)	linjsus1	28	201	59	9	1997
	New England Coastal Basins (NECB)	necbsus1	28	188	25	12	1999–2000
		necbsus2	30	303	35	23	1999–2000
Piedmont and Blue Ridge crystalline-rock aquifers (PBx)	Kanawha–New River Basins (KANA)	kanasus2	18	159	49	44	1995
	Lower Susquehanna River Basins (LSUS)	lsussus2	30	147	69	42	1994
	Potomac River Basin (POTO)	potosus1	23	142	44	36	1997
	Santee River Basin and Coastal Drainages (SANT)	santsus3	29	200	61	26	1997
Rocky Mountain Front Range crystalline-rock aquifers (RMx)	South Platte River Basin (SPLT)	spltsus1	27	225	82	--	1995
		Aquifer not determined					
Aquifer not determined	Hudson River Basin (HDSN)	hdsnsus1	44	125	(91)	6	1994
	Upper Snake River Basin (USNK)	usnksus2	1	(615)	(504)	--	1995
		usnksus3	1	(75)	(52)	(5)	1995

Table 2–2. Characteristics, principal aquifers, study units, and assessment studies of domestic wells sampled for the NAWQA Program in agricultural land-use studies, 1991–2004, by aquifer rock type.

[Well and water depths in parentheses are single values only. Numbers of wells for well depth, depth to top of open interval, and depth to water may differ. --, not applicable or not available]

Principal aquifer	NAWQA study unit	Study code	Primary agricultural land use	Number of wells	Median well depth, in feet below land surface	Median depth to top of open interval, in feet below land surface	Median depth to water, in feet below land surface	Sampling period
Basin-fill and other non-glacial sand and gravel aquifers (BFSG)								
Central Valley aquifer system (CV)	San Joaquin–Tulare Basins (SANJ)	sanjluscr1a	Row crops	23	147	110	76	1995, 2002
		sanjlusor1a	Vineyards	27	155	120	47	1993, 2001
		sanjlusor2a	Almonds	26	155	118	39	1994, 2001
Columbia Plateau basin-fill aquifers (CPf)	Central Columbia Plateau (CCPT)	ccptlusag2a	Row crops	12	126	109	(30)	1993–94
		ccptlusor1a	Orchards	9	160	141	121	1994–95
Other stream valley alluvial aquifers (OS)	Mobile River Basin (MOBL)	moblluscr1	--	1	(40)	(30)	(25)	2001
	Potomac River Basin (POTO)	potolusag2	--	1	(71)	--	--	1995
Snake River Plain basin-fill aquifers (SPf)	Upper Snake River Basin (USNK)	usnkluscr1	Row crops	25	35	32	9	1993
		usnkluscr3	Row crops	1	(180)	(121)	(77)	1994
Glacial sand and gravel aquifers (GLAC)								
West central glacial aquifers (Gwc)	Red River of the North Basin (REDN)	rednlusag1	--	2	54	47	--	1994
	Upper Mississippi River Basin (UMIS)	umisluscr1	Row crops	3	28	(53)	(27)	1998
Western glacial aquifers (Gw)	Puget Sound Basin (PUGT)	pugtluscr1	Raspberries	3	41	35	18	1997–98
Coastal plain aquifers in semi-consolidated sand (CP)								
North Atlantic Coastal Plain aquifer system (NA)	Albemarle–Pamlico Drainage Basin (ALBE)	albelusag2	Row crops	10	118	75	(3)	1994
	Delmarva Peninsula (DLMV)	dlmvluscr1	Row crops	2	37	31	21	2001
Sandstone aquifers (SS)								
Valley and Ridge sandstone and shale aquifers (VRs)	Potomac River Basin (POTO)	potolusag2	--	23	122	31	29	1996
Carbonate-rock aquifers (CARB)								
Ozark Plateaus aquifer system (OP)	Ozark Plateaus (OZRK)	ozrklusag1a	Cattle pasture	19	165	--	45	1994
		ozrklusag2a	Poultry pasture	20	180	28	34	1995
Piedmont and Blue Ridge carbonate-rock aquifers (PBc)	Lower Susquehanna River Basin (LSUS)	lsuslusag1	--	29	160	102	33	1993

Table 2–2. Characteristics, principal aquifers, study units, and assessment studies of domestic wells sampled for the NAWQA Program in agricultural land-use studies, 1991–2004, by aquifer rock type.—Continued

[Well and water depths in parentheses are single values only. Numbers of wells for well depth, depth to top of open interval, and depth to water may differ. --, not applicable or not available]

Principal aquifer	NAWQA study unit	Study code	Primary agricultural land use	Number of wells	Median well depth, in feet below land surface	Median depth to top of open interval, in feet below land surface	Median depth to water, in feet below land surface	Sampling period
Carbonate-rock aquifers (CARB)—Continued								
Valley and Ridge carbonate-rock aquifers (VRc)	Lower Susquehanna River Basin (LSUS)	lsuslusag2	--	29	170	100	64	1994
		lsuslusag3	--	29	158	109	56	1995
	Potomac River Basin and Delmarva Peninsula (PODL, POTO)	potolusag1	--	29	144	57	43	1993
		potolusag2	--	1	(280)	(42)	--	1995
Basaltic-rock aquifers (BAS)								
Columbia Plateau basaltic-rock aquifers (CPb)	Central Columbia Plateau (CCPT)	ccptlusag1a	Row crops	16	102	32	32	1993–94
		ccptlusag2a	Row crops	17	157	74	(96)	1993–94
		ccptlusor1a	Orchards and vineyards	9	170	98	30	1994–95
Snake River Plain basaltic-rock aquifers (SPb)	Upper Snake River Basin (USNK)	usnkluscr2	Row crops	27	228	63	180	1993
		usnkluscr3	Row crops	26	205	20	157	1994
		usnkluscr4	Row crops	14	357	19	292	1995
Aquifer not determined								
Aquifer not determined	Central Columbia Plateau (CCPT)	ccptlusag1a	--	1	(60)	--	--	1994
	Upper Snake River Basin (USNK)	usnkluscr2	Row crops	1	--	--	(132)	1995
		usnkluscr4	Row crops	1	(420)	(18)	--	1995

Appendix 3. Sampling and analytical methods and summary of field quality control data for chemical contaminants measured in domestic wells sampled for the NAWQA Program, 1991–2004

Contents

Sampling and Analytical Methods 102
Summary of Field Quality Control Data 103
Field Quality Control Data Overview 103
Major Ions 104
Trace Elements 104
Nutrients 104
Radon and Other Radionuclides 105
Organic Compounds 105
Pesticides 105
Volatile Organic Compounds 106
Fecal Indicator Bacteria 106
References Cited 106

Sampling and Analytical Methods

The sampling methods used in the NAWQA assessment studies are described in Koterba and others (1995), U.S. Geological Survey (variously dated), Kolpin and others (1998), Embrey and Runkle (2006), and Moran and others (2006). Wells were pumped until a minimum volume of water was removed (at least three well-casing volumes in most cases) and the field measurements of pH, water temperature, specific conductance, and dissolved oxygen had stabilized. After diversion from the well, the water contacted only Teflon, stainless steel, glass, or aluminum materials and was processed in an environmental chamber to minimize contamination. A low flow rate (about 0.1 gallon or 500 milliliters per minute) was used for sampling. Equipment was cleaned after sampling following procedures described in Koterba and others (1995). Samples were analyzed for alkalinity, major ions, nutrients, dissolved organic carbon, trace elements, pesticides, VOCs, and radon; for some wells, the samples were analyzed for fecal indicator bacteria, gross alpha- and beta-particle radioactivities, and radium.

Samples collected for analysis of alkalinity, major ions, dissolved nutrients, trace elements, gross alpha- and beta-particle radioactivities, and radium were filtered on site through 0.45-micron capsule or plate filters. Samples for analysis of major cations and trace elements were preserved with nitric acid to pH less than 2; samples for analysis of major anions were not preserved. Samples for analysis of nutrients were collected in brown polyethylene bottles and were immediately chilled on ice for shipment to the laboratory. Before 1995, nutrient samples were preserved using mercuric chloride for all analytes; thereafter, samples were not preserved except for those for analysis of total concentrations, which, after 1998, were preserved with sulfuric acid to pH less than 2. Samples collected for analysis of pesticides were filtered through 0.7-micron baked glass-fiber filters into amber-colored glass bottles and were immediately chilled. Samples for analysis of VOCs, radon, and fecal indicator bacteria were not filtered. VOC samples were collected into 40-milliliter septum vials with no headspace, preserved with hydrochloric acid to pH less than 2, and immediately chilled. Radon samples were collected using a pressurized in-line sampling assembly and a gas-tight syringe and were injected into glass scintillation vials below mineral oil. Samples for analysis of dissolved organic carbon were filtered through 0.45-micron silver membrane filters, and silver from the filters served as a preservative; samples were immediately chilled on ice. Samples for analysis of fecal indicator bacteria were collected in sterile, amber-colored bottles and immediately chilled.

The physical properties pH, water temperature, specific conductance, and dissolved oxygen were measured at the time of sampling in a flow-through chamber using methods described in the U.S. Geological Survey National Field Manual (U.S. Geological Survey, variously dated). Alkalinity (carbonate alkalinity) was determined on site with incremental titration with sulfuric acid (Koterba and others, 1995; U.S. Geological Survey, variously dated). For about 25 percent of samples in this study, alkalinity [in mg/L as calcium carbonate ($CaCO_3$)] was calculated from reported bicarbonate concentrations. Samples collected for analysis of the fecal indicator bacteria, total coliform bacteria and *Escherichia coli (E. coli)*, were processed on site within 6 hours of collection (U.S. Geological Survey, variously dated; Embrey and Runkle, 2006). Total coliform bacteria were enumerated using mENDO medium (method 9222B, American Public Health Association and others, 1992) or MI medium (method 1604, U.S. Environmental Protection Agency, 2002c); *E. coli* were enumerated using NA-MUG medium (method 9222G, American Public Health Association and others, 1992), mTEC medium (method 1103.1, U.S. Environmental Protection Agency, 2002b), or MI medium.

Water samples were analyzed at the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colorado, for inorganic and organic analytes. The inorganic analytes and methods used were: major ions, by atomic absorption spectrometry (AA), colorimetry, or inductively-coupled plasma (ICP) (Fishman and Friedman, 1989; Fishman, 1993); nutrients, by various methods (Fishman, 1993; Patton and Truitt, 2000); trace elements, by ICP-atomic emission spectroscopy (ICP-AES), ICP-mass spectrometry (ICP-MS), graphite-furnace AA, or hydride generation AA (Fishman and Friedman, 1989; Faires, 1993; McClain, 1993; Garbarino, 1999); and radon, by liquid scintillation (American Society for Testing and Materials, 1996). Dissolved organic carbon was analyzed by ultraviolet-light-promoted persulfate oxidation and infrared spectrometry (Brenton and Arnett, 1993). Iron and manganese were analyzed using methods for major ions and trace elements; data used in this study were the results of the trace-element methods because these had lower reporting limits than the methods for major ions. Nitrate was analyzed as nitrite plus nitrate; however, nitrite concentrations were very low, averaging less than 0.1 percent of nitrite plus nitrate concentrations. Consequently, nitrite plus nitrate is referred to as nitrate in this report.

