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Trace Elements and Radon in Groundwater Across the United States, 1992–2003

Scientific Investigations Report 2011–5059

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

Cover. Left photograph: Outcrop of crystalline bedrock. (Photograph by James Degnan, U.S. Geological Survey). Middle photograph: Domestic well in crystalline bedrock aquifer. Right photograph: Drinking water from a domestic well.

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By Joseph D. Ayotte, Jo Ann M. Gronberg, and Lori E. Apodaca

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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, 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 groundwater? How are conditions changing over time? How do natural features and human activities affect the quality of streams and groundwater, 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 to 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/studies/study_units.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 selectively reassessed. These assessments extend the findings in the Study Units by determining water-quality 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 groundwater. 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 studies 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, 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.

William H. Werkheiser
USGS Associate Director for Water

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Conversion Factors, Datum, Acronyms, and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	Becquerel per liter (Bq/L)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

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

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

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

Chemical symbols

Al	Aluminum
Sb	Antimony
As	Arsenic
Ba	Barium
Be	Beryllium
B	Boron
Cd	Cadmium
Cr	Chromium
Co	Cobalt
Cu	Copper
Fe	Iron
Pb	Lead
Li	Lithium
Mn	Manganese
Mo	Molybdenum

Ni	Nickel
Se	Selenium
Ag	Silver
Sr	Strontium
Tl	Thallium
U	Uranium
V	Vanadium
Zn	Zinc
Rn	Radon

Aquifer groups

USG	Unconsolidated sand and gravel aquifers
GLA	Glacial unconsolidated sand and gravel aquifers
SCS	Semi-consolidated sand aquifers
SAN	Sandstone aquifers
SCR	Sandstone and carbonate-rock aquifers
CAR	Carbonate-rock aquifers
BAV	Basaltic- and other volcanic-rock aquifers
CRL	Crystalline-rock aquifers
USGD	Unconsolidated sand and gravel aquifers from dry climates
USGH	Unconsolidated sand and gravel aquifers from humid climates

Other abbreviations

α	Acceptable statistical significance level for rejecting null hypothesis
AL	Action level
AMCL	Alternative maximum contaminant level (applies only to proposed radon standard)
CDC	U.S. Centers for Disease Control and Prevention
CFC	Chlorofluorocarbon
DO	Dissolved oxygen
GCMS	Gas chromatography/mass spectrometry
HA	Health advisory
HBSL	Health-based screening level
HHB	Human-health benchmark

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
LUS	Land-use study
MAS	Major aquifer study
MCL	Maximum contaminant level
N	number of samples
NAWQA	National Water-Quality Assessment
NWIS	National Water Information System
p	Attained statistical significance level
QC	Quality control
R^2	Coefficient of determination, or fraction of variance explained by regression
ROS	Regression-on-order statistics
RPD	Relative percent difference
RSD	Relative standard deviation
TDS	Total dissolved solids
TU	Tritium units
SMCL	Secondary maximum contaminant level
SSMDC	Sample-specific minimum detectable concentration
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VOC	Volatile organic compound

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By Joseph D. Ayotte, Jo Ann M. Gronberg, and Lori E. Apodaca

Abstract

Trace-element concentrations in groundwater were evaluated for samples collected between 1992 and 2003 from aquifers across the United States as part of the U.S. Geological Survey National Water-Quality Assessment Program. This study describes the first comprehensive analysis of those data by assessing occurrence (concentrations above analytical reporting levels) and by comparing concentrations to human-health benchmarks (HHBs). Data from 5,183 monitoring and drinking-water wells representing more than 40 principal and other aquifers in humid and dry regions and in various land-use settings were used in the analysis. Trace elements measured include aluminum (Al), antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), boron (B), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), lithium (Li), manganese (Mn), molybdenum (Mo), nickel (Ni), selenium (Se), silver (Ag), strontium (Sr), thallium (Tl), uranium (U), vanadium (V), and zinc (Zn). Radon (Rn) gas also was measured and is included in the data analysis.

Climate influenced the occurrence and distribution of trace elements in groundwater whereby more trace elements occurred and were found at greater concentrations in wells in drier regions of the United States than in humid regions. In particular, the concentrations of As, Ba, B, Cr, Cu, Mo, Ni, Se, Sr, U, V, and Zn were greater in the drier regions, where processes such as chemical evolution, ion complexation, evaporative concentration, and redox (oxidation-reduction) controls act to varying degrees to mobilize these elements. Al, Co, Fe, Pb, and Mn concentrations in groundwater were greater in humid regions of the United States than in dry regions, partly in response to lower groundwater pH and (or) more frequent anoxic conditions. In groundwater from humid regions, concentrations of Cu, Pb, Rn, and Zn were significantly greater in drinking-water wells than in monitoring wells.

Samples from drinking-water wells in dry regions had greater concentrations of As, Ba, Pb, Li, Sr, V, and Zn, than samples from monitoring wells. In humid regions, however, concentrations of most trace elements were greater in monitoring wells than in drinking-water wells; the exceptions were Cu, Pb, Zn, and Rn. Cu, Pb, and Zn are common trace elements in pumps and pipes used in the construction of drinking-water wells, and contamination from these sources may have contributed to their concentrations. Al, Sb, Ba, B, Cr, Co, Fe, Mn, Mo, Ni, Se, Sr, and U concentrations were all greater in monitoring wells than in drinking-water wells in humid regions.

Groundwater from wells in agricultural settings had greater concentrations of As, Mo, and U than groundwater from wells in urban settings, possibly owing to greater pH in the agricultural wells. Significantly greater concentrations of B, Cr, Se, Ag, Sr, and V also were found in agricultural wells in dry regions. Groundwater from dry-region urban wells had greater concentrations of Co, Fe, Pb, Li, Mn, and specific conductance than groundwater from agricultural wells.

The geologic composition of aquifers and aquifer geochemistry are among the major factors affecting trace-element occurrence. Trace-element concentrations in groundwater were characterized in aquifers from eight major groups based on geologic material, including (1) unconsolidated sand and gravel; (2) glacial unconsolidated sand and gravel; (3) semiconsolidated sand; (4) sandstone; (5) sandstone and carbonate rock; (6) carbonate rock; (7) basaltic and other volcanic rock; and (8) crystalline rock. The majority of groundwater samples and the largest percentages of exceedences of HHBs were in the glacial and nonglacial unconsolidated sand and gravel aquifers; in these aquifers, As, Mn, and U are the most common trace elements exceeding HHBs.

Overall, 19 percent of wells (962 of 5,097) exceeded an HHB for at least one trace element. The trace elements with HHBs included in this summary were Sb, As, Ba, Be, B, Cd, Cr, Cu, Pb, Mn, Mo, Ni, Se, Ag, Sr, Tl, U, and Zn. Mn occurred most often at concentrations greater than its human-health benchmark (12 percent), followed by As (7.0 percent), Sr (4.3 percent), U (4.0 percent), B (1.9 percent), and Mo (1.5 percent). Rn occurred at concentrations greater than the U.S. Environmental Protection Agency (USEPA) proposed maximum contaminant level of 300 pCi/L in more than 65 percent of water samples, and concentrations of Rn in 2.7 percent of samples were greater than the USEPA-proposed alternate maximum contaminant level of 4,000 pCi/L. There were more exceedences of HHBs in the dry-region groundwater than in the humid-region groundwater.

Groundwater pH and redox conditions were significant factors for the occurrence of many trace elements. Low pH (less than 7) was a significant factor in the occurrence of many cationic metals, such as Al, Fe, Mn, and Ni; these metals, as well as Cu, Pb, and Zn, adsorb more strongly to aquifer materials as pH increases. Anoxic conditions often were related to the increased occurrence of many oxyanion-forming elements, such as As, Cr, and Mo, whereas oxic conditions often were related to higher Se occurrence. Groundwater redox and pH effects were evident for As, Cr, Mo, and Se. Based on all samples, As occurrence generally increased as geochemical conditions became increasingly anoxic for groundwater with pH less than 7, but was consistently high for samples with pH greater than 7. A similar pattern was evident for Mo and, to a lesser extent, Cr. For groundwater in aquifers in glacial unconsolidated sand and gravel, however, As occurrence increased as groundwater became increasingly anoxic and as pH increased, indicating that redox is an important process throughout the range of pH. Al, Cu, Pb, and Zn occurred more often in low-pH groundwater and, except for Al, in oxic conditions.

In general, older waters (mostly pre-1953) had more occurrences of trace elements, greater pHs, were from deeper wells, and had lower concentrations of dissolved oxygen than younger waters (defined as waters containing a fraction younger than 1953). Most oxyanion-forming trace elements occurred more frequently in old groundwater. However, although U occurrence was greater in older water collected from dry-region aquifers, U occurred more often in young water in humid-region aquifers. This difference may be related to old, humid-region groundwater having lower concentrations of dissolved oxygen, a condition which can inhibit U mobility.

Overall, As co-occurred primarily with silica (SiO_2) and Mo in water with slightly high pH. About 12 percent of water samples without SiO_2 or Mo had concentrations of As greater than or equal to 1 µg/L. This number increased to about 45 percent if either Mo or silica were present and to about 85 percent if both Mo and SiO_2 were present. From a subset of water samples selected from 2,714 wells for co-occurrence analysis, samples from 572 wells (21.1 percent) had HHB exceedences of one or more trace elements. Of the 2,714 samples, 62 (2.3 percent) had two or more trace elements that exceeded HHBs. Fifty of the 62 (80 percent) were from unconsolidated sand and gravel aquifers and involved at least As and Mn, Mn and U, or As and U.

Introduction

In 2000, groundwater accounted for about 46 percent of water used in the United States, with about 31 percent of use for public supply and about 15 percent from domestic wells (also known as private wells). Total withdrawals from groundwater have generally increased over the past 5 decades along with increases in population (Hutson and others, 2004). For example, groundwater withdrawals of freshwater increased by 9 percent from 1995 to 2000, and population increased by 7 percent over the same period (Hutson and others, 2004). Trace elements in groundwater used for drinking have long been a concern because of potential adverse effects on human health. Many trace elements in drinking water can have adverse health effects at high concentrations, whereas others may present aesthetic or nuisance problems.

As used in this report, the term “trace elements” refers to metals and semimetallic elements that typically are found in concentrations less than 1 mg/L in natural waters (Hem, 1985). These elements are mobilized primarily from rock weathering, and their concentrations in groundwater reflect their presence and abundance in aquifer materials, geochemical conditions (such as pH and oxidation-reduction potential), the presence and abundance of complexing ions and organic matter, and attenuation processes such as adsorption (Hem, 1985; Salbu and Steinnes, 1994). Human activities, such as mining and waste disposal, also can affect concentrations of trace elements in groundwater.

Studies worldwide have shown that high concentrations of trace elements can have adverse effects on human health (Wu and others, 1989; Haglund and others, 1996; Hopenhayn-Rich and others, 1996; Cantor, 1997; Karagas and others, 1998; National Academy of Sciences, 1999; Chappell and others, 2001; Karagas and others, 2001; Smedley and others, 2001; Kendall and Smith, 2002; Smedley, 2003; Seiler, 2004; Selinus and others, 2005; Wasserman and others, 2006; Meliker and others, 2007; Walker and others, 2008). Several trace elements, including arsenic, cadmium, chromium, lead, and radon gas, have known and established toxicity (Selinus and others, 2005). Other trace elements, such as copper and selenium, in too small an amount, can cause adverse health outcomes (Selinus and others, 2005; Chrosniak and others, 2006). Because many trace elements are widely dispersed in rocks and unconsolidated materials, the individual occurrence rate of a specific trace element may be low, but the overall chance of having at least one trace element of concern in a water sample may be relatively high. Because of differences in well characteristics and regulations, concentrations of trace elements in groundwater from domestic wells could differ from those in groundwater withdrawn from public wells. Thus, the distinction between drinking waters supplied by public and domestic wells may be a significant factor for health scientists assessing exposure to trace elements through drinking water.

The National Water-Quality Assessment Program

Knowledge of the quality of the Nation’s streams and aquifers is important because of the effect on human and aquatic health and the substantial costs associated with decisions involving land and water management, conservation, and regulation. Understanding regional patterns and environmental factors affecting trace-element concentrations in streams and groundwater is essential for effectively developing programs to manage and protect these water resources and human health. The U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program was implemented in 1991 to improve the scientific and public understanding of water quality in the Nation's major river basins and groundwater systems. The goals of the NAWQA Program are to describe current water-quality conditions and trends in the Nation's rivers and groundwater to determine the natural characteristics and human influences that affect water quality (Gilliom and others, 1995).

Groundwater quality in the United States has been characterized by the NAWQA Program through studies that use nationally consistent methods and are distributed within 51 major river basins and aquifers nationwide (figs. 1A and B). The analysis in this report is based on NAWQA Program data collected from 1992 to 2003. More information on the design, components, and current activities of the NAWQA Program is available (Gilliom and others, 1995; Lapham and others, 1995; Rosen and Lapham, 2008). Prior to 1999, trace-element sampling in groundwater was mainly done for NAWQA major aquifer studies (MASs) and to a lesser extent for agricultural and urban land-use studies (LUSs). Trace-element sampling was fully implemented in the NAWQA Program in 1999.

Purpose and Scope

The primary purpose of this report is to describe the occurrence and distribution of 23 trace elements and radon (Rn) in water from wells sampled by the USGS NAWQA Program from 1992 to 2003. The term occurrence is used in this report to describe concentrations of trace elements above a specified analytical reporting level—in most cases 1 µg/L, unless otherwise noted. The analyses presented are based on single samples from 5,183 wells. The trace elements evaluated include aluminum (Al), antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), boron (B), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), lithium (Li), manganese (Mn), molybdenum (Mo), nickel (Ni), selenium (Se), silver (Ag), strontium (Sr), thallium (Tl), uranium (U), vanadium (V), and zinc (Zn). Rn, a direct decay product of ^{226}radium, was included because of its known adverse effects on human health (U.S. Environmental Protection Agency, 2010). Physical properties (pH, dissolved oxygen (DO) concentration, specific conductance, and water temperature) and concentrations of major inorganic constituents and nutrients also were measured.

The occurrence and distribution of trace elements in groundwater is described at the national scale and by major aquifer group (groups of principal and other aquifers) with a focus on areas where concentrations of trace elements from wells exceed health-based standards. As part of this objective, measured trace-element concentrations in groundwater are compared to U.S. Environmental Protection Agency (USEPA) drinking-water standards and proposed standards (for Rn)—including maximum contaminant levels (MCL), health advisories (HA), and action levels (AL)—and to Health-Based Screening Levels (HBSLs) published by the USGS (Toccalino and Norman, 2006). Collectively, these are referred to as human-health benchmarks (HHBs). Also compared are selected secondary maximum contaminant levels (SMCL), which are nonhealth guidelines.