Pesticides were analyzed by two methods at the NWQL: 47 pesticides were analyzed by solid-phase extraction using a C-18 cartridge and gas chromatography/mass spectrometry (GCMS) (Zaugg and others, 1995), and 36 pesticides and pesticide degradates were analyzed by graphitized carbon-based solid-phase extraction and high-performance liquid chromatography/mass spectrometry (HPLC) (Werner and others, 1996; Furlong and others, 2001). Data in this study for carbaryl, carbofuran, and linuron, which were analyzed by both methods, were the results of analysis by GCMS. Results from HPLC analyses during March 1999 to March 2000, in which sample holding times were exceeded (E.T. Furlong and others, U.S. Geological Survey, written commun., 2003), were excluded from the study. Nearly all VOCs were analyzed using purge and trap capillary column GCMS (Rose and Schroeder, 1995; Connor and others, 1998). Another method (USGS 0-3120-90; Fishman, 1993) was sometimes used

for ethylene dibromide (EDB) and dibromochloropropane (DBCP) to achieve lower detection limits for these compounds (Moran and others, 2005). Gross alpha- and beta-particle radioactivity were analyzed at the NWQL by low background Planchet counting post-evaporation (USEPA method 900.0, U.S. Environmental Protection Agency, 1980). Radium isotopes (radium-226 and radium-228) were analyzed by coprecipitation and alpha planchet counting, radon de-emanation, or beta counting after progeny ingrowth (U.S. Environmental Protection Agency methods 903.0, 903.1, and 904.0, respectively; U.S. Environmental Protection Agency, 1980) or by alpha and gamma spectral methods (Focazio and others, 2001; Szabo and others, 2005; Zoltan Szabo, U.S. Geological Survey, written commun., 2007).

Analytical results from the NWQL for the analytes measured during the study period were given using several reporting conventions. Major ions, nutrients, trace elements, and radon were reported primarily in terms of minimum reporting levels (MRLs). MRLs were defined for the NWQL as the minimum concentration of a constituent that can be reliably measured with an analytical method (Childress and others, 1999). MRLs for individual analytes were established using various methods that may have included statistical analysis of quality-control samples. Pesticides and VOCs were reported relative to MRLs that were statistically determined and, towards the end of the study period, relative to long-term method-detection levels (LT-MDLs). The LT-MDL is similar to the method detection level (MDL) defined by the U.S. Environmental Protection Agency in that it is statistically determined as the minimum concentration of an analyte that can be measured and reported with 99-percent confidence that the concentration is greater than zero (Childress and others, 1999). In other words, for analytical results at or above the MDL or LT-MDL, there is at most a 1-percent chance that an analyte is reported as detected when it is not there (false positive). The LT-MDL differs from the USEPA-defined MDL in that it accounts for more potential sources of variability, for example, from multiple analytical instruments and operators; the LT-MDL is recalculated each year. For methods that incorporated the use of LT-MDLs, analytical results were reported in terms of LT-MDLs and laboratory reporting levels (LRLs). The LRL is the concentration at which there is no more than a 1-percent chance that an analyte will not be detected when it is actually present (false negative; the chance of false negatives occurring at the LT-MDL is 50 percent). The LRL is about two times higher than the LT-MDL. For methods that use LT-MDLs, non-detections were reported relative to the LRL by the NWQL and were stored in this way in the NAWQA Data Warehouse; positive detections at concentrations less than the LRL were not censored but were reported as estimated values (Childress and others, 1999). Analytical results less than the lowest calibration standard or greater than the highest calibration standard also were reported as estimated. The uncertainty associated with estimated values is expected to be higher than that of other, unqualified concentrations (Childress and others, 1999). In this study, estimated values were used without qualification, and non-detections that were reported relative to LRLs were redefined relative to their associated LT-MDLs using information on historical LT-MDLs for analytical methods from the NWQL. The LT-MDL and LRL reporting conventions were phased into use at the NWQL beginning in October 1998. Radon, near the end of the study period, and radium isotopes, throughout the study period, were reported relative to sample-specific minimum detectable concentrations (SSMDC; Zoltan Szabo, U.S. Geological Survey, written commun., 2006).

Summary of Field Quality Control Data

Field Quality Control Data Overview

The collection of field quality-control (QC) samples was an integral part of NAWQA assessment studies. For each assessment study of about 25 to 30 wells, the study design included routine collection of at least 2 to 3 field blanks for all analytes except radionuclides; 2 to 3 replicates for major ions, nutrients, trace elements, and radon; 2 to 3 field-spiked samples and field-spike replicates for pesticides and VOCs; 1 source-solution blank for DOC, and trip blanks and (or) source-solution blanks for VOCs (Koterba and others, 1995). Field blanks were collected by passing water that did not contain the analyte(s) of interest (except for some VOCs) through sampling equipment in the field; these can be used to assess the introduction of contamination into environmental samples during sampling and analysis. Trip blanks can be used to assess contamination from sample shipping and handling. Replicate samples are sequentially collected ground-water samples, which can be used to assess the effects of sampling and analysis procedures on measurement variability. Field-spiked samples are environmental samples to which a known amount of the analyte(s) of interest was added in the field; these can be used to assess bias from matrix interferences or analyte loss during sample holding and processing. Spiked samples also were routinely prepared in the laboratory using environmental samples or other solutions. The USGS Branch of Quality Systems also routinely submitted and analyzed the results from blind samples for inorganic and organic analytes to the USGS NWQL during the study period (http://bqs.usgs.gov). Field QC sample data have been evaluated in reports by individual study units (http://water.usgs.gov/nawqa) and also have been evaluated at the national scale for nutrients, trace elements, pesticides, VOCs, fecal-indicator bacteria, and radionuclides. QC results for various contaminants in ground water sampled in the NAWQA Program are described in this section; the discussion is based on summaries at the national scale, where available.

Environmental data determined to be affected by contamination are specifically identified in the NAWQA Data Warehouse (“V-coded” data); these data were not used in the

present study of domestic-well water quality. Criteria for identifying these data were as follows: there was direct evidence of contamination, concentrations were significant compared to environmental concentrations, and the contamination was well understood, for example in terms of source and magnitude (U.S. Geological Survey, 1997). Analyses of field blanks, of other QC samples, and of sampling processes were used by study unit and national synthesis personnel to identify data that were affected by contamination. Environmental data were rarely V-coded; about 0.1 percent of analytical results (excluding radionuclides or fecal indicator bacteria) for the domestic wells in the present study received the V-code designation. Analytes with the most V-coded analyses included (in descending order) aluminum, chloroform, 1,2,4-trimethylbenzene, zinc, ammonia, tetrachloroethene, copper, orthophosphate, 1,2-dichloropropane, toluene, chromium, nitrite plus nitrate, and several other VOCs.

Major Ions

Concentrations of major ions in water samples from domestic wells appeared unaffected by contamination and were reproducible based on a review of field QC data described in reports from 20 NAWQA study units. Most major ions were either not detected in blank samples or were detected at concentrations much lower than those in environmental samples (for example, see Menheer and Brigham, 1997; Hamlin and others, 2002; Bruce and McMahon, 1998; Reutter and Dunn, 2000; Fong and others, 1998; Apodaca and Bails, 2000). Silica was detected in blanks in a few study units at concentrations near those in environmental samples (Savoca and others, 1999; Inkpen and others, 2000), but these findings were not widespread. The variability of measured concentrations of major ions was low, with relative percent differences (RPDs) of replicate pairs nearly always less than 10 percent; larger RPDs sometimes occurred when concentrations were near MRLs (for example, see Coes and others, 2000; Glass, 2001; Pope and others, 2001; Robinson, 2003; Bexfield and Anderholm, 1997; Milby-Dawson, 2001). In many cases, RPDs of replicate pairs were less than 5 percent.

Trace Elements

QC data for 23 trace elements were evaluated at the national scale to estimate bias and variability in all water samples collected by the NAWQA Program from 1991 to 2002 (Apodaca and others, 2006). The number of field blanks and replicates varied by trace element, but there were about 350 blanks and about 275 to 350 replicate-sample pairs for most trace elements. Potential contamination in ground-water samples was estimated from field blanks with 95-percent confidence to be less or near 1 mg/L in 95 percent of samples for many trace elements; this value (1 mg/L) was the MRL for many trace elements. Potential contamination for antimony, arsenic, beryllium, cadmium, cobalt, lead, molybdenum, nickel, selenium, silver, thallium, and uranium was estimated to be less than 1 mg/L in 95 percent of samples; for barium, chromium, and manganese, potential contamination was estimated to be at or near 1 mg/L in 95 percent of samples. The potential for contamination was relatively large for aluminum, boron, and zinc. Potential contamination for these three trace elements was estimated with 95-percent confidence to be at or greater than 1 mg/L in at least 50 percent of samples, and concentrations greater than 9 mg/L for aluminum, 15 mg/L for boron, and 18 mg/L for zinc were estimated to occur in at least 5 percent of samples. Potential contamination for copper, iron, and strontium was estimated to be at or greater than 1 mg/L in 75 to 85 percent of samples. Too few field blanks were collected for lithium or vanadium to estimate potential contamination for these trace elements. Except for aluminum, the concentration levels for potential contamination in samples analyzed for trace elements were less than one-tenth of any drinking-water standards at the 95- or 99-percent confidence levels (Apodaca and others, 2006). Variability, represented by the mean relative standard deviation (RSD) for all concentration ranges, was estimated to be less than 10 percent for antimony, arsenic, barium, boron, cobalt, iron, lithium, manganese, molybdenum, strontium, and uranium; variability was less than or equal to 15 percent for the remaining trace elements aluminum, cadmium, chromium, copper, lead, nickel, selenium, vanadium, and zinc. Variability could not be estimated for beryllium, silver, or thallium because there were too few replicate pairs. This analysis indicates that potential contamination and variability are unlikely to affect interpretations in this report for most trace elements at the national scale.

Nutrients

A national-scale evaluation of field QC data indicated that little significant contamination had occurred from field or laboratory procedures and low variability for nutrients in all ground-water samples collected for the NAWQA Program (Mueller and Titus, 2005). The analysis was based on 541 field blanks and 520 replicate sample pairs collected along with environmental samples from 1991 through 2001. For nitrite plus nitrate, ammonia plus organic nitrogen, orthophosphate, and total phosphorus, potential contamination was estimated to be near the associated MRLs in at least 80 percent of environmental samples, and near the MRLs in at least 75 percent of samples for ammonia. Potential contamination in 95 percent of samples was estimated with 99-percent confidence to be less than 0.09 mg/L as N for nitrite plus nitrate, less than 0.044 mg/L as N for ammonia, less than the MRL of 0.2 mg/L as N for ammonia plus organic nitrogen, and less than 0.02 mg/L as P for orthophosphate. Variability was estimated separately for low and high concentration ranges using the standard deviation (SD; low concentrations) or RSD (high concentrations) of replicate-sample pairs. For high concentrations, average variability was estimated to be 2.9 percent for

nitrite plus nitrate (concentrations greater than 1 mg/L as N), 1.3 percent for ammonia (concentrations greater than 0.3 mg/L as N), 7.8 percent for ammonia plus organic nitrogen (concentrations greater than 0.5 mg/L as N), and 10 percent for orthophosphate (concentrations greater than 0.1 mg/L as P). For low concentrations, variability was estimated to be 0.043 mg/L as N for nitrite plus nitrate, 0.0047 mg/L as N for ammonia, 0.022 mg/L as N for ammonia plus organic nitrogen, and 0.0039 mg/L as P for orthophosphate.

Radon and Other Radionuclides

The variability of radon was estimated from 343 replicate ground-water sample pairs collected by the NAWQA Program from 1991 to 2002 (Apodaca and others, 2006). The mean SD for low concentrations of radon (about 45 to 700 pCi/L) was 19.9 pCi/L, and the mean RSD for high concentrations (about 700 pCi/L to about 200,000 pCi/L) was 5.9 percent, indicating that radon results were reproducible with low variability at most concentrations. The quality of radium-226 and radium-228 data is described in Zoltan Szabo, U.S. Geological Survey, written commun., 2006.

Organic Compounds

Pesticides

Potential contamination in pesticide samples collected by NAWQA was investigated by Martin (1999a and 1999b) using field blanks collected during 1992–95. Most ground-water field blanks during this time had no detections of any pesticide compound (89 and 98 percent of blanks analyzed by GCMS and HPLC, respectively), and most compounds were not detected in any blank. Overall, pesticides of any kind were detected in 0.3 percent of the analyses of pesticides in blank samples (33 detections in 10,458 analyses). Thirty-two of 47 pesticides analyzed using GCMS were not detected in any field blanks (*n* equal to 145), and 33 of 37 pesticides analyzed using HPLC were not detected in field blanks (*n* equal to 98–104). The most frequently detected pesticides in field blanks were p,p'-DDE (4.1 percent), atrazine (2.8 percent), and benfluralin, chlorpyrifos, metolachlor, simazine, and triallate (1.4 percent each); all others were detected in 1 percent or less of field blanks. Greater use in the environment and lower detection limits for pesticides determined using the GCMS method, compared to the HPLC method, likely explained the higher frequency of detections in blanks with the GCMS method (Martin, 1999a). Detected concentrations were very low; maximum concentrations of individual pesticides in ground-water field blanks ranged from 0.001 µg/L (estimated) to 0.02 µg/L. The potential contamination indicated by these low detection frequencies and concentrations of pesticides in field blanks could affect interpretations of environmental data, however, for compounds that occur with comparable low frequency and concentrations, such as bromacil, benfluralin, chlorphyrifos, dachtal, p,p´-DDE, diazonon, diuron, fenuron, *cis*-permethrin, pronamide, propanil, triallate, and triflualin (Martin, 1999a). Maximum concentrations of any pesticides detected in field blanks were two to four orders of magnitude less than drinking-water standards or other human-health-based screening levels (except for p,p´-DDE, for which the health standard was 50 times the maximum concentration in blanks), indicating that potential contamination was negligible when evaluating concentrations of potential concern for human health.

The variability of detections and concentrations in pesticide samples collected for the NAWQA Program was investigated using field replicate samples collected during 1992–97 by Martin (2002). The assessment was based on 335 replicate sets of samples for GCMS analysis and 253 replicate sets for HPLC analysis, and included surface- and ground-water samples. The variability of pesticide detections was described by calculating the percentage of replicate sets with inconsistent detections for each pesticide compound (that is, sets in which a pesticide compound is detected in one replicate sample but not in the other), using all detections, including those less than the laboratory MRLs or MDLs. The percentage of inconsistent replicate sets generally decreased with increasing pesticide concentration; it was more likely that compounds would have been detected if they were present in the sample at higher concentrations. For all replicate sets analyzed for all pesticides, the overall rates of inconsistent replicates were 60 percent for pesticide concentrations less than MRLs or MDLs, 14 percent for concentrations at or within an order of magnitude of MRLs or MDLs, and 1 percent for concentrations greater than 10 times the MRLs or MDLs. The variability of measured pesticide concentrations also decreased with increasing concentrations. The typical variability of pesticide concentrations in the data set studied, measured by the median pooled RSD of field replicates with consistent detections, was 11 to 15 percent for concentrations less than 1 µg/L and less than 10 percent for concentrations greater than 1 µg/L (Martin, 2002).

The bias from matrix interferences or analyte loss during sample shipment or holding was investigated using field and laboratory spiked samples and other laboratory QC data. Median recovery for most pesticides analyzed by GSMS and HPLC ranged from 70 to 106 percent for field matrix spiked samples (61 pesticides) and laboratory reagent spikes (70 pesticides) collected during 1992–96 (Martin, 1999b). For several pesticides, laboratory QC data indicated that analytical results were considered to be negatively biased or unusually variable, and were qualified as "estimated" (Zaugg and others, 1995; Werner and others, 1996; U.S. Geological Survey, 1998; Gilliom and others, 2006). These pesticides were azinphos-methyl, carbaryl, carbofuran, deethylatrazine and terbacil (analyzed by GCMS) and aldicarb, aldicarb sulfone, aldicarb sulfoxide, chlorothalonil, dichlobenil, and 2-methyl-4,6-dinitrophenol (analyzed by HPLC).

Volatile Organic Compounds

Potential contamination of VOC samples collected for the NAWQA Program was investigated using analyses of blank samples collected during three periods during 1997–2005. About 70 percent (64) of all VOCs analyzed were detected infrequently (less than 1 percent) or not at all in field blanks (total *n* equal to 519; J.S. Zogorski and D.A. Bender, U.S. Geological Survey, written commun., 2008). Of the remaining VOCs, 11 were detected in 1 to 5 percent of field blanks and 11 were detected in more than 5 percent of field blanks. The VOCs detected in more than 5 percent of field blanks were (in decreasing order) toluene, 1,2,4-trimethylbenzene, *m*- and *p*-xylenes, chloroform, ethylbenzene, acetone, dichloromethane, benzene, styrene, carbon disulfide, and *o*-xylene. Because of several factors, including the presence on occasion of some VOCs in the blank water used to process field blanks (Taglioli and others, 2000) and the effectiveness of sampling-equipment rinsing with well water prior to the collection of a ground-water sample in eliminating this and other potential contamination sources, the results for the field blanks overstate the potential for random contamination associated with field protocols in ground-water samples. Analysis of field blank and environmental sample pairs was used to determine whether assessment levels were required to address the potential random contamination associated with field protocols for those VOCs detected in 1 or more percent of field blanks (J.S. Zogorski and D.A. Bender, U.S. Geological Survey, written commun., 2008). Assessment levels of 0.03 µg/L for toluene and 0.05 µg/L for 1,2,4-trimethylbenzene thus were determined to be appropriate. These assessment levels are adequate to limit the estimated probability of false detections of these compounds due to random sample contamination to less than 1 percent, and were used in the present study.

The bias from matrix interferences or analyte loss for VOC compounds during sample shipment or holding was investigated using field and laboratory spiked samples collected during 1997–2001 by Rowe and others (2005). The assessment was based on 428 spiked samples, including field spikes, field spike replicates, laboratory matrix spikes, and laboratory reagent spikes, for 85 VOCs in ground water and surface water. The median recoveries for all 85 VOCs ranged from 64 to 102 percent in field matrix spikes and ranged from 90 to 120 percent in laboratory reagent spikes; these were acceptable levels for all VOCs (Rowe and others, 2005).

Fecal Indicator Bacteria

Data on fecal indicator bacteria in most (95 percent) samples in this study were collected following standard USGS quality-assurance procedures, which at a minimum included the collection of filter-blank QC samples before and after filtration of each water sample (U.S. Geological Survey, variously dated; Embrey and Runkle, 2006). After October 2002, field blanks and positive and negative control samples also were collected (Embrey and Runkle, 2006). QC data for bacteria samples collected prior to October 2002 were not readily available at the national scale at the time this report was written (2007). However, analysis of available QC data associated with microbiological data after October 2002 indicated that target organisms were infrequently detected in filter blanks (3.4 percent or 13 of 379 blanks; Embry and Runkle, 2006). Environmental data associated with filter blanks in which target bacteria colonies were greater than 5 percent of the environmental bacteria colony concentrations ("V"-coded data) were not used in this study. Replicate QC samples were collected after October 2002 for microbiological data; RPDs for replicate pairs (*n* equal to 402) ranged from 0 to 200 percent, with average and median values of 13 and 0, respectively (Embry and Runkle, 2006).

References Cited

American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1992, Standard methods for the examination of water and wastewater (18th ed.): Washington, D.C., American Public Health Association, variously paginated.

American Society for Testing Materials, 1996, Annual book of ASTM standards, section 11: Water and Environmental Technology, v. 11.02, D5072-92, p. 674–676.

Apodaca, L.E., and Bails, J.B., 2000, Water quality in alluvial aquifers of the Southern Rocky Mountains Physiographic Province, Upper Colorado River Basin, Colorado, 1997: U.S. Geological Survey Water-Resources Investigations Report 99–4222, 68 p.

Apodaca, L.E., Mueller, D.K., and Koterba, M.T., 2006, Review of trace element blank and replicate data collected in ground and surface water for the National Water-Quality Assessment Program, 1991–2002: U.S. Geological Survey Scientific Investigations Report 2006–5093, 32 p.

Bexfield, L.M., and Anderholm, S.K., 1997, Water-quality assessment of the Rio Grande Valley, Colorado, New Mexico, and Texas—Ground-water quality in the Rio Grande flood plain, Cochiti Lake, New Mexico, to El Paso, Texas, 1995: U.S. Geological Survey Water-Resources Investigations Report 96–4249, 93 p.

Brenton, R.W., and Arnett, T.L., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of dissolved organic carbon by UV-promoted persulfate oxidation and infrared spectrometry: U.S. Geological Survey Open-File Report 92–480, 12 p.

Bruce, B.W., and McMahon, P.B., 1998, Shallow ground-water quality of selected land-use/aquifer settings in the South Platte River Basin, Colorado and Nebraska, 1993–95: U.S. Geological Survey Water-Resources Investigations Report 97–4229, 48 p.

Childress, C.J.O., Foreman, W.T., Connor, B.F., and Maloney, T.J., 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: U.S. Geological Survey Open-File Report 99–193, 19 p.

Coes, A.L., Gellenbeck, D.J., Towne, D.C., and Freark, M.C., 2000, Ground-water quality in the Upper Santa Cruz Basin, Arizona, 1998: U.S. Geological Survey Water-Resources Investigations Report 00–4117, 55 p.

Connor, B.F., Rose, D.L., Noriega, M.C., Murtagh, L.K., and Abney, S.R., 1998, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of 87 volatile organic compounds in water by gas chromatography/mass spectrometry, including detections less than reporting limits: U.S. Geological Survey Open-File Report 97–829, 78 p.

Embrey, S.S., and Runkle, D.L., 2006, Microbial quality of the Nation's ground-water resources, 1993–2004: U.S. Geological Survey Scientific Investigations Report 2006–5290, 34 p.

Faires, L.M., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of metals in water by inductively coupled plasma-mass spectrometry: U.S. Geological Survey Open-File Report 92–634, 28 p.

Fishman, M.J., ed., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of inorganic and organic constituents in water and fluvial sediments: U.S. Geological Survey Open-File Report 98–125, 217 p.

Fishman, M.J., and Friedman, L.C., 1989, Methods for determination of inorganic and organic constituents in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.

Focazio, M.J., Szabo, Zoltan, Kraemer, T.F., Mullin, A.H., Barringer, T.H., and DePaul, V.T., 2001, Occurrence of selected radionuclides in ground water used for drinking water in the United States—A reconnaissance survey, 1998: U.S. Geological Survey Water-Resources Investigations Report 00–4273, 40 p.

Fong, A.L., Andrews, W.J., and Stark, J.R., 1998, Water-quality assessment of part of the Upper Mississippi River Basin, Minnesota and Wisconsin—Ground-water quality in the Prairie du Chien-Jordan Aquifer, 1996: U.S. Geological Survey Water-Resources Investigations Report 98–4248, 45 p.

Furlong, E.T., Anderson, B.D., Werner, S.L., Soliven, P.P., Coffey, L.J., and Burkhardt, M.R., 2001, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of pesticides in water by graphitized carbon-based solid-phase extraction and high-performance liquid chromatography/mass spectrometry: U.S. Geological Survey Water-Resources Investigations Report 01–4134, 73 p.

Gabarino, J.R., 1999, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of dissolved arsenic, boron, lithium, selenium, strontium, thallium, and vanadium using inductively coupled plasma-mass spectrometry: U.S. Geological Survey Open-File Report 99–093, 31 p.

Gilliom, R.J., Barbash, J.E., Crawford, C.G., Hamilton, P.A., Martin, J.D., Nakagaki, Naomi, Nowell, L.H., Scott, J.C., Stackelberg, P.E., Thelin, G.P., and Wolock, D.M., 2006, Pesticides in the Nation's streams and ground water, 1992–2001: U.S. Geological Survey Circular 1291, 172 p., available at http://ca.water.usgs.gov/pnsp/pubs/circ1291.