Additional objectives include (1) the identification of factors that relate to the occurrence of selected trace elements, such as geochemistry, redox, and age of groundwater; and (2) the analysis of co-occurrence of selected trace elements in individual wells where more than one trace element exceeds HHBs.

Previous Studies

It is beyond the scope of this report to provide a comprehensive bibliography of trace-element studies in the United States. The reader is referred to several resources that provide an excellent overview of previous studies of trace-element sources and mobility (Freeze and Cherry, 1979; Drever, 1988; Hem, 1985). Few systematic evaluations of multiple trace elements in groundwater at the scale of this study have been undertaken in the United States. Selected national- and regional-scale studies that are particularly relevant to the current analysis are listed in appendix 1.

Previous studies of trace elements in groundwater throughout the United States have identified important relations among controls on occurrence and mobility. Also, the literature on factors that govern trace-element sources and mobility in specific regions of the United States is extensive, and some studies have compared data across regions. In most studies, however, only one trace element was assessed, or a few trace elements from a particular group (such as As or selected radionuclides) were evaluated, leaving gaps in the available information to assess trace-element occurrence and no opportunity to assess the co-occurrence of trace elements.

Water-Quality Benchmarks for Human Health

The human-health benchmarks used in this study include MCLs and ALs established by the USEPA for public-water supplies (U.S. Environmental Protection Agency, 2004) and HBSLs derived from the analysis of toxicology data for specific contaminants (Toccalino and Norman, 2006). In most cases, the HBSLs are equivalent to USEPA HAs, although HBSLs are updated more often as new toxicological data become available. Although not all of the wells analyzed for this report were used for drinking water, they were all selected with the aim of characterizing trace-element concentrations in aquifers across the United States. Thus, comparisons of trace-element concentrations to HHBs are not intended to represent potential exposure but rather to indicate where and under what conditions groundwater in important aquifers is affected. The

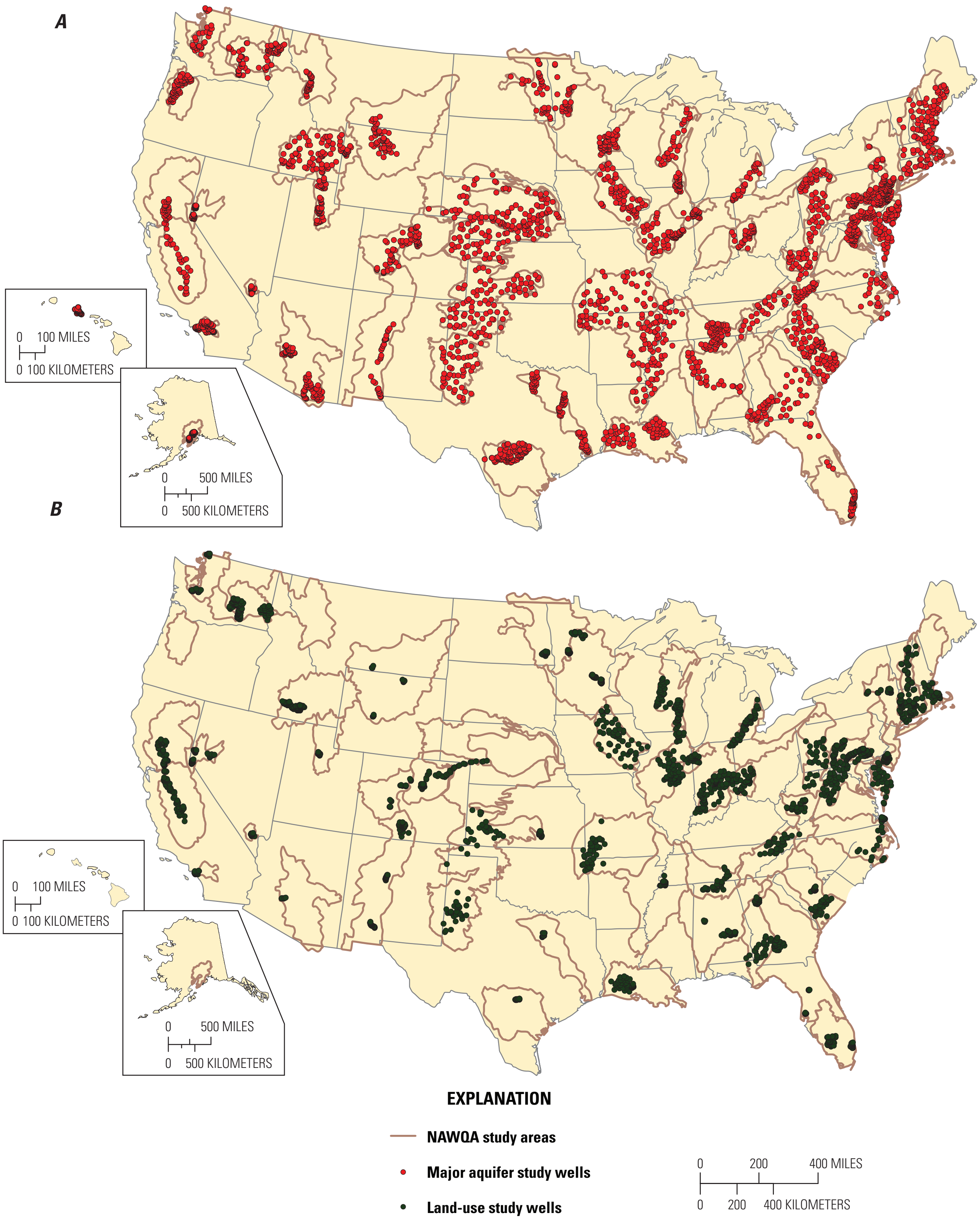


Figure 1. Locations of *(A)* major aquifer study (MAS) wells, and *(B)* land-use study (LUS) wells sampled for trace elements by the National Water-Quality Assessment Program, 1992–2003.

USEPA has established enforceable MCLs for Sb, As, Ba, Be, Cd, Cr, Se, Tl, and U. ALs have been established for Cu and Pb, and exceedence of these ALs triggers possible treatment or other requirements for a water system. Currently an MCL and alternative MCL (AMCL) have been proposed for Rn. HBSLs, similar to USEPA HAs, are acceptable levels based on health information (nonenforceable) and have been established for B, Mn, Mo, Ni, Ag, Sr, and Zn (Toccalino and Norman, 2006). Nonhealth guidelines, such as SMCLs, are nonenforceable and pertain to water aesthetics, such as for Al and Fe. Three of the trace elements discussed in this report (Co, Li, and V) do not have USEPA drinking-water standards (U.S. Environmental Protection Agency, 2004) or HBSLs.

Methods

This study used data collected by the USGS NAWQA Program to characterize trace-element concentrations in major aquifer groups across the United States. The data were analyzed primarily by determining their distributions and comparing those distributions to factors such as climate, composition of geologic materials, well types, well depths, pH, and redox conditions. A variety of methods were used to develop the data used in the analyses and to identify factors influencing trace element concentrations in groundwater.

Well Selection

Wells included in this study are from NAWQA studies designed to describe the quality of water withdrawn from major aquifers and used for drinking (termed major aquifer studies or MASs) and studies of shallow groundwater within specific land-use settings (termed land-use studies or LUSs) (Gilliom and others, 1995). MASs focused on the quality of groundwater resources throughout an aquifer and used data mostly from existing supply wells irrespective of depth. LUSs targeted the uppermost recently recharged groundwater to identify the effects of the overlying land use and used data mostly from monitoring wells and some supply wells. Individual MASs and LUSs are described in reports for individual NAWQA study areas (see http://water.usgs.gov/nawqa/). The sampling network for each study comprised about 30 wells that were randomly selected within the target area by a geographically distributed sampling method (Scott, 1990). A total of 5,183 wells from which geologic and chemical data had been collected were from networks in 48 NAWQA study areas across the United States (fig. 1). The actual numbers of wells used in the analyses were based on whether or not a particular trace element was analyzed in water from a well or on the availability of ancillary data for that analysis. Additional information on sampling networks and wells is shown in appendix 2.

Specific well-selection protocols designed by the NAWQA Program were used in the design of the MASs and LUSs (Lapham and others, 1995). Ancillary data for each well were collected according to NAWQA protocols (Koterba and others, 1995) and included latitude and longitude, topographic setting, well depth, open interval, casing diameter and material, geologic materials and (or) aquifers contributing water to the well, static water level, potential point sources of contamination near the well, and land use within 50 and 500 m of the well.

Sample Collection and Analysis

Groundwater was collected and analyzed for trace elements, major ions, nutrients, tritium, chlorofluorocarbons (CFCs), and other constituents in accordance with NAWQA protocols (Koterba and others, 1995; Lapham and others, 1995). Prior to collection, wells were pumped until the water temperature, DO, specific conductance, and pH were stable (Koterba and others, 1995). Cleaned polytetrafluoroethylene (PTFE) tubing with stainless-steel fittings was connected to either a submersible pump or to a water line close to the wellhead. Groundwater was collected at a flow rate of 0.5 L/min (0.0083 L/s) in a portable sampling chamber. Samples for trace elements were passed through a 0.45-µm disposable polypropylene capsule filter; the trace-element samples were then acidified with ultra pure nitric acid to a pH of less than 2. Trace elements were analyzed at the USGS National Water Quality Laboratory in Denver, Colo., by using inductively coupled plasma atomic-emission spectrometry (ICP–AES), inductively coupled plasma mass spectrometry (ICP–MS), graphite-furnace atomic-absorption spectrometry (AA), or hydride generation atomic-absorption spectrometry (Fishman and Friedman, 1989; Faires, 1993; McLain, 1993; Ivahnenko and others, 1996; Garbarino, 1999; Ivahnenko and others, 2001). Laboratory reporting levels (LRLs) generally ranged from 0.2 to 1 µg/L, except for the LRLs for Fe and B, which were higher. Concentrations of Rn were analyzed by liquid scintillation methods; LRLs for Rn ranged from 52 to 80 pCi/L (Prichard and Gessell, 1977; Mullin and Wanty, 1991).

Study Design

Several factors affect trace-element solubility and mobility. In this study, data were analyzed in relation to climate, the geology of aquifer materials, aquifer geochemistry, and the redox potential and pH of the groundwater. The ancillary data used in the data analyses represent regional- to national-scale conditions. Depending on the scale of the analysis, variables such as climate, geology, pH, and redox can be used to explain differences in trace-element concentrations in groundwater. However, when concentrations of trace elements in groundwater are analyzed at the major aquifer scale, the effect of climate becomes diminished because most aquifer groups are limited in spatial extent and are in either predominantly dry or humid regions.

Climate

In general, concentrations of trace elements are greater in drier climates of the United States, owing to processes such as redox condition, ion competition, complexation, evaporative concentration, and to more chemically evolved groundwater conditions (Hem, 1985; Welch and others, 2000; McMahon and Chapelle, 2008). To characterize general climatic conditions in the United States, a climate variable indicating generally dry or generally humid conditions for North America was used (fig. 2A) (Commission for Environmental Cooperation Working Group, 1997). With a few exceptions, the western United States has a generally dry climate, whereas the east is generally humid (fig. 2A). Local studies have shown that the effects of drier climates can favor increased groundwater concentrations of trace elements, such as Se (Dubrovsky and others, 1993; Seiler and others, 2003), As (Seiler, 2004; Thiros and Manning, 2004), B, Mo, and U (Fujii and Swain, 1995; Welch and Lico, 1998). In humid regions, by contrast, larger groundwater fluxes and shorter groundwater residence times may result in lower pH, favoring mobility of trace elements such as Al, Fe, Mn, Pb, and Zn to a greater extent than in dry regions. In addition, precipitation in much of the humid east has been more acidic than in the west (National Atmospheric Deposition Program, 2001) (fig. 2B); greater acidity can lead to increased weathering of geologic materials containing trace elements and potentially greater mobility of those elements in groundwater young enough (post-1960) to be affected by that precipitation (Jacks, 1993).

Aquifer Groups and Geology

Most trace elements in groundwater are derived from minerals in the rocks and sediment through which groundwater flows; thus, regional and subregional differences in geology can have implications for trace-element occurrence in groundwater. For example, some Cretaceous-age deposits of the central Great Plains have been shown to contain labile concentrations of As, B, Cr, Cu, Ni, Se, V, and U (Tourtelot, 1956). Some materials derived from these deposits have been shown to be related to high concentrations of Se in groundwater and surface water in parts of the western United States (Seiler and others, 2003). Arsenic occurrence in groundwater may be similarly controlled by availability in aquifer materials, as well as by groundwater geochemistry (Welch and others, 2000; Smedley and Kinniburgh, 2002; Welch and Stollenwerk, 2003; Thomas, 2007). Aquifers in some carbonate lithologies, such as the Floridan aquifer system and parts of the Edwards-Trinity aquifer system in Texas, have high concentrations of Sr that ultimately affect the concentrations in the associated groundwater (Hanshaw and Back, 1979; Back and others, 1988; Musgrove and Banner, 2004). Although most trace elements in groundwater are from natural sources, it is important to note that the sources of some trace elements in groundwater may be anthropogenic, and that some naturally occurring trace elements can be mobilized by anthropogenic activities (Böhlke, 2002; Seiler and others, 2003; Stollenwerk and Colman, 2004; Eberts and others, 2005; deLemos and others, 2006; Dubrovsky and others, 2010; Ayotte and others, 2011).

For this study, more than 40 aquifers were divided into 8 major aquifer groups based on the geologic materials from which they derive water (table 1; fig. 3). These groups are based on important aquifers in the United States (Miller, 2000) and the principal aquifers of the United States map (U.S. Geological Survey, 2003). Principal aquifers are defined as aquifers that are regionally extensive and can yield useable quantities of water (U.S. Geological Survey, 2003). The eight major aquifer groups used in this report are (1) unconsolidated sand and gravel aquifers; (2) glacial unconsolidated sand and gravel aquifers; (3) semiconsolidated sand aquifers; (4) sandstone aquifers; (5) sandstone and carbonate-rock aquifers; (6) carbonate-rock aquifers; (7) basaltic- and other volcanic-rock aquifers; and (8) crystalline-rock aquifers.

In most cases, wells in the major aquifer groups used in this study are predominantly in either dry or humid regions. The primary exceptions are the wells in the unconsolidated sand and gravel aquifers and the sandstone and carbonate-rock aquifer groups, in which the number of wells is split more evenly between dry and humid regions of the United States (table 1).