Glass, R.L., 2001, Ground-water quality in Cook Inlet Basin, Alaska, 1999: U.S. Geological Survey Water-Resources Investigations Report 01–4208, 58 p.

Hamlin, S.N., Belitz, Kenneth, Kraja, Sarah, and Dawson, Barbara, 2002, Ground-water quality in the Santa Ana Watershed, California—Overview and data summary: U.S. Geological Survey Water-Resources Investigations Report 02–4243, 137 p.

Inkpen, E.L., Tesoriero, A.J., Ebbert, J.C., Silva, S.R., and Sandstrom, M.W., 2000, Ground-water quality in regional, agricultural, and urban settings in the Puget Sound Basin, Washington and British Columbia, 1996–1998: U.S. Geological Survey Water-Resources Investigations Report 00–4100, 66 p.

Kolpin, D.W., Barbash, J.E., and Gilliom, R.J., 1998, Occurrence of pesticides in shallow groundwater of the United States—Initial results from the National Water-Quality Assessment: Environmental Science & Technology, v. 32, p. 558–566.

Koterba, M.T., Wilde, F.D., and Lapham, W.W., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program—Collection and documentation of water-quality samples and related data: U.S. Geological Survey Open-File Report 99–399, 113 p.

Martin, J.D., 1999a, Summary and evaluation of pesticides in field blanks collected for the National Water-Quality Assessment Program, 1992–95: U.S. Geological Survey Open-File Report 98–412, 102 p.

Martin, J.D., 1999b, Quality of pesticides for environmental water samples collected for the National Water-Quality Assessment Program, 1992–96, and examples of the use of quality-control information in water-quality assessments: accessed November 2, 2006, at http://ca.water.usgs.gov/pnsp/rep/qcsummary.

Martin, J.D., 2002, Variability of pesticide detections and concentrations in field replicate water samples collected for the National Water-Quality Assessment Program, 1992–97: U.S. Geological Survey Water-Resources Investigations Report 01–4178, 84 p.

McLain, Betty, 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of chromium in water by graphite furnace atomic absorption spectrophotometry: U.S. Geological Survey Open-File Report 93–449, 16 p.

Menheer, M.A., and Brigham, M.E., 1997, Ground-water sampling methods and quality-control data for the Red River of the North Basin, Minnesota, North Dakota, and South Dakota, 1993–95: U.S. Geological Survey Water-Resources Investigations Report 96–4317, 34 p.

Milby-Dawson, B.J., 2001, Ground-water quality in the southeastern Sacramento Valley Aquifer, California, 1996: U.S. Geological Survey Water-Resources Investigations Report 01–4125, 24 p.

Moran, M.J., Zogorski, J.S., and Rowe, B.L., 2006, Approach to an assessment of volatile organic compounds in the Nation's ground water and drinking-water supply wells: U.S. Geological Survey Open-File Report 2005–1452, 36 p.

Moran, M.J., Zogorski, J.S., and Squillace, P.J., 2005, MTBE and gasoline hydrocarbons in ground water of the United States: Ground Water, v. 43, no. 4, p. 615–627.

Mueller, D.K., and Titus, C.J., 2005, Quality of nutrient data from streams and ground water sampled during water years 1992–2001: U.S. Geological Survey Scientific Investigations Report 2005–5106, 27 p.

Patton, C.J., and Truitt, E.P., 2000, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of ammonium plus organic nitrogen by a Kjeldahl digestion method and an automated photometric finish that includes digest cleanup by gas diffusion: U.S. Geological Survey Open-File Report 00–170, 31 p.

Pope, L.M., Bruce, B.W., and Hansen, C.V., 2001, Ground-water quality in the Quaternary deposits of the central High Plains Aquifer, south-central Kansas, 1999: U.S. Geological Survey Water-Resources Investigations Report 00–4259, 44 p.

Reutter, D.C., and Dunn, D.D., 2000, Water-quality assessment of the Trinity River Basin, Texas—Ground-water quality of the Trinity, Carrizo-Wilcox, and Gulf Coast Aquifers, February–August 1994: U.S. Geological Survey Water-Resources Investigations Report 99–4233, 56 p.

Robinson, J.L., 2003, Comparison between agricultural and urban ground-water quality in the Mobile River Basin, 1999–2001: U.S. Geological Survey Water-Resources Investigations Report 03–4182, 37 p.

Rose, D.L., and Schroeder, M.P., 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: U.S. Geological Survey Open-File Report 94–708, 26 p.

Rowe, B.L., Delzer, G.C., Bender, D.A., and Zogorski, J.S., 2005, Volatile organic compound matrix spike recoveries for ground- and surface-water samples, 1997–2001: U.S. Geological Survey Scientific Investigations Report 2005–5225, 51 p.

Savoca, M.E., Sadorf, E.M., and Akers, K.K., 1999, Ground-water quality in the eastern part of the Silurian-Devonian and Upper Carbonate Aquifers in the Eastern Iowa Basins, Iowa and Minnesota, 1996: U.S. Geological Survey Water-Resources Investigations Report 98–4224, 31 p.

Szabo, Zoltan, DePaul, V.T., Kraemer, T.F., and Parsa, Bahman, 2005, Occurrence of radium-224 and comparison to that of radium-226 and radium-228 in water from the unconfined Kirkwood-Cohansey aquifer system, southern New Jersey: U.S. Geological Survey Scientific Investigations Report 2004–5224, 92 p.

Taglioli, B.L., Delzer, G.C., and Zogorski, J.S., 2000, Study design and analytical results used to evaluate carry-over contamination by volatile organic compounds in surface- and ground-water sampling procedures: U.S. Geological Survey Open-File Report 00–384, 36 p.

U.S. Environmental Protection Agency, 1980, Prescribed procedures for measurement of radioactivity in drinking water: U.S. Environmental Protection Agency, Environmental Monitoring and Support Laboratory, Office of Resarch and Development, EPA 600-4-80-032, August 1980, 133 p.

U.S. Environmental Protection Agency, 2002b, Method 1103.1—*Escherichia coli (E. coli)* in water by membrane filtration using membrane-thermotolerant *E. coli* agar (MTec): U.S. Environmental Protection Agency, Office of Water, September 2002, EPA 821-R-02-020, 17 p.

U.S. Environmental Protection Agency, 2002c, Method 1604—Total coliforms and *Escherichia coli* in water by membrane filtration using a simultaneous detection technique (MI Medium): U.S. Environmental Protection Agency, Office of Water, September 2002, EPA 821-R-02-024, 18 p.

U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1–A9, accessed October 17, 2006, at http://water.usgs.gov/owq/FieldManual.

U.S. Geological Survey, 1997, NWIS—New remark code (V) for water-quality data: Office of Water Quality Technical Memorandum 97.08, accessed November 6, 2006, at http://water.usgs.gov/admin/ memo/QW/qw97.08.html.

U.S. Geological Survey, 1998, Changes in reporting levels and data qualifiers for selected pesticides and degradation products in schedules 2050 and 2051: National Water Quality Laboratory Technical Memorandum 98.03A, accessed November 6, 2006, at http://nwql.usgs.gov/Public/tech_memos/nwql.98-03A.html.

Werner, S.L., Burkhardt, M.R., and DeRusseau, S.N., 1996, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of pesticides in water by Carbopak-B solid-phase extraction and high-performance liquid chromatography: U.S. Geological Survey Open-File Report 96–216, 42 p.

Zaugg, S.D., Sandstrom, M.W., Smith, S.G., and Fehlberg, K.M., 1995, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of pesticides in water by C-18 solid-phase extraction and capillary-column gas chromatography/mass spectrometry with selected-ion monitoring: U.S. Geological Survey Open-File Report 95–181, 60 p.

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix 4. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water

Table

4–1. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water 112

Table 4–1. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water.

[USGS, U.S. Geological Survey; CAS, Chemical Abstract Service. Common method reporting levels (MRLs) and long-term method detection levels (LT-MDLs) are those used for at least about 10 percent of samples. Predominant use group is from Gilliom and others (2006) and Moran and others (2005) and includes compound class for pesticides (AMD, amide; CAB, carbamate; CBE, chlorobenzoic acid esters; CPA, chlorophenoxy acids; DNA, dinitroanalines; MSA, miscellaneous acids; MSC, miscellaneous; NPH, nitrophenols; OCL, organochlorines; OPH, organophosphates; PHN, phenols; PYR, pyrethroids; SFE, sulfite esters; TRZ, triazines, URC, uracils; URA, ureas). Pesticide degradation products are designated by use group "DP" with parent compound indicated in parentheses. MCL, U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level for public water supplies; AMCL, USEPA proposed Alternative Maximum Contaminant Level for public water supplies; HBSL, Health-Based Screening Level developed by USGS using USEPA toxicity information and methods (Toccalino and Norman, 2006); °C, degrees Celsius; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; ROE, residue on evaporation; µg/L, micrograms per liter; pCi/L, picocuries per liter; CFU/100 mL, colony-forming units per 100 milliliters; --, not available or not applicable]

Property or contaminant	Units	USGS parameter code	CAS number	Predominant use group	Common MRLs and LT-MDLs	Human-health benchmark		Number of analyses		
						Value	Type	Aquifer studies	Agri-cultural land-use studies	Aquifer and agricultural land-use studies
Physical properties										
Temperature	°C	00010	--	--	--	--	--	2,140	428	2,568
Specific conductance	µS/cm at 25°C	00095	--	--	1	--	--	2,138	432	2,570
Dissolved oxygen	mg/L	00300	--	--	0.1	--	--	2,053	431	2,484
pH	Standard units	00400	--	--	--	--	--	2,144	432	2,576
Alkalinity as $CaCO_3$	mg/L	--	--	--	1	--	--	2,038	379	2,412
Major ions										
Bromide	mg/L	71870	24959-67-9	--	0.01	--	--	2,058	418	2,476
Calcium	mg/L	00915	7440-70-2	--	0.01–0.02	--	--	2,160	424	2,584
Chloride	mg/L	00940	16887-00-6	--	0.1	--	--	2,157	422	2,579
Fluoride	mg/L	00950	16984-48-8	--	0.1	4	MCL	2,156	422	2,578
Magnesium	mg/L	00925	7439-95-4	--	0.01	--	--	2,160	424	2,584
Potassium	mg/L	00935	7440-70-2	--	0.1	--	--	2,160	424	2,584
Silica	mg/L	00955	7631-86-9	--	0.01	--	--	2,160	424	2,584
Sodium	mg/L	00930	7440-23-5	--	0.2	--	--	2,160	424	2,584
Sulfate	mg/L	00945	14808-79-8	--	0.1	--	--	2,157	422	2,579
Dissolved solids (ROE)	mg/L	70300	--	--	1–10	--	--	2,102	422	2,524
Trace elements										
Aluminum	µg/L	01106	7429-90-5	--	0.8–1	--	--	1,454	98	1,552
Antimony	µg/L	01095	7440-36-0	--	0.05–1	6	MCL	1,552	78	1,630
Arsenic	µg/L	01000	7440-38-2	--	0.2–1	10	MCL	1,774	116	1,890
Barium	µg/L	01005	7440-39-3	--	1	2,000	MCL	1,593	78	1,671
Beryllium	µg/L	01010	7440-41-7	--	0.03–1	4	MCL	1,572	78	1,650
Boron	µg/L	01020	7440-42-8	--	7–16	1,000	HBSL	535	26	561

Table 4–1. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water.—Continued

[USGS, U.S. Geological Survey; CAS, Chemical Abstract Service. Common method reporting levels (MRLs) and long-term method detection levels (LT-MDLs) are those used for at least about 10 percent of samples. Predominant use group is from Gilliom and others (2006) and Moran and others (2005) and includes compound class for pesticides (AMD, amide; CAB, carbamate; CBE, chlorobenzoic acid esters; CPA, chlorophenoxy acids; DNA, dinitroanalines; MSA, miscellaneous acids; MSC, miscellaneous; NPH, nitrophenols; OCL, organochlorines; OPH, organophosphates; PHN, phenols; PYR, pyrethroids; SFE, sulfite esters; TRZ, triazines, URC, uracils; URA, ureas). Pesticide degradation products are designated by use group "DP" with parent compound indicated in parentheses. MCL, U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level for public water supplies; AMCL, USEPA proposed Alternative Maximum Contaminant Level for public water supplies; HBSL, Health-Based Screening Level developed by USGS using USEPA toxicity information and methods (Toccalino and Norman, 2006); °C, degrees Celsius; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; ROE, residue on evaporation; µg/L, micrograms per liter; pCi/L, picocuries per liter; CFU/100 mL, colony-forming units per 100 milliliters; --, not available or not applicable]

Property or contaminant	Units	USGS parameter code	CAS number	Predominant use group	Common MRLs and LT-MDLs	Human-health benchmark		Number of analyses		
						Value	Type	Aquifer studies	Agri-cultural land-use studies	Aquifer and agricultural land-use studies
Trace elements—Continued										
Cadmium	µg/L	01025	7440-43-9	--	0.02–1	5	MCL	1,639	78	1,717
Chromium	µg/L	01030	7440-47-3	--	0.4–1	100	MCL	1,614	78	1,692
Cobalt	µg/L	01035	7440-48-4	--	1	--	--	1,572	78	1,650
Copper	µg/L	01040	7440-50-8	--	0.2–1	1,300	Action level	1,619	78	1,697
Iron	µg/L	01046	7439-89-6	--	3–10	--	--	2,157	424	2,581
Lead	µg/L	01049	7439-92-1	--	0.04–1	15	Action level	1,639	78	1,717
Lithium	µg/L	01130	7439-93-2	--	0.3–3	--	--	662	36	698
Manganese	µg/L	01056	7439-96-5	--	0.1–1	300	HBSL	2,159	424	2,583
Molybdenum	µg/L	01060	7439-98-7	--	0.03–1	40	HBSL	1,572	78	1,650
Nickel	µg/L	01065	7440-02-0	--	0.2–1	100	HBSL	1,572	78	1,650
Selenium	µg/L	01145	7782-49-2	--	0.7–1.2	50	MCL	1,625	78	1,703
Silver	µg/L	01075	7440-22-4	--	0.1–1	100	HBSL	1,573	77	1,650
Strontium	µg/L	01080	7440-24-6	--	10	4,000	HBSL	488	82	570
Thallium	µg/L	01057	7440-28-0	--	0.02–0.9	2	MCL	613	36	649
Uranium	µg/L	22703	7440-61-1	--	0.01–1	30	MCL	1,725	190	1,915
Vanadium	µg/L	01085	7440-62-2	--	0.2–1	--	--	662	36	698
Zinc	µg/L	01090	7440-66-6	--	0.5–1	2,000	HBSL	1,594	78	1,672
Nutrients and dissolved organic carbon										
Nitrite as N	mg/L	00613	14797-65-0	--	0.003–0.01	1	MCL	2,141	424	2,565
Nitrate as N	mg/L	00631	[1]14797-55-8	--	0.02–0.05	10	MCL	2,132	424	2,556
Ammonia as N	mg/L	00608	7664-41-7	--	0.02	--	--	2,095	424	2,519
Ammonia plus organic nitrogen as N	mg/L	00623	--	--	0.05–0.2	--	--	2,086	424	2,510
Phosphorus, dissolved as P	mg/L	00666	7723-14-0	--	0.002–0.01	--	--	1,776	399	2,175
Orthophosphate as P	mg/L	00671	14265-44-2	--	0.01	--	--	2,121	419	2,540
Dissolved organic carbon	mg/L	00681	--	--	0.1, 0.3	--	--	1,932	414	2,346

Table 4–1. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water.—Continued

[USGS, U.S. Geological Survey; CAS, Chemical Abstract Service. Common method reporting levels (MRLs) and long-term method detection levels (LT-MDLs) are those used for at least about 10 percent of samples. Predominant use group is from Gilliom and others (2006) and Moran and others (2005) and includes compound class for pesticides (AMD, amide; CAB, carbamate; CBE, chlorobenzoic acid esters; CPA, chlorophenoxy acids; DNA, dinitroanalines; MSA, miscellaneous acids; MSC, miscellaneous; NPH, nitrophenols; OCL, organochlorines; OPH, organophosphates; PHN, phenols; PYR, pyrethroids; SFE, sulfite esters; TRZ, triazines, URC, uracils; URA, ureas). Pesticide degradation products are designated by use group "DP" with parent compound indicated in parentheses. MCL, U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level for public water supplies; AMCL, USEPA proposed Alternative Maximum Contaminant Level for public water supplies; HBSL, Health-Based Screening Level developed by USGS using USEPA toxicity information and methods (Toccalino and Norman, 2006); °C, degrees Celsius; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; ROE, residue on evaporation; µg/L, micrograms per liter; pCi/L, picocuries per liter; CFU/100 mL, colony-forming units per 100 milliliters; --, not available or not applicable]

Property or contaminant	Units	USGS parameter code	CAS number	Predominant use group	Common MRLs and LT-MDLs	Human-health benchmark		Number of analyses		
						Value	Type	Aquifer studies	Agri-cultural land-use studies	Aquifer and agricultural land-use studies
Radon and other radionuclides										
Radon	pCi/L	82303	14859-67-7	--	26–80	4,000 and 300	Proposed AMCL and MCL	1,958	323	2,281
Gross alpha-particle radio-activity	pCi/L	04126	12587-46-1	--	3	15	MCL	378	0	378
Gross beta-particle radio-activity	pCi/L	03515	12587-47-2	--	4	50	Screening level	375	0	375
Radium-226 plus radium-228	pCi/L	Various	--	--	--	5	MCL	438	6	444
Pesticides										
Acetochlor	µg/L	49260	34256-82-1	Herbicide (AMD)	0.002, 0.003	[2]1	HBSL	1,822	224	2,046
Acifluorfen	µg/L	49315	50594-66-6	Herbicide (MCA)	0.007–0.062	90	HBSL	1,372	397	1,769
Alachlor	µg/L	46342	15972-60-8	Herbicide (AMD)	0.001, 0.002	2	MCL	2,115	425	2,540
Aldicarb	µg/L	49312	116-06-3	Insecticide (CAB)	0.016–0.55	9	HBSL	1,374	398	1,772
Aldicarb sulfone	µg/L	49313	1646-88-4	DP (Aldicarb) (CAB)	0.016–0.16	7	HBSL	1,366	392	1,758
Aldicarb sulfoxide	µg/L	49314	1646-87-3	DP (Aldicarb) (CAB)	0.008–0.027	7	HBSL	1,369	392	1,761
Atrazine	µg/L	39632	1912-24-9	Herbicide (TRZ)	0.001, 0.004	3	MCL	2,116	425	2,541
Azinphos-methyl (Guthion)	µg/L	82686	86-50-0	Insecticide (OPH)	0.001, 0.02	10	HBSL	2,115	420	2,535
Benfluralin	µg/L	82673	1861-40-1	Herbicide (DNA)	0.002, 0.005	4	HBSL	2,113	424	2,537
Bentazon	µg/L	38711	25057-89-0	Herbicide (MSC)	0.011–0.019	200	HBSL	1,370	397	1,767
Bromacil	µg/L	04029	314-40-9	Herbicide (URA)	0.033–0.081	70	HBSL	1,379	398	1,777
Bromoxynil	µg/L	49311	1689-84-5	Herbicide (PHN)	0.017–0.057	10	HBSL	1,371	397	1,768
Butylate	µg/L	04028	2008-41-5	Herbicide (CAB)	0.001, 0.002	400	HBSL	2,115	424	2,539
Carbaryl	µg/L	82680	63-25-2	Insecticide (CAB)	0.003, 0.021	[2]40	HBSL	2,115	425	2,540
Carbofuran	µg/L	82674	1563-66-2	Insecticide (CAB)	0.003, 0.01	40	MCL	2,114	425	2,539
Chloramben methyl ester	µg/L	61188	7286-84-2	Herbicide (MCA)	0.011–0.42	--	--	1,379	398	1,777

Table 4–1. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water.—Continued

[USGS, U.S. Geological Survey; CAS, Chemical Abstract Service. Common method reporting levels (MRLs) and long-term method detection levels (LT-MDLs) are those used for at least about 10 percent of samples. Predominant use group is from Gilliom and others (2006) and Moran and others (2005) and includes compound class for pesticides (AMD, amide; CAB, carbamate; CBE, chlorobenzoic acid esters; CPA, chlorophenoxy acids; DNA, dinitroanalines; MSA, miscellaneous acids; MSC, miscellaneous; NPH, nitrophenols; OCL, organochlorines; OPH, organophosphates; PHN, phenols; PYR, pyrethroids; SFE, sulfite esters; TRZ, triazines, URC, uracils; URA, ureas). Pesticide degradation products are designated by use group "DP" with parent compound indicated in parentheses. MCL, U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level for public water supplies; AMCL, USEPA proposed Alternative Maximum Contaminant Level for public water supplies; HBSL, Health-Based Screening Level developed by USGS using USEPA toxicity information and methods (Toccalino and Norman, 2006); °C, degrees Celsius; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; ROE, residue on evaporation; µg/L, micrograms per liter; pCi/L, picocuries per liter; CFU/100 mL, colony-forming units per 100 milliliters; --, not available or not applicable]

Property or contaminant	Units	USGS parameter code	CAS number	Predominant use group	Common MRLs and LT-MDLs	Human-health benchmark		Number of analyses		
						Value	Type	Aquifer studies	Agri-cultural land-use studies	Aquifer and agricultural land-use studies
Pesticides—Continued										
Chlorothalonil	µg/L	49306	1897-45-6	Fungicide (OCL)	0.035–0.48	[2]5	HBSL	1,377	398	1,775
Chlorpyrifos	µg/L	38933	2921-88-2	Insecticide (OPH)	0.003, 0.004	2	HBSL	2,113	424	2,537
Clopyralid	µg/L	49305	1702-17-6	Herbicide (MCA)	0.014–0.23	--	--	1,376	394	1,770
Cyanazine	µg/L	04041	21725-46-2	Herbicide (TRZ)	0.004, 0.009	1	HBSL	2,115	425	2,540
2,4-D	µg/L	39732	94-75-7	Herbicide (CPA)	0.022–0.15	70	MCL	1,368	397	1,765
Dacthal monoacid	µg/L	49304	887-54-7	Herbicide (CBE)	0.012–0.072	--	--	1,367	395	1,762
2,4-DB	µg/L	38746	94-82-6	Herbicide (CPA)	0.016–0.24	200	HBSL	1,377	396	1,773
DCPA (Dacthal)	µg/L	82682	1861-32-1	Herbicide (CBE)	0.002	70	HBSL	2,115	424	2,539
p,p'-DDE	µg/L	34653	72-55-9	DP (*p,p'*-DDT) (OCL)	0.001, 0.006	[2]0.1	HBSL	2,114	424	2,538
Deethylatrazine	µg/L	04040	6190-65-4	DP (Atrazine) (TRZ)	0.002, 0.003	--	--	2,116	425	2,541
Diazinon	µg/L	39572	333-41-5	Insecticide (OPH)	0.002, 0.003	1	HBSL	2,115	424	2,539
Dicamba	µg/L	38442	1918-00-9	Herbicide (MSA)	0.013–0.096	3,000	HBSL	1,376	397	1,773
Dichlobenil	µg/L	49303	1194-65-6	Herbicide (OCL)	0.020, 1.2	9	HBSL	924	363	1,287
Dichlorprop	µg/L	49302	120-36-5	Herbicide (CPA)	0.014–0.05	300	HBSL	1,377	396	1,773
Dieldrin	µg/L	39381	60-57-1	Insecticide, DP (Aldrin) (OCL)	0.001, 0.002	[2]0.002	HBSL	2,115	424	2,539
2,6-Diethylaniline	µg/L	82660	579-66-8	DP (Alachlor) (AMD)	0.001, 0.003	--	--	2,115	424	2,539
Dinoseb	µg/L	49301	88-85-7	Herbicide (NPH)	0.012–0.043	7	MCL	1,371	397	1,768
Disulfoton	µg/L	82677	298-04-4	Insecticide (OPH)	0.011, 0.017	0.9	HBSL	2,115	424	2,539
Diuron	µg/L	49300	330-54-1	Herbicide (URA)	0.015–0.079	[2]2	HBSL	1,374	398	1,772
DNOC (2-Methyl-4,6-dinitrophenol)	µg/L	49299	534-52-1	Herbicide (NPH)	0.035–0.42	--	--	919	362	1,281
EPTC	µg/L	82668	759-94-4	Herbicide (CAB)	0.001, 0.002	200	HBSL	2,115	424	2,539