Some principal aquifers (and aquifer systems) contain deposits from multiple types of geologic materials. In this study, however, the composition of geologic materials was a primary factor in analyzing the water chemistry data so that individual wells from the same principal aquifer could be grouped into different categories based on rock type. An example of this is the Valley and Ridge aquifers, which are listed as sandstone and carbonate-rock aquifers on the principal aquifer map of the United States (U.S. Geological Survey, 2003) and described together in the Ground Water Atlas of the United States (Miller, 2000). For this analysis, the Valley and Ridge aquifers were separated into the sandstone aquifer group and the carbonate-rock aquifer group. This was done to account for differences in geochemical conditions, which can differ widely between these rock types. In addition, crystalline-rock aquifers in New York and New England (Miller, 2000) and in the Rocky Mountain Front Range, which are described as "other" aquifers on the principal aquifers map of the United States (U.S. Geological Survey, 2003), were included in this report as unofficially named aquifers in the crystalline-rock aquifer group. Also in this report, unconsolidated deposits were separated into groups of unconsolidated aquifers of glacial origin and unconsolidated aquifers of nonglacial origin. The glacial sand and gravel aquifers include deposits of both Laurentide and Cordilleran continental glaciations (Warner and Arnold, 2006). Additional information about aquifer groups, principal aquifers, and other aquifers is available at http://water.usgs.gov/nawqa/studies/praq/ or http://pubs.usgs.gov/ha/ha730/gwa.html.

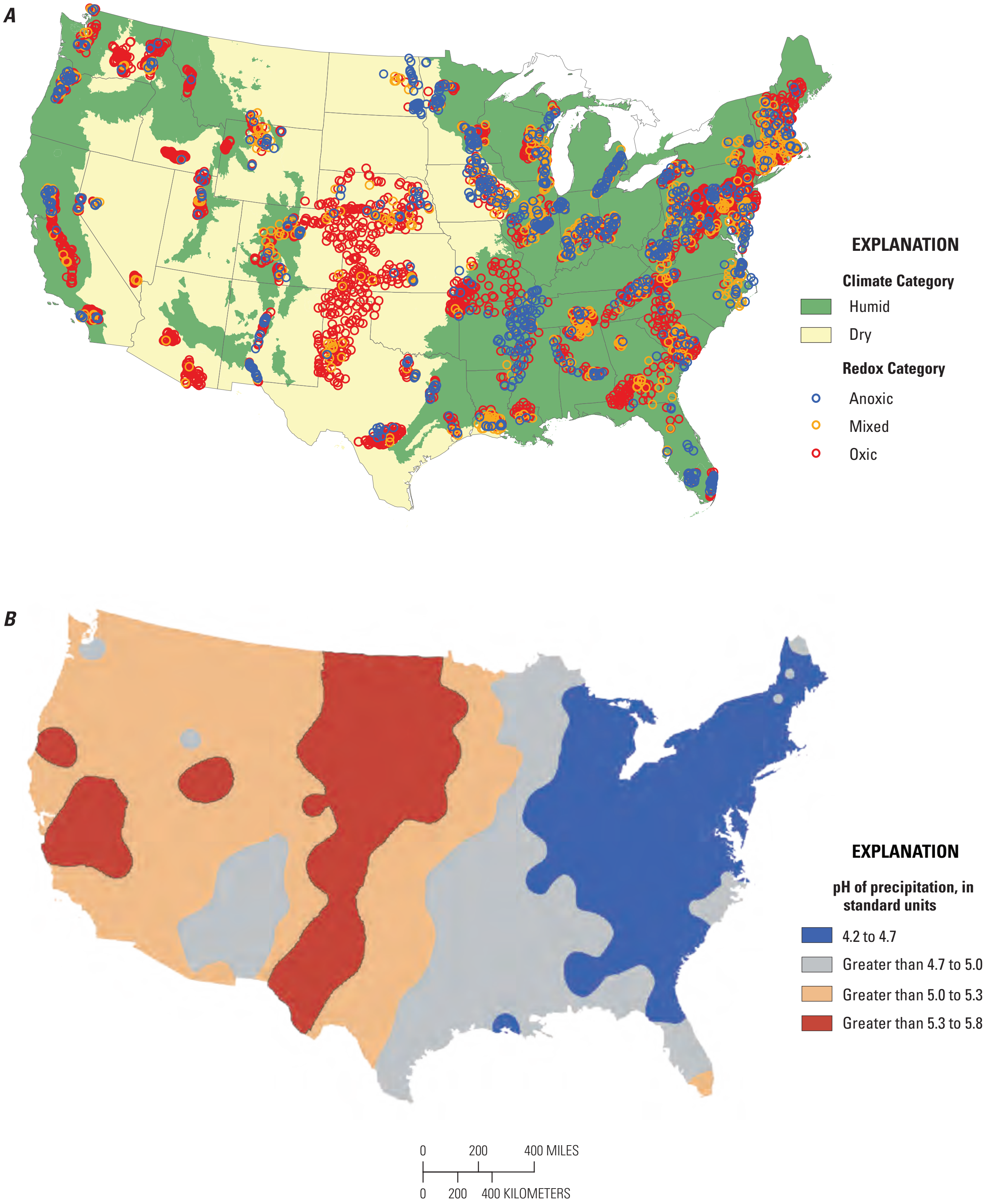


Figure 2. *(A)* Generalized categories of oxidation-reduction potential (redox) in samples from wells in humid and dry regions of the United States (Commission for Environmental Cooperation Working Group, 1997), and *(B)* pH of precipitation in 2001 (National Atmospheric Deposition Program, 2001).

Table 1. Generalized description of the major aquifer groups sampled for the NAWQA Program across the United States.

[Groups were compiled and modified from the U.S. Geological Survey Ground Water Atlas of the United States (Miller, 2000) and Principal Aquifer Map of the United States (U.S. Geological Survey, 2003)]

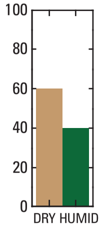
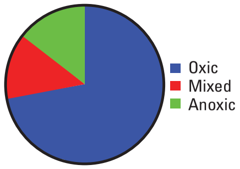
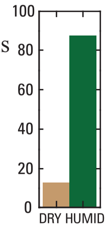
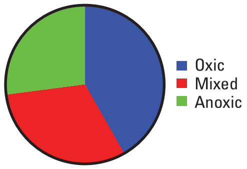
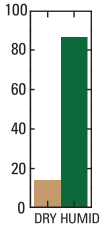
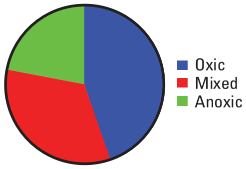
Aquifer group code and identifier	Major aquifer group (bold) and principal and other aquifers	Geologic framework	Hydrologic system	Percentage of wells in dry or humid climate region	Percentage of wells inferred to be of oxic, mixed, or anoxic redox state
USG	**Unconsolidated sand and gravel aquifers**				
1 2 3 4 5 6 7 8 9 10 11 A	Basin and Range basin-fill aquifers California Coastal Basin aquifers Central Valley aquifer system Columbia Plateau basin-fill aquifers High Plains aquifer Mississippi River Valley alluvial aquifer Northern Rocky Mountains Intermontane Basins aquifer system Rio Grande aquifer system Snake River Plain basin-fill aquifers Surficial aquifer system Willamette Lowland basin-fill aquifers Stream valley aquifers (not a principal aquifer)	The unconsolidated sand and gravel aquifers can be grouped into the following categories: basin-fill (valley-fill) aquifers and sand and gravel aquifers. Also, stream-valley aquifers are located beneath channels, flood plains, and terraces in the valleys of major streams. Unconsolidated sand and gravel aquifers are characterized by intergranular porosity, and all contain water primarily under unconfined or water-table conditions and can occupy different hydrogeologic settings.	These aquifers mostly contain water under unconfined or water-table conditions but confined conditions exist locally where the aquifers contain beds of low-permeability silt, clay, or marl. The High Plains aquifer is the most intensively pumped aquifer in the United States. During the 1990s, the pumping rate was about 15 billion gallons per day.		
GLA	**Glacial unconsolidated sand and gravel aquifers**				
12 13	Glacial aquifer system Unconsolidated-deposit aquifers (Alaska)	Large areas of the central and northeastern United States as well as Alaska are covered with sediments that were deposited during several cycles of continental glaciation. The GLA aquifers are unconsolidated sand and gravel characterized by intergranular porosity, contain water primarily under unconfined, or water-table conditions, and can occupy different hydrogeologic settings. Includes some alluvial aquifers.	Local movement of water in the glacial aquifers generally is from the valley walls toward streams; regional movement of water is down the valley. Yields of wells completed in the glacial-deposit aquifers are as much as 3,000 gallons per minute where the aquifers consist of thick sand and gravel.		
SCS	**Semiconsolidated sand aquifers**				
14 15 16 17 18	Coastal lowlands aquifer system Mississippi embayment aquifer system Northern Atlantic Coastal Plain aquifer system Southeastern Coastal Plain aquifer system Texas coastal uplands aquifer system	Sediments that primarily consist of semiconsolidated sand, silt, and clay, interbedded with some carbonate rocks, underlie the Coastal Plains that border the Atlantic Ocean and the Gulf of Mexico. Depositional environments include fluvial, deltaic, and shallow marine. The rocks are Cretaceous and Tertiary in age. In general, older rocks crop out farthest inland.	Many local aquifers and confining units are in the area underlain by this aquifer system. Based on similarities in their hydraulic characteristics and water levels, sequences of local aquifers and confining units can be grouped into regional aquifers and confining units.		

Table 1. Generalized description of the major aquifer groups sampled for the NAWQA Program across the United States.—Continued

[Groups were compiled and modified from the U.S. Geological Survey Ground Water Atlas of the United States (Miller, 2000) and Principal Aquifer Map of the United States (U.S. Geological Survey, 2003)]

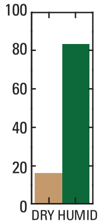
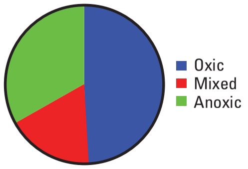
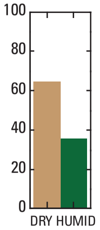
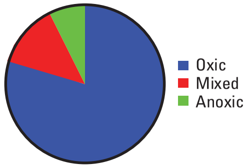
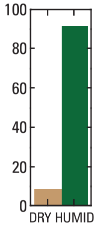
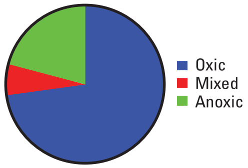
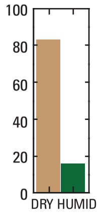
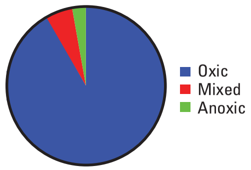
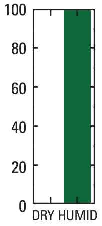
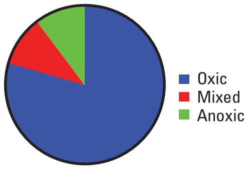
Aquifer group code and identifier	Major aquifer group (bold) and principal and other aquifers	Geologic framework	Hydrologic system	Percentage of wells in dry or humid climate region	Percentage of wells inferred to be of oxic, mixed, or anoxic redox state
SAN	**Sandstone aquifers**				
19	Cambrian-Ordovician aquifer system	Aquifers in sandstone are more widespread than those in all other kinds of consolidated rocks. Sandstone aquifers commonly grade laterally into fine-grained, low-permeability rocks such as shale or siltstone. Many sandstone aquifers are parts of complex interbedded sequences of sedimentary rocks.	Sandstones retain some primary porosity unless cementation has filled the pores; most of the porosity consists of secondary openings such as joints, fractures, and bedding planes. Groundwater movement primarily is along bedding planes, but the joints and fractures cut across bedding and facilitate vertical flow.		
20	Early Mesozoic basin aquifers				
21	Lower Tertiary aquifers				
22	Pennsylvanian aquifers				
23	Valley and Ridge aquifers (sandstone, unofficial name)				
B	Woodbine aquifer (not a principal aquifer)				
SCR	**Sandstone and carbonate-rock aquifers**				
24	Edwards-Trinity aquifer system	Aquifers in sandstone and carbonate rocks are most widespread in the eastern U.S., but also occur in Texas, Oklahoma, Arkansas, Montana, Wyoming, and South Dakota. These aquifers consist of interbedded sandstone and carbonate rocks.	The carbonate rocks are the most productive aquifers, whereas the interbedded sandstones yield less water. The presence or absence of solution openings affects aquifer recharge and discharge and is reflected by the water levels in wells completed in different rock types.		
25	Mississippian aquifers				
CAR	**Carbonate-rock aquifers**				
26	Biscayne aquifer	Aquifers in carbonate rocks are prominent in the central and southeastern parts of the Nation, but are also in southeastern California and northeastern Maine and in Puerto Rico. The rocks that compose these aquifers range in age from Precambrian to Miocene. Most of the carbonate-rock aquifers consist of limestone, but dolomite and marble are local sources of water.	The water-yielding properties of carbonate rocks are highly variable; some yield almost no water and are considered to be confining units, whereas others are among the most productive aquifers. Vertical passages, usually developed at the intersections of joints, connect the horizontal bedding plane openings.		
27	Floridan aquifer system				
28	Ordovician aquifers				
29	Ozark Plateaus aquifer system				
30	Piedmont and Blue Ridge carbonate-rock aquifers				
31	Silurian-Devonian aquifers				
32	Valley and Ridge aquifers (carbonate) (unofficial name)				

Table 1. Generalized description of the major aquifer groups sampled for the NAWQA Program across the United States.—Continued

[Groups were compiled and modified from the U.S. Geological Survey Ground Water Atlas of the United States (Miller, 2000) and Principal Aquifer Map of the United States (U.S. Geological Survey, 2003)]

Aquifer group code and identifier	Major aquifer group (bold) and principal and other aquifers	Geologic framework	Hydrologic system	Percentage of wells in dry or humid climate region	Percentage of wells inferred to be of oxic, mixed, or anoxic redox state
BAV	**Basaltic- and volcanic-rock aquifers**				
33 34 35 36	Columbia Plateau basaltic-rock aquifers Hawaiian volcanic-rock aquifers Snake River Plain basaltic-rock aquifers Early Mesozoic basin aquifers (volcanic)	Volcanic rocks have a wide range of chemical, mineralogic, structural, and hydraulic properties. The variability of these properties is related largely to rock type and the way the rock was ejected and deposited.	The permeability of basaltic rocks depends on the cooling rate of the lava flow, the character of interflow zones, and the thickness of the flow. Fractures and joints develop in the upper and lower parts, but few open spaces develop in the center because it cools slowly.		
CRL	**Crystalline-rock aquifers**				
37 38 C	New York and New England crystalline-rock aquifers (unofficial name) Piedmont and Blue Ridge crystalline-rock aquifers Rocky Mountain Front Range crystalline-rock aquifers (unofficial name)	The igneous and metamorphic rocks are permeable where fractured and generally yield only small amounts of water to wells. In many places they are the only reliable source of water supply. Crystalline rocks are in northern Minnesota and northeastern Wisconsin, northeastern New York, and the New England, Piedmont, and Blue Ridge Physiographic Provinces.	The permeability of igneous and metamorphic rocks depends on secondary porosity, where joints and fractures transmit and store water that can flow to a well. Hydraulic conductivity is low compared to other aquifers but can vary by orders or magnitude. In the fracture-flow system, storage is typically low and groundwater velocities high.		