Table 4–1. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water.—Continued

[USGS, U.S. Geological Survey; CAS, Chemical Abstract Service. Common method reporting levels (MRLs) and long-term method detection levels (LT-MDLs) are those used for at least about 10 percent of samples. Predominant use group is from Gilliom and others (2006) and Moran and others (2005) and includes compound class for pesticides (AMD, amide; CAB, carbamate; CBE, chlorobenzoic acid esters; CPA, chlorophenoxy acids; DNA, dinitroanalines; MSA, miscellaneous acids; MSC, miscellaneous; NPH, nitrophenols; OCL, organochlorines; OPH, organophosphates; PHN, phenols; PYR, pyrethroids; SFE, sulfite esters; TRZ, triazines, URC, uracils; URA, ureas). Pesticide degradation products are designated by use group "DP" with parent compound indicated in parentheses. MCL, U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level for public water supplies; AMCL, USEPA proposed Alternative Maximum Contaminant Level for public water supplies; HBSL, Health-Based Screening Level developed by USGS using USEPA toxicity information and methods (Toccalino and Norman, 2006); °C, degrees Celsius; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; ROE, residue on evaporation; µg/L, micrograms per liter; pCi/L, picocuries per liter; CFU/100 mL, colony-forming units per 100 milliliters; --, not available or not applicable]

Property or contaminant	Units	USGS parameter code	CAS number	Predominant use group	Common MRLs and LT-MDLs	Human-health benchmark		Number of analyses		
						Value	Type	Aquifer studies	Agri-cultural land-use studies	Aquifer and agricultural land-use studies
Pesticides—Continued										
Ethalfluralin	µg/L	82663	55283-68-6	Herbicide (DNA)	0.004, 0.005	30	HBSL	2,115	424	2,539
Ethoprop (Ethoprophos)	µg/L	82672	13194-48-4	Herbicide (OPH)	0.002, 0.003	[2]1	HBSL	2,115	425	2,540
Fenuron	µg/L	49297	101-42-8	Fenuron (URA)	0.013–0.074	--	--	1,371	398	1,769
Fluometuron	µg/L	38811	2164-17-2	Herbicide (URA)	0.031–0.062	4	HBSL	1,378	398	1,776
Fonofos	µg/L	04095	944-22-9	Insecticide (OPH)	0.001, 0.003	10	HBSL	2,115	424	2,539
alpha-HCH	µg/L	34253	319-84-6	DP (gamma-HCH) (OCL)	0.002	[2]0.006	HBSL	2,115	424	2,539
gamma-HCH (Lindane)	µg/L	39341	58-89-9	Insecticide (OCL)	0.002, 0.004	0.2	MCL	2,115	424	2,539
3-Hydroxycarbofuran	µg/L	49308	16655-82-6	DP (Carbofuran) (CAB)	0.006–0.062	--	--	1,371	398	1,769
Linuron	µg/L	82666	330-55-2	Herbicide (URA)	0.002, 0.018	5	HBSL	2,115	424	2,539
Malathion	µg/L	39532	121-75-5	Insecticide (OPH)	0.005, 0.014	50	HBSL	2,115	424	2,539
MCPA	µg/L	38482	94-74-6	Herbicide (CPA)	0.016–0.17	30	HBSL	1,377	397	1,774
MCPB	µg/L	38487	94-81-5	Herbicide (CPA)	0.015–0.14	100	HBSL	1,377	396	1,773
Methiocarb	µg/L	38501	2032-65-7	Insecticide (CAB)	0.008–0.08	40	HBSL	1,378	398	1,776
Methomyl	µg/L	49296	16752-77-5	Insecticide (CAB)	0.004–0.077	200	HBSL	1,366	392	1,758
Metolachlor	µg/L	39415	51218-45-2	Herbicide (AMD)	0.002, 0.006	700	HBSL	2,115	425	2,540
Metribuzin	µg/L	82630	21087-64-9	Herbicide (TRZ)	0.003, 0.004	90	HBSL	2,115	424	2,539
Molinate	µg/L	82671	2212-67-1	Herbicide (CAB)	0.001, 0.004	0.7	HBSL	2,115	424	2,539
Napropamide	µg/L	82684	15299-99-7	Herbicide (AMD)	0.003	800	HBSL	2,115	425	2,540
Neburon	µg/L	49294	555-37-3	Herbicide (URA)	0.012–0.075	--	--	1,378	398	1,776
Norflurazon	µg/L	49293	27314-13-2	Herbicide (MSC)	0.016–0.078	10	HBSL	1,378	398	1,776
Oryzalin	µg/L	49292	19044-88-3	Herbicide (DNA)	0.018–0.31	[2]4	HBSL	1,376	398	1,774
Oxamyl	µg/L	38866	23135-22-0	Insecticide (CAB)	0.012–0.018	200	MCL	1,365	392	1,757
Parathion (Ethyl parathion)	µg/L	39542	56-38-2	Insecticide (OPH)	0.003–0.005	0.02	HBSL	2,115	424	2,539

Table 4–1. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water.—Continued

[USGS, U.S. Geological Survey; CAS, Chemical Abstract Service. Common method reporting levels (MRLs) and long-term method detection levels (LT-MDLs) are those used for at least about 10 percent of samples. Predominant use group is from Gilliom and others (2006) and Moran and others (2005) and includes compound class for pesticides (AMD, amide; CAB, carbamate; CBE, chlorobenzoic acid esters; CPA, chlorophenoxy acids; DNA, dinitroanalines; MSA, miscellaneous acids; MSC, miscellaneous; NPH, nitrophenols; OCL, organochlorines; OPH, organophosphates; PHN, phenols; PYR, pyrethroids; SFE, sulfite esters; TRZ, triazines, URC, uracils; URA, ureas). Pesticide degradation products are designated by use group "DP" with parent compound indicated in parentheses. MCL, U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level for public water supplies; AMCL, USEPA proposed Alternative Maximum Contaminant Level for public water supplies; HBSL, Health-Based Screening Level developed by USGS using USEPA toxicity information and methods (Toccalino and Norman, 2006); °C, degrees Celsius; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; ROE, residue on evaporation; µg/L, micrograms per liter; pCi/L, picocuries per liter; CFU/100 mL, colony-forming units per 100 milliliters; --, not available or not applicable]

Property or contaminant	Units	USGS parameter code	CAS number	Predominant use group	Common MRLs and LT-MDLs	Human-health benchmark		Number of analyses		
						Value	Type	Aquifer studies	Agri-cultural land-use studies	Aquifer and agricultural land-use studies
Pesticides—Continued										
Parathion-methyl (Methyl parathion)	µg/L	82667	298-00-0	Insecticide (OPH)	0.003, 0.006	1	HBSL	2,115	424	2,539
Pebulate	µg/L	82669	1114-71-2	Herbicide (CAB)	0.001–0.004	50	HBSL	2,115	424	2,539
Pendimethalin	µg/L	82683	40487-42-1	Herbicide (DNA)	0.004–0.011	70	HBSL	2,115	424	2,539
cis-Permethrin	µg/L	82687	54774-45-7	Insecticide (PYR)	0.003, 0.005	[2]4	HBSL	2,115	424	2,539
Phorate	µg/L	82664	298-02-2	Insecticide (OPH)	0.002, 0.006	4	HBSL	2,115	424	2,539
Picloram	µg/L	49291	1918-02-1	Herbicide (MSA)	0.02–0.071	500	MCL	1,361	387	1,748
Prometon	µg/L	04037	1610-18-0	Herbicide (TRZ)	0.007, 0.018	400	HBSL	2,115	425	2,540
Pronamide (Propyzamide)	µg/L	82676	23950-58-5	Herbicide (AMD)	0.002, 0.003	[2]1	HBSL	2,115	425	2,540
Propachlor	µg/L	04024	1918-16-7	Herbicide (AMD)	0.005, 0.007	[2]1	HBSL	2,115	425	2,540
Propanil	µg/L	82679	709-98-8	Herbicide (AMD)	0.004, 0.005	6	HBSL	2,115	425	2,540
Propargite	µg/L	82685	2312-35-8	Acaricide (SFE)	0.011, 0.013	[2]1	HBSL	2,107	424	2,531
Propham	µg/L	49236	122-42-9	Herbicide (CAB)	0.01–0.0072	100	HBSL	1,378	398	1,776
Propoxur (Baygon)	µg/L	38538	114-26-1	Insecticide (CAB)	0.008–0.06	[2]9	HBSL	1,369	398	1,767
Simazine	µg/L	04035	122-34-9	Herbicide (TRZ)	0.002–0.006	4	MCL	2,114	425	2,539
2,4,5-T	µg/L	39742	93-76-5	Herbicide (CPA)	0.035	70	HBSL	919	361	1,280
Tebuthiuron	µg/L	82670	34014-18-1	Herbicide (URA)	0.008, 0.01	1,000	HBSL	2,116	425	2,541
Terbacil	µg/L	82665	5902-51-2	Herbicide (URC)	0.007, 0.017	90	HBSL	2,108	420	2,528
Terbufos	µg/L	82675	13071-79-9	Insecticide (OPH)	0.009, 0.013	0.4	HBSL	2,115	424	2,539
Thiobencarb	µg/L	82681	28249-77-6	Herbicide (CAB)	0.002	70	HBSL	2,115	424	2,539
2,4,5-TP (Silvex)	µg/L	39762	93-72-1	Herbicide (CPA)	0.021	50	MCL	920	362	1,282
Triallate	µg/L	82678	2303-17-5	Herbicide (CAB)	0.001	20	HBSL	2,115	424	2,539
Triclopyr	µg/L	49235	55335-06-3	Herbicide (OCL)	0.022–0.25	400	HBSL	1,372	397	1,769
Trifluralin	µg/L	82661	1582-09-8	Herbicide (DNA)	0.002, 0.005	20	HBSL	2,115	424	2,539

Table 4–1. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water.—Continued

[USGS, U.S. Geological Survey; CAS, Chemical Abstract Service. Common method reporting levels (MRLs) and long-term method detection levels (LT-MDLs) are those used for at least about 10 percent of samples. Predominant use group is from Gilliom and others (2006) and Moran and others (2005) and includes compound class for pesticides (AMD, amide; CAB, carbamate; CBE, chlorobenzoic acid esters; CPA, chlorophenoxy acids; DNA, dinitroanalines; MSA, miscellaneous acids; MSC, miscellaneous; NPH, nitrophenols; OCL, organochlorines; OPH, organophosphates; PHN, phenols; PYR, pyrethroids; SFE, sulfite esters; TRZ, triazines, URC, uracils; URA, ureas). Pesticide degradation products are designated by use group "DP" with parent compound indicated in parentheses. MCL, U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level for public water supplies; AMCL, USEPA proposed Alternative Maximum Contaminant Level for public water supplies; HBSL, Health-Based Screening Level developed by USGS using USEPA toxicity information and methods (Toccalino and Norman, 2006); °C, degrees Celsius; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; ROE, residue on evaporation; µg/L, micrograms per liter; pCi/L, picocuries per liter; CFU/100 mL, colony-forming units per 100 milliliters; --, not available or not applicable]