Chemical Evolution and Groundwater Age

The geochemistry of groundwater evolves over time in large part because of contact with aquifer materials. Groundwater is rarely in chemical equilibrium with the minerals in the aquifer through which it flows; it is constantly changing along its flow path through reactions with minerals in what has been described as chemical evolution (Plummer and Back, 1980; Hem, 1985). In general, the longer the water has been in an aquifer, the greater the concentrations of dissolved solids, and the more chemically evolved the water is considered to be. Chemical evolution also may be affected by factors other than age (which is related to the rate of flow of groundwater through an aquifer). Factors that affect chemical evolution include the geologic and geochemical composition of the aquifer, the geochemical composition of the groundwater, and biogeochemical processes in the aquifer.

Trilinear diagrams, a method for showing ratios of major cations and anions in water samples, are used to indicate water type information about samples from various aquifer groups in this report. Trilinear diagrams have been used successfully to assess water type and infer chemical evolution (Hanshaw and Back, 1979; Back and others, 1988; Drever, 1988; Rogers, 1989; Hem, 1985; Welch and Lico, 1998).

The occurrence of many trace elements in groundwater is related to the length of time that the water has been in contact with the soil and underlying aquifer materials—that is, the time elapsed since recharge. Measurement of the time water is in an aquifer (apparent age of the water) is complicated by the potential mixing of waters of different ages. For wells with short open intervals, like many monitoring wells, the effects of mixing may be minimized. Groundwater samples that were collected by the NAWQA Program for age dating were analyzed for several constituents, including , tritium-helium, and CFCs (Plummer and others, 1993). In this report, only samples that were analyzed for tritium (number of samples (*N)* equal to 1,932) were used to estimate the age of groundwater.

The most basic use of tritium analysis in groundwater is to indicate whether it is present at measurable concentrations in the water sample; if it is, at least some of the water in the sample postdates the advent of nuclear testing in about 1953 (Plummer and others, 1993). Groundwater samples recharged after 1953 are defined as "young" waters, and those recharged before 1953 are defined as "old". Concentrations of tritium in recharge water derived entirely from precipitation prior to nuclear testing are estimated to have been less than about 0.2 to 0.8 tritium units (TU) (0.65 to 2.6 pCi/L) by the early 1990s (Plummer and others, 1993) and about 0.12 to 0.5 TU (about 0.39 to 1.6 pCi/L) by the early 2000s (Rupert and Plummer, 2005). In this report, the presence of tritium above the common reporting limit of 2.5 pCi/L was considered to indicate that at least some young groundwater was present in the sample. Groundwater samples with tritium activities less than or equal to 2.5 pCi/L are interpreted as containing water predominantly recharged before 1953.

Redox and pH

Other factors, such as redox status or pH, may have a controlling effect on trace-element concentrations despite the degree of chemical evolution of the water sample. Methods for inferring redox state from commonly measured chemical constituents, including concentrations of DO, may provide a useful context for evaluating trace-element occurrence on a national and regional scale. Redox is a measure of the oxidation-reduction state of the groundwater, which in natural systems can be measured by the hierarchical progression of terminal electron acceptors for the reduction of compounds in groundwater (Froelich and others, 1979; Chapelle and others, 1995; Chapelle and others, 2002; Paschke, 2007; McMahon and Chapelle, 2008; McMahon and others, 2009). Redox conditions for the water in each well in this analysis were determined from a scheme that evaluates concentrations of DO, nitrate, Mn, Fe, and sulfate, and methane (Paschke, 2007; McMahon and Chapelle, 2008). For this study, redox was generalized into three categories: (1) groundwater that was O_2 or nitrate-reducing was considered generally oxic; (2) groundwater that was Mn(IV) reducing, Fe(III)/sulfate-reducing, or methanogenic was considered generally anoxic; and (3) groundwater without a distinct redox signal, or for which more than one redox process criterion was met, was considered mixed. Water samples used in this study from dry climates have redox conditions that are generally oxic, whereas humid-region samples are more often anoxic (fig. 2A). The generalized redox classification and results for wells in this study are presented in table 2.

Groundwater pH is another important geochemical control that can affect the solubility and mobility of trace metals, often through sorption/desorption processes (Drever, 1988; Welch and Stollenwerk, 2003; Paschke, 2007). For many metals, such as Al, Cu, Fe, Mn, and Zn, solubility in water often decreases with increasing pH. For others, such as As and U, solubility can increase with increasing pH over the normal pH range of most natural waters. Thus, consideration of pH along with redox conditions is important to the overall distribution of trace elements in groundwater. For this analysis, samples are grouped into two categories: less than 7 (low pH) and greater than or equal to 7 (high pH), based on the midpoint of the pH scale and the control of reactions involving trace elements by processes that predominate at pH values either smaller or greater than 7.

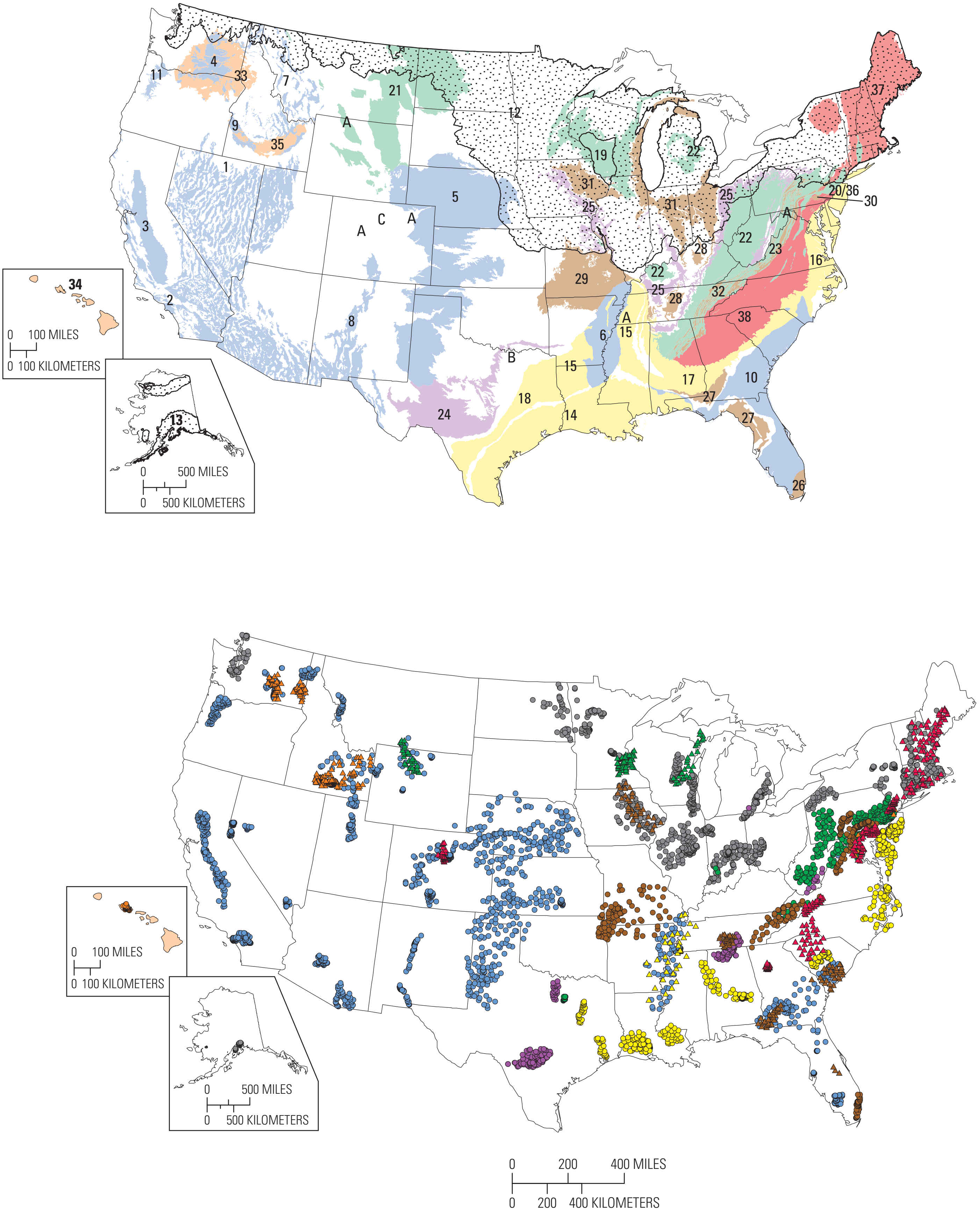


Figure 3. *(A)* Principal aquifers of the United States and major aquifer groups used in the current study, and *(B)* wells sampled by the National Water-Quality Assessment Program, 1992–2003, color coded by aquifer (see explanation). Areal extent of aquifers from U.S. Geological Survey (2003).

EXPLANATION

Aquifers and well locations—Aquifers are shown by major aquifer group (colored areas) and are identified by number. Well location is shown by colored circles (colored triangles if the well is completed in the material beneath the uppermost aquifer).

Unconsolidated sand and gravel aquifers

● 1 Basin and Range basin-fill aquifers
● 2 California Coastal Basin aquifers
● 3 Central Valley aquifer system
● 4 Columbia Plateau basin-fill aquifers
● 5 High Plains aquifer
● 6 Mississippi River Valley alluvial aquifer
● 7 Northern Rocky Mountains Intermontane Basins aquifer system
● 8 Rio Grande aquifer system
● 9 Snake River Plain basin-fill aquifers
● 10 Surficial aquifer system
● 11 Willamette Lowland basin-fill aquifers
● A stream valley aquifers (not a principal aquifer)

Glacial unconsolidated sand and gravel aquifers

● 12 Glacial aquifer system
● 13 Unconsolidated-deposit aquifers (Alaska)

Semiconsolidated sand aquifers

● 14 Coastal lowlands aquifer system
▲ 15 Mississippi embayment aquifer system
● 16 Northern Atlantic Coastal Plain aquifer system
● 17 Southeastern Coastal Plain aquifer system
● 18 Texas coastal uplands aquifer system

Sandstone aquifers

▲ 19 Cambrian-Ordovician aquifer system
● 20 Early Mesozoic basin aquifers
▲ 21 Lower Tertiary aquifers
● 22 Pennsylvanian aquifers
● 23 Valley and Ridge aquifers (sandstone)
● B Woodbine aquifer (not a principal aquifer)

Sandstone and carbonate-rock aquifers

● 24 Edwards-Trinity aquifer system
● 25 Mississippian aquifers

Carbonate-rock aquifers

● 26 Biscayne aquifer
▲ 27 Floridan aquifer system
▲ 28 Ordovician aquifers
● 29 Ozark Plateaus aquifer system
● 30 Piedmont and Blue Ridge carbonate-rock aquifers
▲ 31 Silurian-Devonian aquifers
● 32 Valley and Ridge aquifers (carbonate)

Basaltic- and other volcanic-rock aquifers

▲ 33 Columbia Plateau basaltic-rock aquifers
● 34 Hawaiian volcanic-rock aquifers
▲ 35 Snake River Plain basaltic-rock aquifers
▲ 36 Early Mesozoic basin aquifers (volcanic)

Crystalline-rock aquifers

▲ 37 New York and New England crystalline-rock aquifers (unofficial name)
▲ 38 Piedmont and Blue Ridge crystalline-rock aquifers
▲ C Rocky Mountain Front Range crystalline-rock aquifers (unofficial name)

Figure 3. *(A)* Principal aquifers of the United States and major aquifer groups used in the current study, and *(B)* wells sampled by the National Water-Quality Assessment Program, 1992–2003, color coded by aquifer (see explanation). Areal extent of aquifers from U.S. Geological Survey (2003).—Continued

Table 2. Threshold concentrations for classification of generalized groundwater redox conditions and number of samples collected for the NAWQA Program across the United States by pH category, 1992–2003.

[<, less than; ≥, greater than or equal to; mg/L, milligrams per liter; O_2, oxygen; NO_3^-, nitrate; Mn, manganese; Fe, iron; SO_4^{2-}, sulfate; >, greater than; ≤, less than or equal to; --, not applicable]

Reduction process	Number of samples		Criteria (mg/L)				
	pH < 7	pH ≥ 7	O_2	NO_3^-	Mn, total	Fe, total	SO_4^{2-}
			Oxic				
O_2	949	1,764	> 0.5	> 0.5	≤ 0.05	≤ 0.1	--
NO_3^-	46	264	≤ 0.5	> 0.5	≤ 0.05	≤ 0.1	--
			Mixed				
Mixed	495	420	Multiple criteria met				
			Anoxic				
Mn	32	113	≤ 0.5	≤ 0.5	> 0.05	≤ 0.1	--
Fe/high SO_4^{2-}	250	359	≤ 0.5	≤ 0.5	> 0.05	> 0.1	> 4
Fe/low SO_4^{2-}	63	116	≤ 0.5	≤ 0.5	> 0.05	> 0.1	≤ 4
Total	1,835	3,036					

Data Handling and Statistical Methods

Trace-element data used in this report were retrieved from the USGS NAWQA data warehouse in 2006 (Bell and Williamson, 2006). The NAWQA data warehouse contains water-quality data, field parameters, and ancillary information for all groundwater sites sampled as part of the NAWQA Program. The original data also are available at http://water.usgs.gov/nawqa/data. The trace-element dataset includes 5,183 sites; however, the number of trace elements analyzed differs from site to site.

A large proportion of the trace-element and other water-chemistry data were censored at various LRLs. The censoring level for each trace element and Rn was adjusted to the respective Long Term Method Detection Limit (LT–MDL; a value that is usually one-half the LRL), thus providing a lower reporting level for each element (Childress and others, 1999). For this report, data censored to the LT–MDL were used for distributional data summaries; the censored data are available with this report (at http://water.usgs.gov/nawqa/trace/pubs/sir2011-5059). Because LRLs change over time, multiple reporting levels have been defined for many trace elements. For this report, the data were recensored to the most common reporting level for each trace element to allow comparisons among data from different groups. The common reporting level was 1 µg/L for most trace elements and 80 pCi/L for Rn. Reporting levels for B, Fe, and Sr were 12, 10, and 0.9 µg/L, respectively. Statistical analyses were based on all data values, including censored data. Maps were used to show the geographic distribution for all trace elements.

Summary statistics, which include the minimum, maximum, and common percentiles, were computed for all trace elements by using regression-on-order statistics (ROS)—statistics appropriate for data with a large proportion (up to 80 percent) of censored values (Helsel and Hirsch, 1992; Helsel, 2005). Data summaries that refer to the proportion of samples with concentrations above specified common reporting levels are not affected by the recensoring because the reporting levels are equal to or greater than the LT–MDLs.

Nonparametric statistics, which do not require distributional assumptions about the censored data, were used to describe distributions or compare data among groups. The Wilcoxon and Kruskal-Wallis tests were used to determine whether the distributions of the data from two or more groups were significantly different (Helsel and Hirsch, 1992; SAS Institute, 1999; Helsel, 2005). If multiple-comparison tests indicated significant differences, the Tukey test was used on the ranks of the data to identify which group means were significantly different (Helsel and Hirsch, 1992; SAS Institute, 1999; Helsel, 2005). Although other methods are available for comparing groups, such as substitution and distributional methods (Helsel, 2005), nonparametric methods offer several benefits, including no assumption of normally distributed data; good statistical power; and the use of data below the censoring level without having to create values for them, resulting in an accurate portrayal of the censored information (Helsel and Hirsch, 1992; Helsel, 2005). Spearman correlation coefficients (rho) were computed to measure the strength of the relation between environmental factors (ancillary data) and concentrations of selected trace elements (Helsel and Hirsch, 1992). The significance level (α) for all statistical tests was equal to 0.05. Thus, for *p*-values less than 0.05, the null hypothesis can be rejected in favor of the alternate hypothesis.

Logistic regression was used to help identify processes and factors affecting trace-element concentrations in groundwater for each aquifer group. For logistic regression methods, the dependent variable is a binary response variable, and the regression model predicts the probability of an event outcome, or the probability that a response is observed. In this way, logistic regression models can be used with data that are highly censored without violating assumptions about the distribution of the data (Helsel, 2005). Independent variables were either continuous or binary variables. For logistic regression models, common reporting levels and HHBs for selected trace elements were used as cut points for binary dependent and independent variable development, unless otherwise noted. Models were evaluated by consideration of the Hosmer-Lemeshow goodness of fit (Hosmer and Lemeshow, 2000). Higher *p*-values indicate better fit because the null hypothesis is that the model fits the data. Also model discrimination was evaluated with the *c* statistic, which is an estimate of the area under the receiver operating characteristic curve—values greater than 0.7 are considered acceptable, and values greater than 0.8 are considered excellent (Hosmer and Lemeshow, 2000).

All statistical tests and models were computed by SAS System software (SAS Institute, 1999). Statistical summaries were computed by robust ROS methods (Helsel, 2005) by using a SAS macro for such a method (Practical Stats, 2007).

Quality Control

As part of the quality control (QC) for groundwater samples collected by the NAWQA Program, additional samples were collected and analyzed to determine if the measured concentrations of trace elements were representative of environmental concentrations and were reproducible. Two primary types of QC samples for evaluation of the environmental data included blanks and replicates. Blanks are samples of water free of constituents of interest, are collected prior to collection of an environmental sample, and indicate if trace elements were introduced to the QC sample (and by association, the environmental sample) during collection, handling, or analysis. Replicates are also collected sequentially after the environmental sample and indicate variability in reported results for a given constituent. The analysis of blank samples was performed by using analytical methods with detection limits at or below those for the environmental samples (Apodaca and others, 2006).

Potential sample contamination levels, at the 95-percent confidence level, were determined from the blank data for each trace element (Apodaca and others, 2006). For a given trace element, the percentages of blank concentrations greater than the common reporting levels used in this report were used to evaluate the possible effects of contamination on the dataset. The results of the trace-element-blank analysis indicate that Sb, Be, Mo, and Tl in groundwater were largely unaffected by contamination (fewer than 1 percent of samples had concentrations greater than 1 µg/L) (table 3). Limited numbers of blanks for Li and V in groundwater did not allow for a reliable assessment of the potential contamination associated with these trace elements. Blank samples for Al and Zn had the largest potential for contamination, with 50 percent or more of blanks having concentrations greater than 1 µg/L. In this study, a common reporting level of 12 µg/L was used for B, and 15 percent of the blank samples exceeded this value (table 3).

Potential contamination, at the 95-percent upper confidence level, was identified in blank samples for 17 trace elements (Al, As, Ba, B, Cd, Co, Cr, Cu, Fe, Pb, Mn, Ni, Se, Ag, Sr, U, and Zn) at the common reporting levels used in this report (Apodaca and others, 2006). About 3 percent or fewer of blank samples for As, Cd, Co, Pb, Ni, Se, Ag, and U were contaminated. Four to 10 percent of blanks for Ba, Cr, Fe, Mn, and Sr were possibly contaminated. Al, B, Cu, and Zn were the most affected, with possible contamination detected in 15 to more than 50 percent of blank samples (table 3).

Contamination of samples can also be viewed in terms of its effect on evaluation of samples exceeding HHBs or nonhealth guidelines. The contamination levels for most of the trace elements reported here are at concentrations that are less than 10 percent of HHBs or nonhealth-guideline concentrations; therefore, potential contamination of samples would not affect the comparison of concentrations of trace elements in groundwater with benchmarks or guidelines (Apodaca and others, 2006). The exceptions are possibly Al, Cd, and Pb. Potential contamination identified for these trace elements is greater than 10 percent of the HHBs or nonhealth guidelines, but affects only 5 percent or fewer of the Cd and Pb samples. For most trace elements, the level of potential contamination is not large enough to affect the measured concentration of the environmental sample significantly.

Replicate groundwater-sample concentration differences for all trace elements were less than 15 percent except for Tl (18.3 percent) and V (15.2 percent). This indicates that sampling, handling, and analysis of samples had a relatively small effect on the reported value and that reproducibility of sample concentrations was generally good (Apodaca and others, 2006).

The analysis of the QC data indicated that the potential contamination from sample processing and analysis for most trace elements of interest was small and did not significantly affect data interpretation for most elements. For this reason, all concentration data were used unaltered.

Table 3. Summary of blank data for trace elements in groundwater sampled for the NAWQA Program, 1992–2003, across the United States.

[µg/L, micrograms per liter; pCi/L, picocuries per liter for radon; UCL, upper confidence level; >, greater than; <, less than; --, no data]

Element	Number of blank samples	Common reporting level used in this report (µg/L or pCi/L)	Percentage of blank samples with 95-percent UCL contamination concentrations (modified from Apodaca and others, 2006, table 1) equal to or exceeding common reporting levels used in this report
Aluminum	330	1	> 50
Antimony	347	1	< 1
Arsenic	329	1	1
Barium	344	1	7
Beryllium	346	1	< 1
Boron	164	12	15
Cadmium	353	1	2
Chromium	343	1	6
Cobalt	343	1	2
Copper	345	1	15
Iron	423	10	10
Lead	343	1	1
Lithium	37	1	< 8
Manganese	546	1	10
Molybdenum	341	1	< 1
Nickel	339	1	3
Radon	0	80	--
Selenium	302	1	2
Silver	343	1	1
Strontium	186	0.9	8
Thallium	151	1	< 1
Uranium	368	1	1
Vanadium	37	1	< 8
Zinc	341	1	50

Occurrence of Trace Elements in Groundwater

The occurrence of trace elements in groundwater from wells across the United States was highly variable. Concentrations of Ba, B, Li, Rn, and Sr were above their reporting levels in nearly all samples; however, as noted in the section on quality control, measured concentrations of some elements, such as Al, B, Cu, Fe, and Zn, may be excessive on the basis of data from blank samples, which suggest systematic low-level bias in the dataset. Concentrations of Al, Ba, B, Cr, Li, Mn, Ni, Rn, Sr, V, and Zn exceeded the common reporting level in more than 50 percent of samples (median) compared to Sb, As, Be, Cd, Co, Cu, Fe, Pb, Mo, Se, Ag, Tl, and U, which were equal to or above their common reporting level in fewer than 50 percent of samples (table 4). As, B, Mn, Mo, Rn, Sr, and U occurred at concentrations greater than HHBs in more than 1 percent of water samples, and Fe and Mn occurred at concentrations greater than nonhealth guidelines in 19 and 31 percent of water samples, respectively (table 4).

Most trace elements (particularly common oxyanion or ion-complex forming elements) occurred in greater concentrations in dry regions than in humid regions (table 5). This was true for As, Ba, B, Cr, Cu, Li, Mo, Ni, Se, Sr, U, V, and Zn (tables 5 and 6; figs. 4 and 5). In contrast, concentrations of elements that are mobile in anoxic and (or) low-pH groundwater conditions (such as Al, Co, Fe, Mn, and Pb) are commonly greater in the humid regions than in the dry regions (tables 5 and 6; figs. 4 and 5). These large-scale differences may reflect several processes, including differences in precipitation, the effects of irrigation, ion competition, complexation, redox, and evaporative concentration in the dry parts of the United States. Processes associated with dry climates, especially in conjunction with irrigation, can lead to characteristically high concentrations of total dissolved solids (TDS) in groundwater (Hem, 1985; Seiler and others, 2003; Anning and others, 2007).

Trace-Element Occurrence and Concentrations in Monitoring and Drinking-Water Wells

Well-specific factors, such as depth and type in addition to specific land uses, can influence concentrations of trace elements in groundwater. The concentrations of trace elements were compared among monitoring wells in areas representing primarily agricultural or urban land uses and drinking-water wells, by climate region (table 7).

In humid regions, 14 trace elements had greater concentrations in monitoring wells than in drinking-water wells; however, only Cu, Pb, Rn, and Zn concentrations were greater in drinking-water wells than in monitoring wells in humid regions (table 7). Concentrations of trace elements commonly associated with low-pH recharge and (or) oxic groundwater are expected to be greater in monitoring wells (shallow wells) in humid regions than in drinking-water wells (generally deep wells). Accordingly, concentrations of Al, Sb, Ba, B, Cr, Co, Fe, Li, Mn, Mo, Ni, Se, Sr, and U were all greater in monitoring wells than in drinking-water wells in humid regions of the United States (table 7). The greater concentrations of Cu, Pb, and Zn in drinking-water wells in humid regions (and Pb and Zn in dry regions) may be an indication that these water samples were commonly collected through existing pumps and plumbing, which can contain these metals in parts, fittings, and valves (Fahlquist and Ardis, 2004; Groschen and others, 2008). Concentrations of Fe and Mn, which occur more often in humid regions than in dry, were greater in monitoring wells than in drinking-water wells in dry climate and humid regions (table 7).

In the dry regions of the United States, concentrations of As, Ba, Pb, Li, Sr, V, and Zn were greater in drinking-water wells than in monitoring wells. Some of these elements commonly form oxyanions (As, Cr, and V) under typical groundwater conditions and are soluble in oxic or anoxic alkaline environments (Smedley and Kinniburgh, 2002). For As, this may be related to the fact that pH values are greater in drinking-water wells in this region than in monitoring wells (table 7).

Table 4. Summary statistics with human-health-benchmark and nonhealth-guideline exceedences for trace elements in groundwater sampled for the NAWQA Program, 1992–2003, across the United States.

[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 from USEPA toxicity data and methods (Toccalino and Norman, 2006); Action levels (ALs) are concentrations which, if exceeded, trigger treatment or other requirements in USEPA regulations for public water supplies; --, not applicable; <, value is less than value shown. All benchmarks and guidelines are in micrograms per liter except radon, for which the proposed benchmark is in picocuries per liter; reporting level is 1 microgram per liter except for boron (12 micrograms per liter), iron (10 micrograms per liter), radon (80 picocuries per liter), and strontium (0.9 micrograms per liter). Percentiles below multiple censoring levels were estimated by regression-on-order statistics; percentiles not estimated if percentage of censored values was greater than 80; if percentiles were not estimated, actual values are shown for percentiles greater than or equal to the assessment level. USEPA Secondary Maximum Contaminant Level (SMCL) is a nonenforceable federal guideline to address cosmetic or aesthetic considerations of drinking water]

Element	Number of samples	Percentage of samples with censored values	Concentration percentile, in µg/L (pCi/L for radon)						Human-health benchmark			Nonhealth guideline	
			10th	25th	Median	75th	90th	Maximum	Benchmark value	Type	Percentage exceeding benchmark	Guideline value (SMCL)	Percentage exceeding SMCL
Aluminum	2,826	26.1	0.43	0.98	3.0	4.9	11	1,100	--	--	--	50 or 200	3.2, 1.1
Antimony	3,009	89.2	< 1	< 1	< 1	< 1	< 1	6.3	6	MCL	0.030	--	--
Arsenic	3,396	49.4	0.079	0.23	0.79	3.0	7.4	550	10	MCL	7.0	--	--
Barium	3,122	1.3	9.0	24	54	120	220	5,100	2,000	MCL	0.10	--	--
Beryllium	3,025	97.0	< 1	< 1	< 1	< 1	< 1	18	4	MCL	0.13	--	--
Boron	1,174	10.1	8.5	17	35	82	220	3,400	1,000	HBSL	1.9	--	--
Cadmium	3,124	92.3	< 1	< 1	< 1	< 1	< 1	16	5	MCL	0.26	--	--
Chromium	3,123	37.9	0.41	0.68	1.2	3.0	5.2	150	100	MCL	0.030	--	--
Cobalt	3,026	72.3	0.026	0.063	0.17	0.48	1.1	680	--	--	--	--	--
Copper	3,144	36.7	0.20	0.47	1.0	3.0	8.5	2,000	1,300	AL	0.030	1,000	0.030
Iron	5,131	40.6	0.095	0.81	7.9	93	1,500	81,000	--	--	--	300	19
Lead	3,120	78.9	0.005	0.018	0.070	0.27	1.0	480	15	AL	0.16	--	--
Lithium	936	6.0	0.60	2.0	6.0	18	54	1,200	--	--	--	--	--
Manganese	4,976	30.5	0.14	0.85	7.0	84	360	28,000	300	HBSL	12	50	31
Molybdenum	3,063	42.4	0.13	0.32	1.0	3.3	8.0	4,700	40	HBSL	1.5	--	--
Nickel	3,076	36.7	0.15	0.35	1.1	2.5	4.9	670	100	HBSL	0.23	--	--
Radon	3,877	1.4	140	240	430	790	1,500	220,000	300 or 4,000	MCL[1]/AMCL[2]	65, 2.7	--	--
Selenium	3,166	72.3	0.041	0.12	0.34	1.0	3.0	94	50	MCL	0.19	--	--
Silver	2,988	99.4	< 1	< 1	< 1	< 1	< 1	8.0	100	HBSL	0	100	0
Strontium	1,309	0.2	46	100	270	680	1,700	44,000	4,000	HBSL	4.3	--	--
Thallium	867	89.7	< 1	< 1	< 1	< 1	< 1	< 1	2	MCL	0	--	--
Uranium	3,541	48.8	0.018	0.087	0.52	3.6	12	550	30	MCL	4	--	--
Vanadium	833	30.9	0.11	0.295	1.4	11	27	190	--	--	--	--	--
Zinc	3,006	16.3	0.43	1.6	4.8	18	69	3,300	2,000	HBSL	0.03	5,000	0

[1] USEPA proposed maximum contaminant level (MCL) for radon in water.