Property or contaminant	Units	USGS parameter code	CAS number	Predominant use group	Common MRLs and LT-MDLs	Human-health benchmark		Number of analyses		
						Value	Type	Aquifer studies	Agri-cultural land-use studies	Aquifer and agricultural land-use studies
Volatile organic compounds										
Acetone	µg/L	81552	67-64-1	Solvent	2–5	6,000	HBSL	1,536	37	1,573
Acrylonitrile	µg/L	34215	107-13-1	Organic synthesis	0.6–2	[2]0.06	HBSL	1,537	37	1,574
tert-Amyl methyl ether (Methyl *tert*-pentyl ether)	µg/L	50005	994-05-8	Gasoline oxygenate	0.04–0.112	--	--	1,537	37	1,574
Benzene	µg/L	34030	71-43-2	Gasoline hydro-carbon	0.017–0.2	5	MCL	1,957	313	2,270
Bromobenzene	µg/L	81555	108-86-1	Solvent	0.018–0.2	--	--	1,956	313	2,269
Bromochloromethane	µg/L	77297	74-97-5	Personal care and domestic use product	0.022–0.2	90	HBSL	1,956	312	2,268
Bromodichloromethane	µg/L	32101	75-27-4	Trihalomethane	0.024–0.2	[3]80	MCL	1,956	313	2,269
Bromoform (Tribromomethane)	µg/L	32104	75-25-2	Trihalomethane	0.03–0.2	[3]80	MCL	1,955	313	2,268
Bromomethane	µg/L	34413	74-83-9	Fumigant	0.074–0.2	100	HBSL	1,956	313	2,269
n-Butylbenzene	µg/L	77342	104-51-8	Gasoline hydro-carbon	0.05–0.2	--	--	1,956	313	2,269
sec-Butylbenzene	µg/L	77350	135-98-8	Gasoline hydro-carbon	0.016–0.2	--	--	1,956	313	2,269
tert-Butylbenzene	µg/L	77353	98-06-6	Gasoline hydro-carbon	0.03–0.2	--	--	1,956	313	2,269
Carbon disulfide	µg/L	77041	75-15-0	Organic synthesis	0.013–0.18	700	HBSL	1,536	37	1,573
Carbon tetrachloride (Tetrachloromethane)	µg/L	32102	56-23-5	Solvent	0.03–0.2	5	MCL	1,956	313	2,269
Chlorobenzene (Monochlorobenzene)	µg/L	34301	108-90-7	Solvent	0.014–0.2	100	MCL	1,957	313	2,270
Chloroethane	µg/L	34311	75-00-3	Solvent	0.06–0.2	--	--	1,955	313	2,268

Table 4–1. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water.—Continued

[USGS, U.S. Geological Survey; CAS, Chemical Abstract Service. Common method reporting levels (MRLs) and long-term method detection levels (LT-MDLs) are those used for at least about 10 percent of samples. Predominant use group is from Gilliom and others (2006) and Moran and others (2005) and includes compound class for pesticides (AMD, amide; CAB, carbamate; CBE, chlorobenzoic acid esters; CPA, chlorophenoxy acids; DNA, dinitroanalines; MSA, miscellaneous acids; MSC, miscellaneous; NPH, nitrophenols; OCL, organochlorines; OPH, organophosphates; PHN, phenols; PYR, pyrethroids; SFE, sulfite esters; TRZ, triazines, URC, uracils; URA, ureas). Pesticide degradation products are designated by use group "DP" with parent compound indicated in parentheses. MCL, U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level for public water supplies; AMCL, USEPA proposed Alternative Maximum Contaminant Level for public water supplies; HBSL, Health-Based Screening Level developed by USGS using USEPA toxicity information and methods (Toccalino and Norman, 2006); °C, degrees Celsius; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; ROE, residue on evaporation; µg/L, micrograms per liter; pCi/L, picocuries per liter; CFU/100 mL, colony-forming units per 100 milliliters; --, not available or not applicable]

Property or contaminant	Units	USGS parameter code	CAS number	Predominant use group	Common MRLs and LT-MDLs	Human-health benchmark		Number of analyses		
						Value	Type	Aquifer studies	Agri-cultural land-use studies	Aquifer and agricultural land-use studies
Volatile organic compounds—Continued										
Chloroform (Trichloromethane)	µg/L	32106	67-66-3	Trihalomethane	0.012–0.2	[3]80	MCL	1,956	313	2,269
Chloromethane	µg/L	34418	74-87-3	Organic synthesis	0.09–0.25	30	HBSL	1,901	256	2,157
3-Chloropropene	µg/L	78109	107-05-1	Organic synthesis	0.03–0.196	--	--	1,537	37	1,574
2-Chlorotoluene (*o*-)	µg/L	77275	95-49-8	Solvent	0.013–0.2	100	HBSL	1,956	313	2,269
4-Chlorotoluene (*p*-)	µg/L	77277	106-43-4	Solvent	0.03–0.2	100	HBSL	1,956	313	2,269
Dibromochloromethane	µg/L	32105	124-48-1	Trihalomethane	0.05–0.2	[3]80	MCL	1,956	313	2,269
Dibromochloropropane (DBCP)	µg/L	82625	96-12-8	Fumigant	0.107–1.0	0.2	MCL	1,956	313	2,269
Dibromomethane	µg/L	30217	74-95-3	Solvent	0.025–0.2	--	--	1,956	313	2,269
1,2-Dichlorobenzene (*o*-)	µg/L	34536	95-50-1	Solvent	0.024–0.2	600	MCL	1,957	313	2,270
1,3-Dichlorobenzene (*m*-)	µg/L	34566	541-73-1	Solvent	0.015–0.2	600	HBSL	1,957	313	2,270
1,4-Dichlorobenzene (*p*-)	µg/L	34571	106-46-7	Fumigant	0.025–0.2	75	MCL	1,957	313	2,270
trans-1,4-Dichloro-2-butene	µg/L	73547	110-57-6	Organic synthesis	0.346–5	--	--	1,537	37	1,574
Dichlorodifluoromethane	µg/L	34668	75-71-8	Refrigerant	0.07–0.2	1,000	HBSL	1,957	313	2,270
1,1-Dichloroethane	µg/L	34496	75-34-3	Solvent	0.033–0.2	--	--	1,956	313	2,269
1,2-Dichloroethane	µg/L	32103	107-06-2	Solvent	0.05–0.2	5	MCL	1,945	312	2,257
1,1-Dichloroethene	µg/L	34501	75-35-4	Solvent	0.02–0.2	7	MCL	1,956	313	2,269
cis-1,2-Dichloroethene	µg/L	77093	156-59-2	Solvent	0.019–0.2	70	MCL	1,956	313	2,269
trans-1,2-Dichloroethene	µg/L	34546	156-60-5	Solvent	0.016–0.2	100	MCL	1,956	313	2,269
1,2-Dichloropropane	µg/L	34541	78-87-5	Fumigant	0.014–0.2	5	MCL	1,956	313	2,269
1,3-Dichloropropane	µg/L	77173	142-28-9	Fumigant	0.013–0.2	--	--	1,956	313	2,269
2,2-Dichloropropane	µg/L	77170	594-20-7	Fumigant	0.02–0.2	--	--	1,955	313	2,268
1,1-Dichloropropene	µg/L	77168	563-58-6	Organic synthesis	0.018–0.2	--	--	1,955	313	2,268
cis-1,3-Dichloropropene	µg/L	34704	10061-01-5	Fumigant	0.046–0.2	[2,4]0.3	HBSL	1,956	313	2,269

Table 4–1. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water.—Continued

[USGS, U.S. Geological Survey; CAS, Chemical Abstract Service. Common method reporting levels (MRLs) and long-term method detection levels (LT-MDLs) are those used for at least about 10 percent of samples. Predominant use group is from Gilliom and others (2006) and Moran and others (2005) and includes compound class for pesticides (AMD, amide; CAB, carbamate; CBE, chlorobenzoic acid esters; CPA, chlorophenoxy acids; DNA, dinitroanalines; MSA, miscellaneous acids; MSC, miscellaneous; NPH, nitrophenols; OCL, organochlorines; OPH, organophosphates; PHN, phenols; PYR, pyrethroids; SFE, sulfite esters; TRZ, triazines, URC, uracils; URA, ureas). Pesticide degradation products are designated by use group "DP" with parent compound indicated in parentheses. MCL, U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level for public water supplies; AMCL, USEPA proposed Alternative Maximum Contaminant Level for public water supplies; HBSL, Health-Based Screening Level developed by USGS using USEPA toxicity information and methods (Toccalino and Norman, 2006); °C, degrees Celsius; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; ROE, residue on evaporation; µg/L, micrograms per liter; pCi/L, picocuries per liter; CFU/100 mL, colony-forming units per 100 milliliters; --, not available or not applicable]

Property or contaminant	Units	USGS parameter code	CAS number	Predominant use group	Common MRLs and LT-MDLs	Human-health benchmark		Number of analyses		
						Value	Type	Aquifer studies	Agri-cultural land-use studies	Aquifer and agricultural land-use studies
Volatile organic compounds—Continued										
trans-1,3-Dichloropropene	µg/L	34699	10061-02-6	Fumigant	0.04–0.2	[2,4]0.3	HBSL	1,955	313	2,268
Diethyl ether	µg/L	81576	60-29-7	Solvent	0.085–0.17	1000	HBSL	1,537	37	1,574
Diisopropyl ether	µg/L	81577	108-20-3	Gasoline oxygenate	0.05–0.1	--	--	1,427	37	1,464
Ethyl methacrylate	µg/L	73570	97-63-2	Organic synthesis	0.09–1	--	--	1,536	37	1,573
Ethyl *tert*-butyl ether (*tert*-Butyl ethyl ether)	µg/L	50004	637-92-3	Gasoline oxygenate	0.027–0.1	--	--	1,537	37	1,574
Ethylbenzene	µg/L	34371	100-41-4	Gasoline hydro-carbon	0.015–0.2	700	MCL	1,957	313	2,270
Ethylene dibromide (1,2-Dibromoethane)	µg/L	77651	106-93-4	Fumigant	0.018–0.2	0.05	MCL	1,955	313	2,268
2-Ethyltoluene	µg/L	77220	611-14-3	Gasoline hydro-carbon	0.03–0.1	--	--	1,537	37	1,574
Hexachlorobutadiene	µg/L	39702	87-68-3	Organic synthesis	0.07–0.2	[2]0.9	HBSL	1,956	313	2,269
Hexachloroethane	µg/L	34396	67-72-1	Solvent	0.05–0.362	0.7	HBSL	1,537	37	1,574
Iodomethane	µg/L	77424	74-88-4	Organic synthesis	0.05–0.350	--	--	1,537	37	1,574
Isopropylbenzene	µg/L	77223	98-82-8	Gasoline hydro-carbon	0.016–0.2	700	HBSL	1,956	313	2,269
n-Isopropyltoluene (4-Isopropyltoluene)	µg/L	77356	99-87-6	Gasoline hydro-carbon	0.03–0.2	--	--	1,956	313	2,269
Methyl acrylate	µg/L	49991	96-33-3	Organic synthesis	0.612–2	--	--	1,537	37	1,574
Methyl acrylonitrile (Methacrylonitrile)	µg/L	81593	126-98-7	Organic synthesis	0.3–2	0.7	HBSL	1,537	37	1,574
Methyl butyl ketone (*n*-Butyl methyl ketone)	µg/L	77103	591-78-6	Solvent	0.378–5	--	--	1,537	37	1,574
Methyl ethyl ketone (Ethyl methyl ketone)	µg/L	81595	78-93-3	Solvent	0.825–5	4,000	HBSL	1,537	37	1,574