[2] USEPA proposed alternative maximum contaminant level (AMCL) for radon in water: a proposed higher allowable MCL if accompanied by a multimedia mitigation program to address radon risk in indoor air.

Table 5. Summary statistics with human-health-benchmark and nonhealth-guideline exceedences for trace elements in groundwater sampled for the NAWQA Program by climate region, 1992–2003, across the United States.

[Regions shown in figure 2A. 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); Action levels (ALs) are concentrations which, if exceeded, trigger treatment or other requirements in USEPA regulations for public water supplies; --, not applicable; <, value is less than value shown. All benchmarks and guidelines are in micrograms per liter except radon, for which the proposed benchmark is in picocuries per liter; reporting level is 1 microgram per liter except for boron (12 micrograms per liter), iron (10 micrograms per liter), radon (80 picocuries per liter), and strontium (0.9 micrograms per liter). Percentiles below multiple censoring levels were estimated by regression on order statistics (ROS); percentiles not estimated if percentage of censored values is greater than 80; if percentiles are not estimated, actual values are shown for percentiles greater than or equal to the assessment level. USEPA Secondary Maximum Contaminant Level (SMCL) is a non-enforceable federal guideline to address cosmetic or aesthetic considerations of drinking water]

Element	Number of samples	Percentage of samples with censored values	Concentration percentile, in µg/L or pCi/L						Human-health benchmark			Nonhealth guideline	
			10th	25th	Median	75th	90th	Maximum	Benchmark	Type	Percentage exceeding benchmark	Guideline value (SMCL)	Percentage exceeding SMCL
							Dry regions						
Aluminum	998	34.0	0.50	0.91	2.0	3.9	5.0	270	--	--	--	50 or 200	0.8, 0.2
Antimony	1,115	83.8	< 1	< 1	< 1	< 1	< 1	6.3	6	MCL	0.1	--	--
Arsenic	1,252	29.8	0.27	0.69	2.0	5.5	11	550	10	MCL	11	--	--
Barium	1,178	0.1	21	36	66	120	200	990	2,000	MCL	0	--	--
Beryllium	1,121	99.0	< 1	< 1	< 1	< 1	< 1	18	4	MCL	0.2	--	--
Boron	363	2.2	22	37	65	150	300	2,600	1,000	HBSL	0.83	--	--
Cadmium	1,188	89.2	< 1	< 1	< 1	< 1	< 1	16	5	MCL	0.3	--	--
Chromium	1,198	33.1	0.42	0.70	1.3	3.1	5.4	150	100	MCL	0.080	--	--
Cobalt	1,125	68.5	0.034	0.071	0.16	0.42	1.0	680	--	--	--	--	--
Copper	1,204	27.3	0.30	0.59	1.3	3.0	6.0	480	1,300	AL	0	1,000	0
Iron	1,706	52.4	0.034	0.28	4.0	17	360	38,000	--	--	--	300	11
Lead	1,193	79.0	0.003	0.010	0.043	0.15	0.61	12	15	AL	0	--	--
Lithium	354	0.0	7.6	12	20	53	120	580	--	--	--	--	--
Manganese	1,660	44.4	0.020	0.15	1.4	46	350	5,400	300	HBSL	11	50	24
Molybdenum	1,159	20.9	0.41	0.95	2.5	5.9	11	4,700	40	HBSL	1.9	--	--
Nickel	1,168	30.3	0.20	0.46	1.3	3.0	5.0	670	100	HBSL	0.3	--	--
Radon	1,440	1.46	170	270	430	720	1,100	5,600	300 or 4,000	MCL[1]/AMCL[2]	69, 0.4	--	--
Selenium	1,231	51.3	0.11	0.27	0.84	2.6	6.8	94	50	MCL	0.4	--	--
Silver	1,109	98.7	< 1	< 1	< 1	< 1	< 1	8.0	100	HBSL	0	100	0
Strontium	524	0.2	100	250	540	1,200	3,600	44,000	4,000	HBSL	9.2	--	--
Thallium	346	83.9	< 1	< 1	< 1	< 1	< 1	< 1	2	MCL	0	--	--
Uranium	1,228	23.3	0.21	0.75	3.2	8.8	22	550	30	MCL	7.5	--	--
Vanadium	348	9.5	0.47	1.8	9.6	21	39	190	--	--	--	--	--
Zinc	1,154	12.5	0.58	2.0	5.4	26	87	1,400	2,000	HBSL	0	5,000	0

[1] USEPA proposed maximum contaminant level (MCL) for radon in water.

[2] USEPA proposed alternative maximum contaminant level (AMCL) for radon in water: a proposed higher allowable MCL if accompanied by a multimedia mitigation program to address radon risk in indoor air.

Table 5. Summary statistics with human-health-benchmark and nonhealth-guideline exceedences for trace elements in groundwater sampled for the NAWQA Program by climate region, 1992–2003, across the United States.—Continued

[Regions shown in figure 2A. 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); Action levels (ALs) are concentrations which, if exceeded, trigger treatment or other requirements in USEPA regulations for public water supplies; --, not applicable; <, value is less than value shown. All benchmarks and guidelines are in micrograms per liter except radon, for which the proposed benchmark is in picocuries per liter; reporting level is 1 microgram per liter except for boron (12 micrograms per liter), iron (10 micrograms per liter), radon (80 picocuries per liter), and strontium (0.9 micrograms per liter). Percentiles below multiple censoring levels were estimated by regression on order statistics (ROS); percentiles not estimated if percentage of censored values is greater than 80; if percentiles are not estimated, actual values are shown for percentiles greater than or equal to the assessment level. USEPA Secondary Maximum Contaminant Level (SMCL) is a non-enforceable federal guideline to address cosmetic or aesthetic considerations of drinking water]

Element	Number of samples	Percentage of samples with censored values	Concentration percentile, in µg/L or pCi/L						Human-health benchmark			Nonhealth guideline	
			10th	25th	Median	75th	90th	Maximum	Benchmark	Type	Percentage exceeding benchmark	Guideline value (SMCL)	Percentage exceeding SMCL
Humid regions													
Aluminum	1,828	21.9	0.49	1.2	3.3	5.8	16	1,100	--	--	--	50 or 200	4.4, 1.6
Antimony	1,894	92.3	< 1	< 1	< 1	< 1	< 1	5.0	6	MCL	0	--	--
Arsenic	2,144	60.8	0.037	0.12	0.41	1.6	5.0	340	10	MCL	4.5	--	--
Barium	1,944	2.0	5.5	18	47	110	240	5,100	2,000	MCL	0.2	--	--
Beryllium	1,904	95.8	< 1	< 1	< 1	< 1	< 1	16	4	MCL	0.1	--	--
Boron	811	13.7	7.3	12	26	52	160	3,400	1,000	HBSL	2.8	--	--
Cadmium	1,936	94.2	< 1	< 1	< 1	< 1	< 1	7	5	MCL	0.2	--	--
Chromium	1,925	41.0	0.41	0.68	1.2	3.0	5.0	17	100	MCL	0	--	--
Cobalt	1,901	74.5	0.021	0.055	0.16	0.50	1.3	210	--	--	--	--	--
Copper	1,940	42.5	0.14	0.40	1.0	3.2	11	2,000	1,300	AL	0.05	1,000	0.05
Iron	3,425	35.2	0.18	1.49	11	220	2,100	81,000	--	--	--	300	23.5
Lead	1,927	78.9	0.011	0.033	0.12	0.40	1.2	480	15	AL	0.3	--	--
Lithium	582	9.6	0.50	1.1	2.8	5.7	11	1,200	--	--	--	--	--
Manganese	3,316	23.5	0.37	1.4	13	98	370	28,000	300	HBSL	11.8	50	33.8
Molybdenum	1,904	56.1	0.056	0.16	0.54	2.0	5.0	1,500	40	HBSL	1.3	--	--
Nickel	1,908	40.6	0.12	0.30	1.0	2.2	4.5	170	100	HBSL	0.2	--	--
Radon	2,437	1.4	130	220	430	860	2,100	220,000	300 or 4,000	MCL[1]/AMCL[2]	63.4, 4.1	--	--
Selenium	1,935	85.6	< 1	< 1	< 1	< 1	1.1	56	50	MCL	0.05	--	--
Silver	1,879	99.8	< 1	< 1	< 1	< 1	< 1	1.0	100	HBSL	0	100	0
Strontium	785	0.1	36	74	160	370	890	16,000	4,000	HBSL	1	--	--
Thallium	521	91.0	< 1	< 1	< 1	< 1	< 1	< 1	2	MCL	0	--	--
Uranium	2,313	62.3	0.006	0.025	0.17	1.2	4.5	440	30	MCL	2.1	--	--
Vanadium	485	46.2	0.038	0.13	0.4	2.0	10	120	--	--	--	--	--
Zinc	1,852	18.7	0.36	1.4	4.1	15	56	3,300	2,000	HBSL	0.05	5,000	0

[1] USEPA proposed maximum contaminant level (MCL) for radon in water.

[2] USEPA proposed alternative maximum contaminant level (AMCL) for radon in water: a proposed higher allowable MCL if accompanied by a multimedia mitigation program to address radon risk in indoor air.

Table 6. Frequency and distribution statistics for the occurrence of trace elements in groundwater sampled for the NAWQA Program by climate region, 1992–2003, across the United States.

[Climate regions shown in figure 2A. Yellow shading indicates higher dry-region concentrations; blue shading indicates higher humid-region concentrations; concentrations of elements in same Tukey group do not differ significantly at alpha = 0.05. No shading indicates concentrations that do not differ significantly between well types. Reporting level is 1 microgram per liter except for boron (12 micrograms per liter), iron (10 micrograms per liter), radon (80 picocuries per liter), and strontium (0.9 micrograms per liter). ≥, greater than or equal to; <, less than; N is the number of wells sampled; number of trace element samples varies with availability of grouping variable data and with censoring level]

Element	Number of samples and percentage ≥ reporting level by climate region						
	Dry region			Humid region			*p*-value
	N	Percentage	Tukey group	N	Percentage	Tukey group	
Aluminum	998	65	B	1,828	78	A	< 0.0001
Antimony	1,115	1.0	A	1,894	1.1	A	0.8571
Arsenic	1,252	67	A	2,144	34	B	< 0.0001
Barium	1,178	100	A	1,944	98	B	< 0.0001
Beryllium	1,121	0.4	A	1,904	0.7	A	0.1936
Boron	363	97	A	811	76	B	< 0.0001
Cadmium	1,188	1.3	A	1,936	0.6	A	0.0600
Chromium	1,198	58	A	1,925	53	B	0.0148
Cobalt	1,125	8.4	B	1,901	13	A	0.0004
Copper	1,204	61	A	1,940	51	B	0.0272
Iron	1,706	32	B	3,425	50	A	< 0.0001
Lead	1,193	9.4	B	1,927	13	A	0.0015
Lithium	354	97	A	539	78	B	< 0.0001
Manganese	1,660	51	B	3,316	75	A	< 0.0001
Molybdenum	1,159	74	A	1,904	39	B	< 0.0001
Nickel	1,168	62	A	1,908	54	B	< 0.0001
Radon	1,440	98	A	2,437	96	A	0.7276
Selenium	1,201	46	A	1,854	9.7	B	< 0.0001
Silver	1,109	0.6	A	1,879	0.2	A	0.0674
Strontium	524	100	A	785	100	B	< 0.0001
Thallium	346	0.0	A	521	0.0	A	1.0000
Uranium	1,228	71	A	2,313	28	B	< 0.0001
Vanadium	348	81	A	485	35	B	< 0.0001
Zinc	1,154	87	A	1,852	81	B	< 0.0001

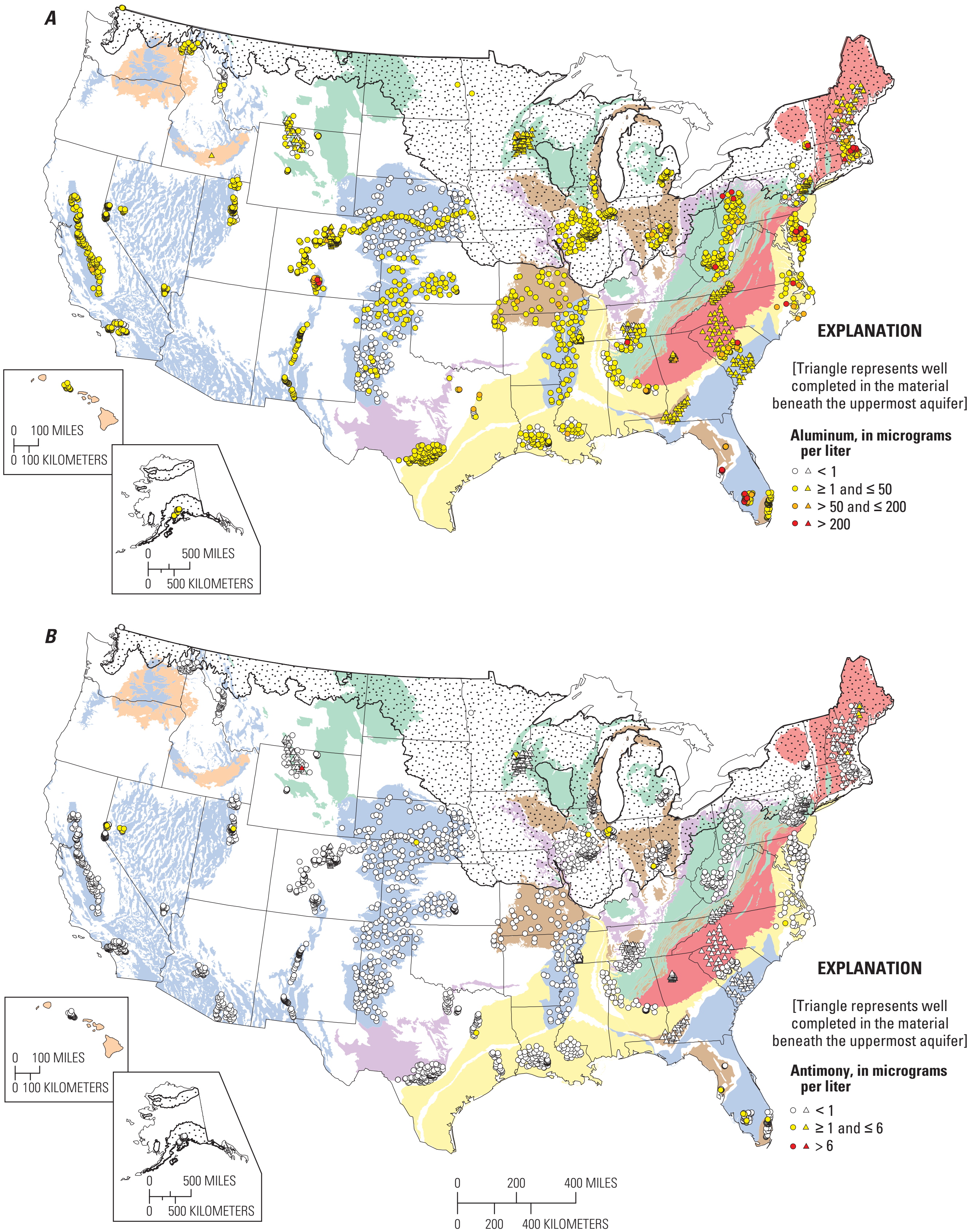
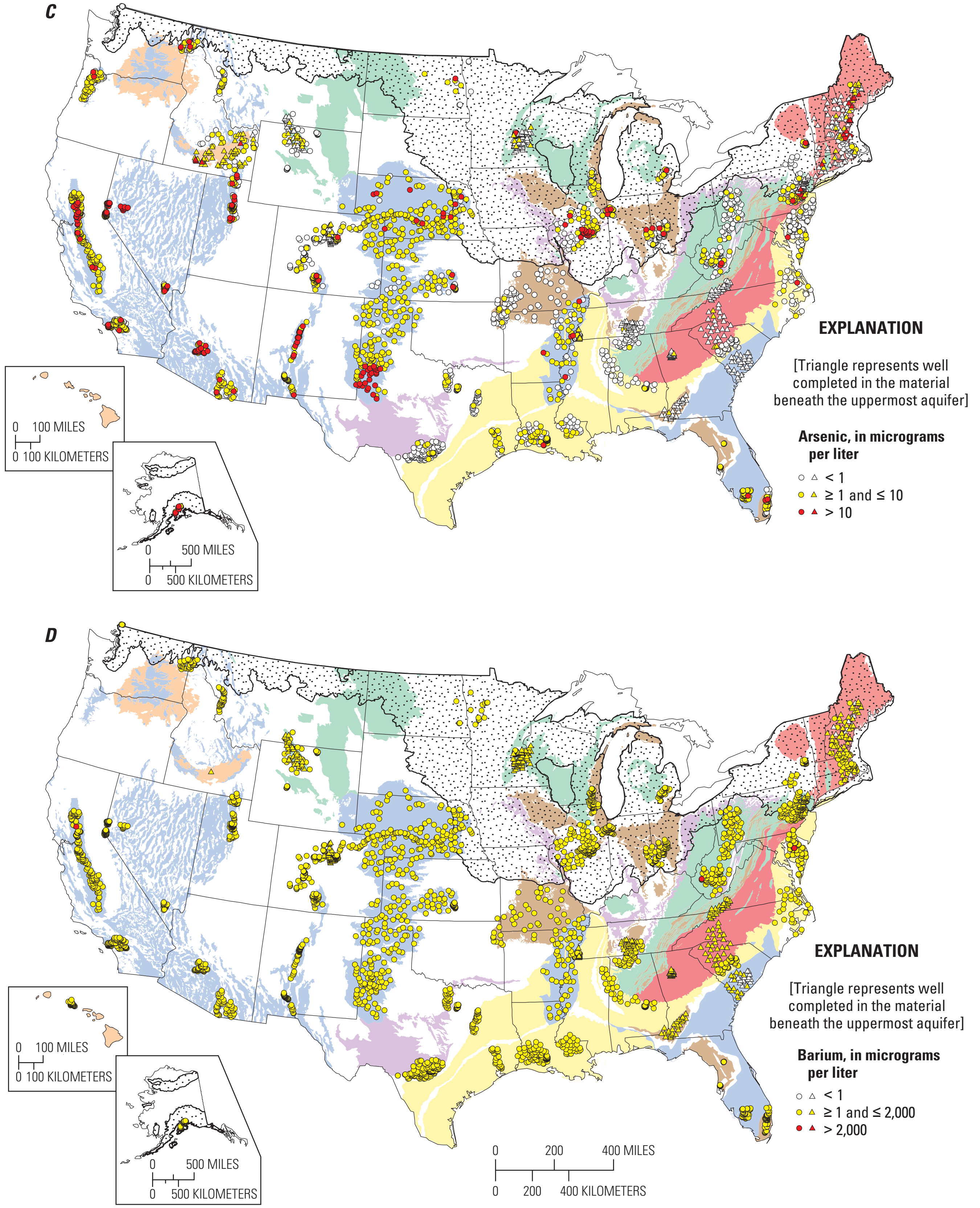


Figure 4. Geographic distribution of trace-element concentrations in groundwater collected from wells as part of the National Water-Quality Assessment Program, 1992–2003: *(A)* aluminum, *(B)* antimony, *(C)* arsenic, *(D)* barium, *(E)* beryllium, *(F)* boron, *(G)* cadmium, *(H)* chromium, *(I)* cobalt, *(J)* copper, *(K)* iron, *(L)* lead, *(M)* lithium, *(N)* manganese, *(O)* molybdenum, *(P)* nickel, *(Q)* radon, *(R)* selenium, *(S)* silver, *(T)* strontium, *(U)* thallium, *(V)* uranium, *(W)* vanadium, and *(X)* zinc.



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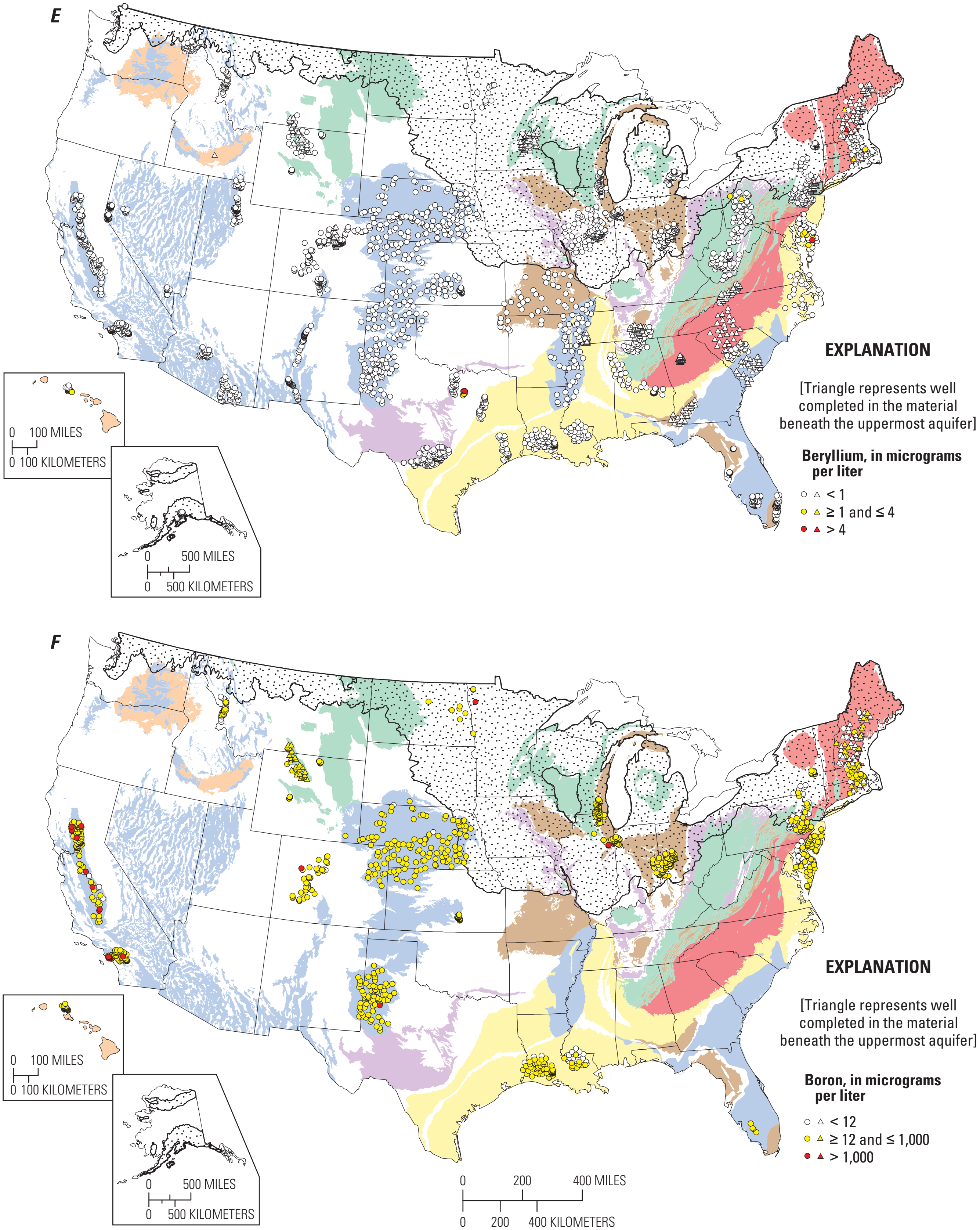

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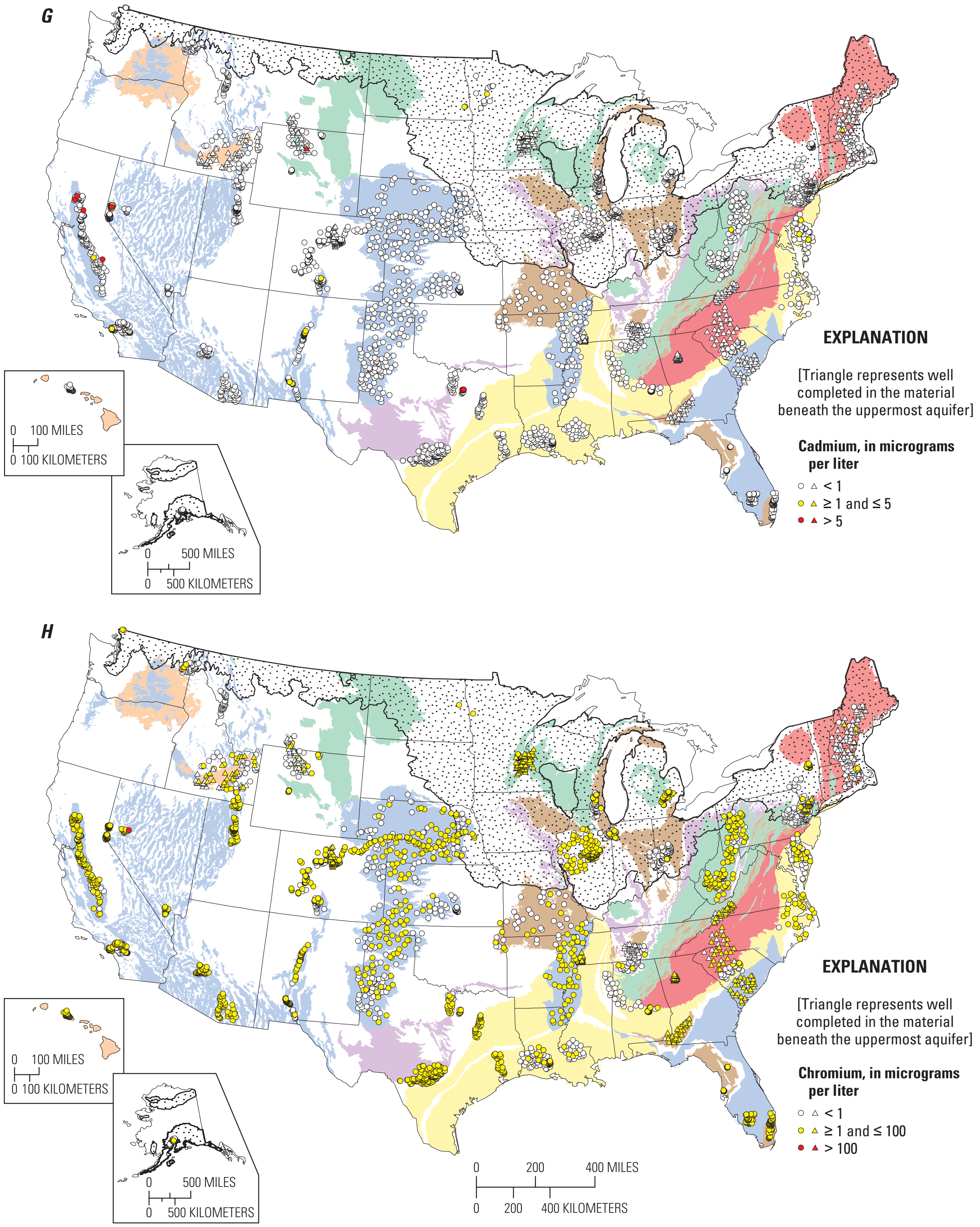