Table 4–1. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water.—Continued

[USGS, U.S. Geological Survey; CAS, Chemical Abstract Service. Common method reporting levels (MRLs) and long-term method detection levels (LT-MDLs) are those used for at least about 10 percent of samples. Predominant use group is from Gilliom and others (2006) and Moran and others (2005) and includes compound class for pesticides (AMD, amide; CAB, carbamate; CBE, chlorobenzoic acid esters; CPA, chlorophenoxy acids; DNA, dinitroanalines; MSA, miscellaneous acids; MSC, miscellaneous; NPH, nitrophenols; OCL, organochlorines; OPH, organophosphates; PHN, phenols; PYR, pyrethroids; SFE, sulfite esters; TRZ, triazines, URC, uracils; URA, ureas). Pesticide degradation products are designated by use group "DP" with parent compound indicated in parentheses. MCL, U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level for public water supplies; AMCL, USEPA proposed Alternative Maximum Contaminant Level for public water supplies; HBSL, Health-Based Screening Level developed by USGS using USEPA toxicity information and methods (Toccalino and Norman, 2006); °C, degrees Celsius; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; ROE, residue on evaporation; µg/L, micrograms per liter; pCi/L, picocuries per liter; CFU/100 mL, colony-forming units per 100 milliliters; --, not available or not applicable]

Property or contaminant	Units	USGS parameter code	CAS number	Predominant use group	Common MRLs and LT-MDLs	Human-health benchmark		Number of analyses		
						Value	Type	Aquifer studies	Agri-cultural land-use studies	Aquifer and agricultural land-use studies
Volatile organic compounds—Continued										
Methyl isobutyl ketone (Isobutyl methyl ketone)	µg/L	78133	108-10-1	Solvent	0.180–5	--	--	1,537	37	1,574
Methyl methacrylate	µg/L	81597	80-62-6	Organic synthesis	0.175–1	10,000	HBSL	1,537	37	1,574
Methyl *tert*-butyl ether	µg/L	78032	1634-04-4	Gasoline oxygenate	0.08–0.2	--	--	1,956	312	2,268
Methylene chloride (Dichloromethane)	µg/L	34423	75-09-2	Solvent	0.08–0.38	5	MCL	1,956	313	2,269
Naphthalene	µg/L	34696	91-20-3	Gasoline hydro-carbon	0.125–0.5	100	HBSL	1,956	313	2,269
Perchloroethene (Tetrachloroethene)	µg/L	34475	127-18-4	Solvent	0.013–0.2	5	MCL	1,927	313	2,240
n-Propylbenzene	µg/L	77224	103-65-1	Solvent	0.021–0.2	--	--	1,956	313	2,269
Styrene	µg/L	77128	100-42-5	Gasoline hydro-carbon	0.021–0.2	100	MCL	1,951	313	2,264
1,1,1,2-Tetrachloroethane	µg/L	77562	630-20-6	Solvent	0.015–0.2	70	HBSL	1,955	313	2,268
1,1,2,2-Tetrachloroethane	µg/L	34516	79-34-5	Solvent	0.04–0.2	0.3	HBSL	1,956	313	2,269
Tetrahydrofuran	µg/L	81607	109-99-9	Solvent	1.1–5	--	--	1,536	37	1,573
1,2,3,4-Tetramethylbenzene	µg/L	49999	488-23-3	Gasoline hydro-carbon	0.05–0.23	--	--	1,537	37	1,574
1,2,3,5-Tetramethylbenzene	µg/L	50000	527-53-7	Gasoline hydro-carbon	0.05–0.24	--	--	1,537	37	1,574
Toluene	µg/L	34010	108-88-3	Gasoline hydro-carbon	0.03–0.2	1,000	MCL	1,891	313	2,204
1,2,3-Trichlorobenzene	µg/L	77613	87-61-6	Organic synthesis	0.133–0.266	--	--	1,956	313	2,269
1,2,4-Trichlorobenzene	µg/L	34551	120-82-1	Solvent	0.09–0.2	70	MCL	1,956	313	2,269
1,1,1-Trichloroethane	µg/L	34506	71-55-6	Solvent	0.016–0.2	200	MCL	1,957	313	2,270
1,1,2-Trichloroethane	µg/L	34511	79-00-5	Solvent	0.03–0.2	5	MCL	1,956	313	2,269
Trichloroethene	µg/L	39180	79-01-6	Solvent	0.019–0.2	5	MCL	1,956	313	2,269

Table 4–1. Physical properties and contaminants analyzed in samples collected from domestic wells for the NAWQA Program, 2001–2004, and associated human-health benchmarks for drinking water.—Continued

[USGS, U.S. Geological Survey; CAS, Chemical Abstract Service. Common method reporting levels (MRLs) and long-term method detection levels (LT-MDLs) are those used for at least about 10 percent of samples. Predominant use group is from Gilliom and others (2006) and Moran and others (2005) and includes compound class for pesticides (AMD, amide; CAB, carbamate; CBE, chlorobenzoic acid esters; CPA, chlorophenoxy acids; DNA, dinitroanalines; MSA, miscellaneous acids; MSC, miscellaneous; NPH, nitrophenols; OCL, organochlorines; OPH, organophosphates; PHN, phenols; PYR, pyrethroids; SFE, sulfite esters; TRZ, triazines, URC, uracils; URA, ureas). Pesticide degradation products are designated by use group "DP" with parent compound indicated in parentheses. MCL, U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level for public water supplies; AMCL, USEPA proposed Alternative Maximum Contaminant Level for public water supplies; HBSL, Health-Based Screening Level developed by USGS using USEPA toxicity information and methods (Toccalino and Norman, 2006); °C, degrees Celsius; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; mg/L, milligrams per liter; ROE, residue on evaporation; µg/L, micrograms per liter; pCi/L, picocuries per liter; CFU/100 mL, colony-forming units per 100 milliliters; --, not available or not applicable]

Property or contaminant	Units	USGS parameter code	CAS number	Predominant use group	Common MRLs and LT-MDLs	Human-health benchmark		Number of analyses		
						Value	Type	Aquifer studies	Agri-cultural land-use studies	Aquifer and agricultural land-use studies
Volatile organic compounds—Continued										
Trichlorofluoromethane	µg/L	34488	75-69-4	Refrigerant	0.046–0.2	2,000	HBSL	1,957	313	2,270
1,2,3-Trichloropropane	µg/L	77443	96-18-4	Organic synthesis	0.08–0.2	40	HBSL	1,956	313	2,269
Trichlorotrifluoroethane (1,1,2-Trichloro-1,2,2-trifluoroethane)	µg/L	77652	76-13-1	Refrigerant	0.016–0.2	200,000	HBSL	1,955	313	2,268
1,2,3-Trimethylbenzene	µg/L	77221	526-73-8	Gasoline hydro-carbon	0.05–0.124	--	--	1,537	37	1,574
1,2,4-Trimethylbenzene	µg/L	77222	95-63-6	Gasoline hydro-carbon	0.028–0.2	--	--	1,913	306	2,219
1,3,5-Trimethylbenzene	µg/L	77226	108-67-8	Gasoline hydro-carbon	0.022–0.2	--	--	1,956	313	2,269
Vinyl bromide (Bromoethene)	µg/L	50002	593-60-2	Organic synthesis	0.050–0.11	--	--	1,537	37	1,574
Vinyl chloride	µg/L	39175	75-01-4	Organic synthesis	0.056–0.2	2	MCL	1,957	313	2,270
o-Xylene	µg/L	77135	95-47-6	Gasoline hydro-carbon	0.019–0.064	[5]10,000	MCL	1,536	37	1,573
m- and *p*-Xylenes	µg/L	85795	108-38-3 and 106-42-3	Gasoline hydro-carbon	0.0300–0.11	[5]10,000	MCL	1,530	37	1,567
Fecal indicator bacteria										
Total coliform, all methods	CFU/100 mL	Various	--	--	--	See text	--	397	86	483
Escherichia coli, all methods	CFU/100 mL	Various	--	--	--	See text	--	378	55	433
Summary										
Total number of analytes	--	--	--	--	--	--	--	219	219	219
Total number of analyses	--	--	--	--	--	--	--	373,578	63,189	436,767

[1]CAS number is for nitrate plus nitrite; see text for additional information.
[2]Value is low end of range, associated with 10^{-6} cancer risk (Toccalino and others, 2006).
[3]MCL is for sum of four trihalomethanes.
[4]HBSL is for sum of *cis*-1,3-dichloropropene and *trans*-1,3-dichloropropene.
[5]MCL is for sum of xylenes.

Appendix 5. Summary statistics for physical properties and concentrations of major ions, trace elements, nutrients, radionuclides, and fecal indicator bacteria in samples collected from domestic wells for the NAWQA Program, 1991–2004

CD-ROM

[In Pocket]

Tables

5–1. Abbreviations for principal aquifer names
5–2. Summary statistics for physical properties of and concentrations of major ions, trace elements, nutrients, radionuclides, and fecal indicator bacteria in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004
5–3. Summary statistics for physical properties of and concentrations of major ions, trace elements, nutrients, radionuclides, and fecal indicator bacteria in samples collected from domestic wells for the NAWQA Program in agricultural land-use studies, 1991–2004
5–4. Summary statistics for physical properties of and concentrations of major ions, trace elements, nutrients, radionuclides, and fecal indicator bacteria in samples collected from domestic wells for the NAWQA Program in aquifer and agricultural land-use studies, 1991–2004

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix 6. Percentages of wells in principal aquifers with values of physical properties or concentrations of major ions, trace elements, nutrients, radionuclides, or organic compounds greater than human-health benchmarks or guidelines for drinking water in samples collected from domestic wells for the NAWQA Program, 1991–2004

CD-ROM

[In Pocket]

Tables

6–1. Abbreviations for principal aquifer names

6–2. Percentage of wells in principal aquifers with values of physical properties or concentrations of major ions, trace elements, nutrients, radionuclides, or organic compounds greater than human-health benchmarks or non-health guidelines for drinking water in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004

6–3. Percentage of wells in principal aquifers with values of physical properties or concentrations of major ions, trace elements, nutrients, radionuclides, or organic compounds greater than human-health benchmarks or non-health guidelines for drinking water in samples collected from domestic wells for the NAWQA Program in agricultural land-use studies, 1991–2004

6–4. Percentage of wells in principal aquifers with values of physical properties or concentrations of major ions, trace elements, nutrients, radionuclides, or organic compounds greater than human-health benchmarks or non-health guidelines for drinking water in samples collected from domestic wells for the NAWQA Program in aquifer and agricultural land-use studies, 1991–2004

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix 7. Detection frequencies of organic compounds at any concentration and at several common reporting levels in samples collected from domestic wells for the NAWQA Program, 1991–2004

CD-ROM

[In Pocket]

Tables

7–1. Detection frequencies of organic compounds at any concentration and at three common reporting levels in samples collected from domestic wells for the NAWQA Program in aquifer studies, 1991–2004

7–2. Detection frequencies of organic compounds at any concentration and at three common reporting levels in samples collected from domestic wells for the NAWQA Program in agricultural land-use studies, 1991–2004

7–3. Detection frequencies of organic compounds at any concentration and at three common reporting levels in samples collected from domestic wells for the NAWQA Program in aquifer and agricultural land-use studies, 1991–2004

Prepared by the Pembroke Publishing Service Center.

For more information concerning this report, contact:

Director
U.S. Geological Survey
Massachusetts-Rhode Island Water Science Center
10 Bearfoot Road
Northborough, MA 01532
dc_ma@usgs.gov

or visit our Web site at:
http://ma.water.usgs.gov

USGS

DeSimone—**Quality of Water from Domestic Wells in Principal Aquifers of the United States, 1991–2004**—Scientific Investigations Report 2008–5227

ISBN 978-1-4113-2351-3

Printed on recycled paper