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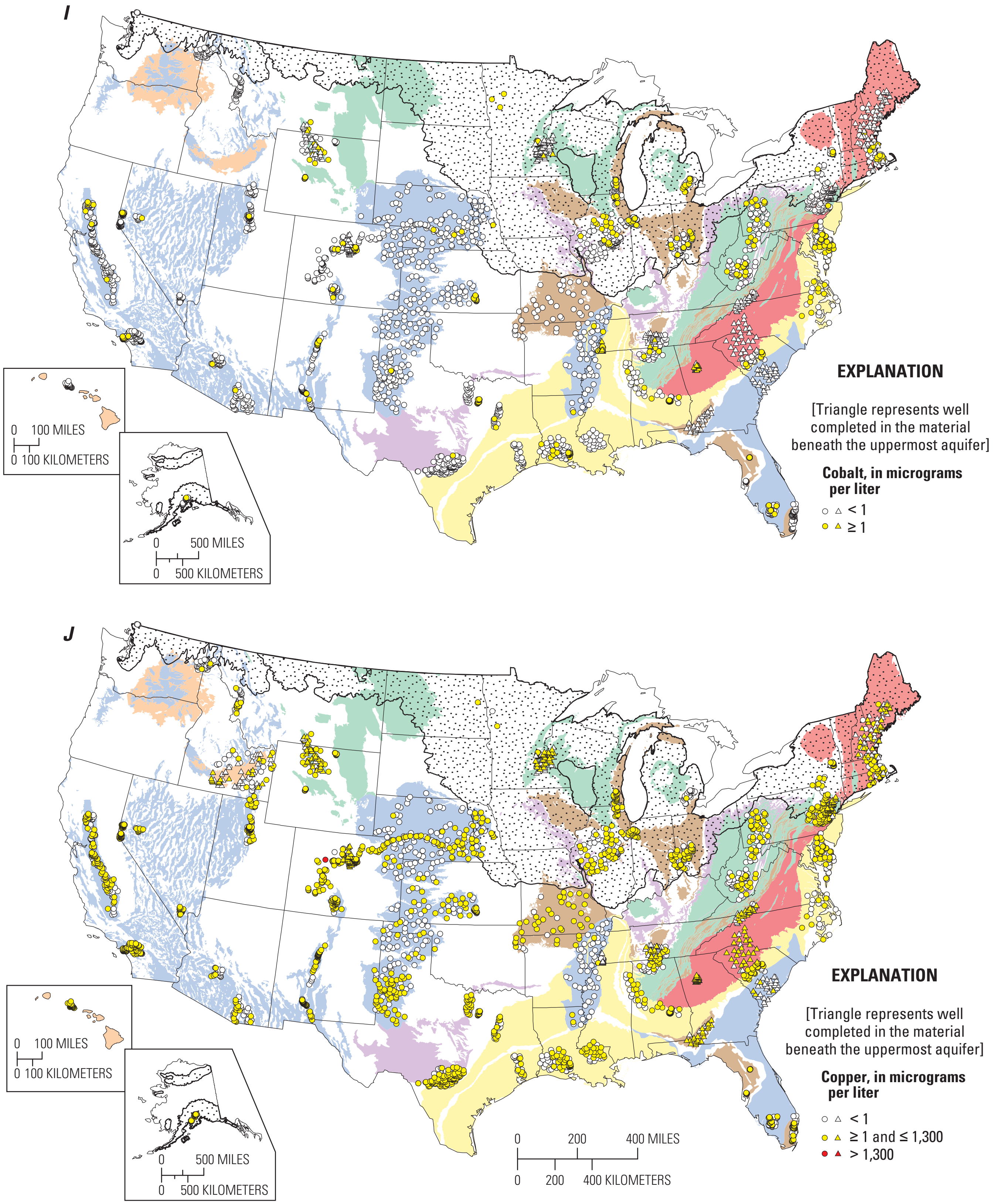

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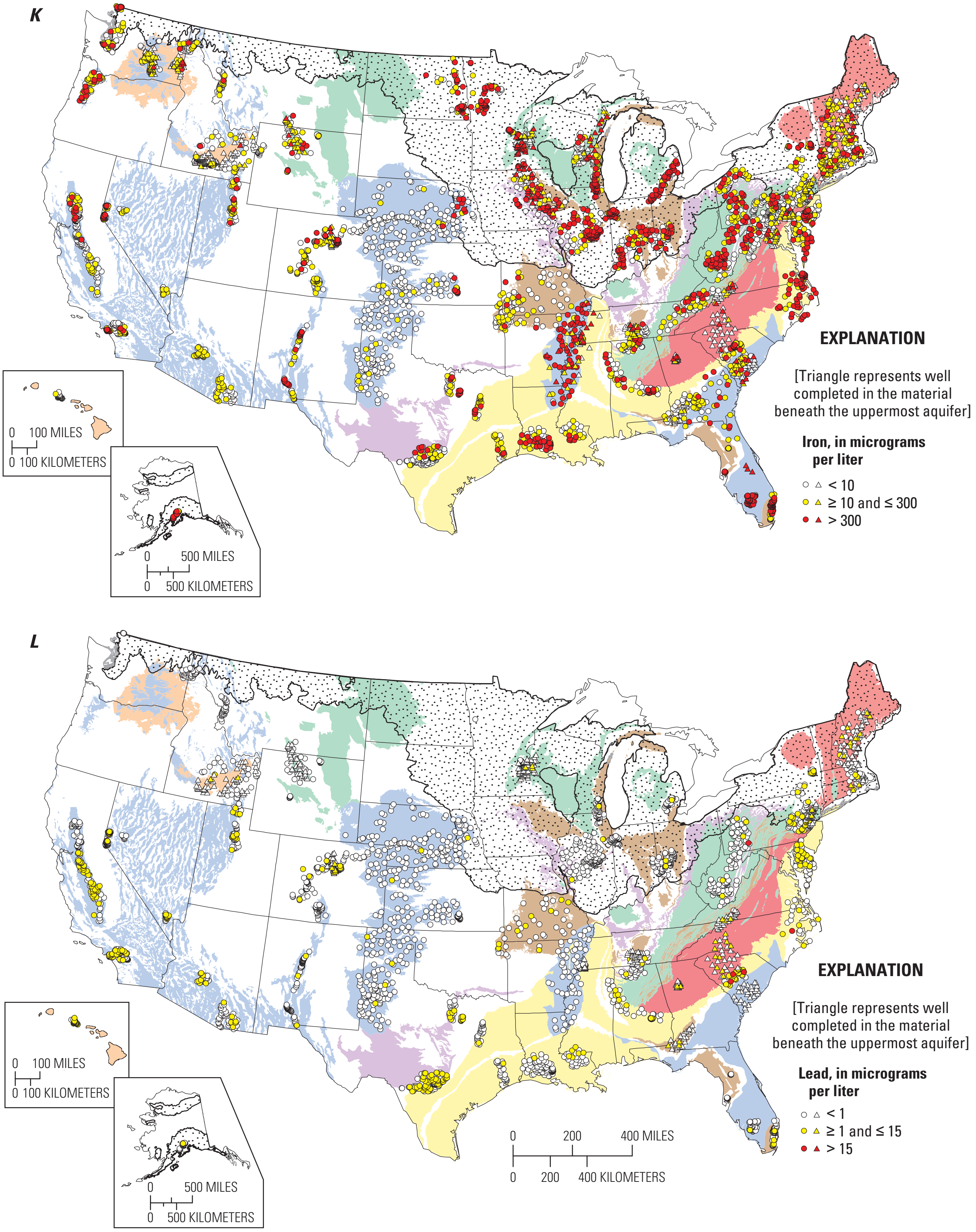

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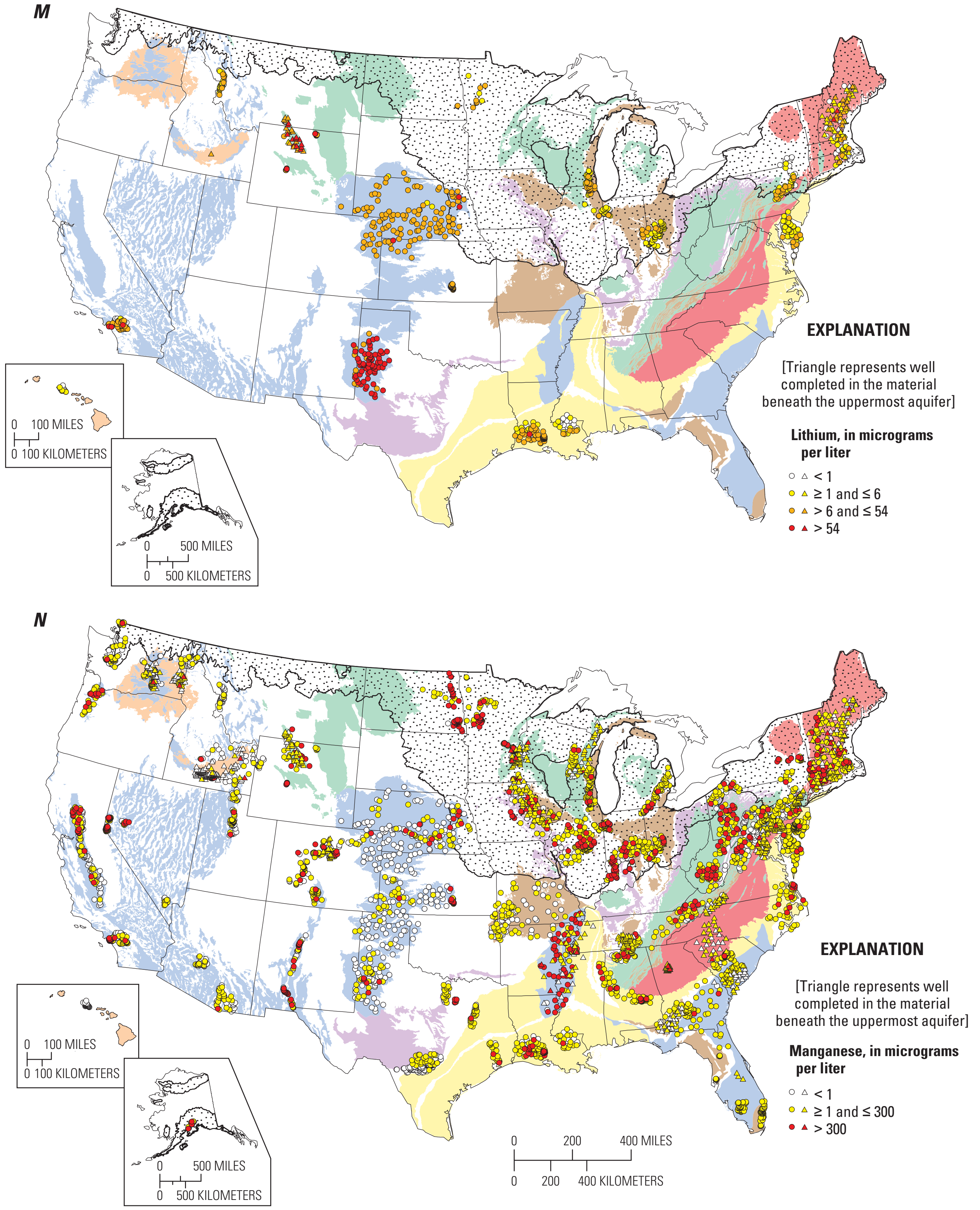

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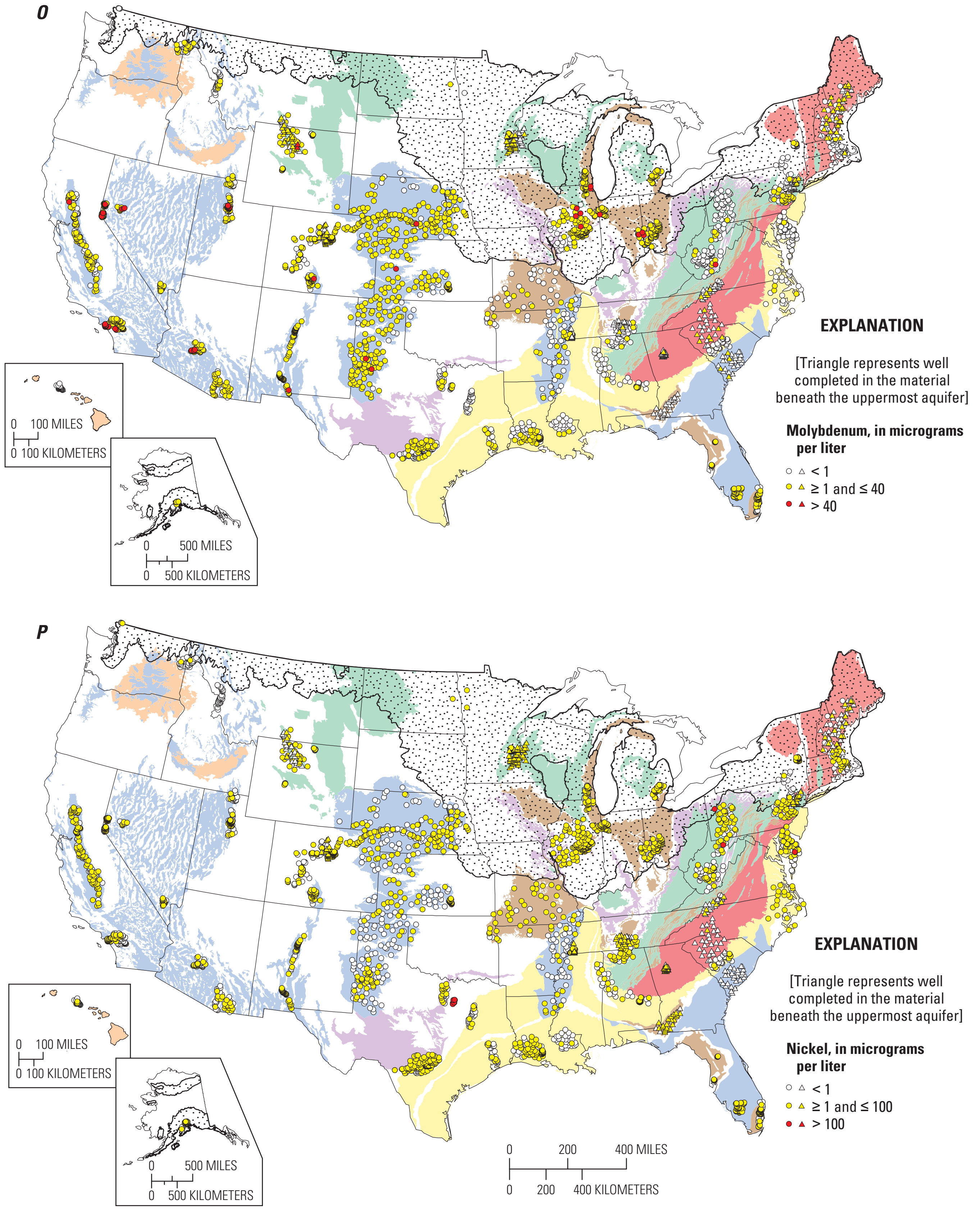
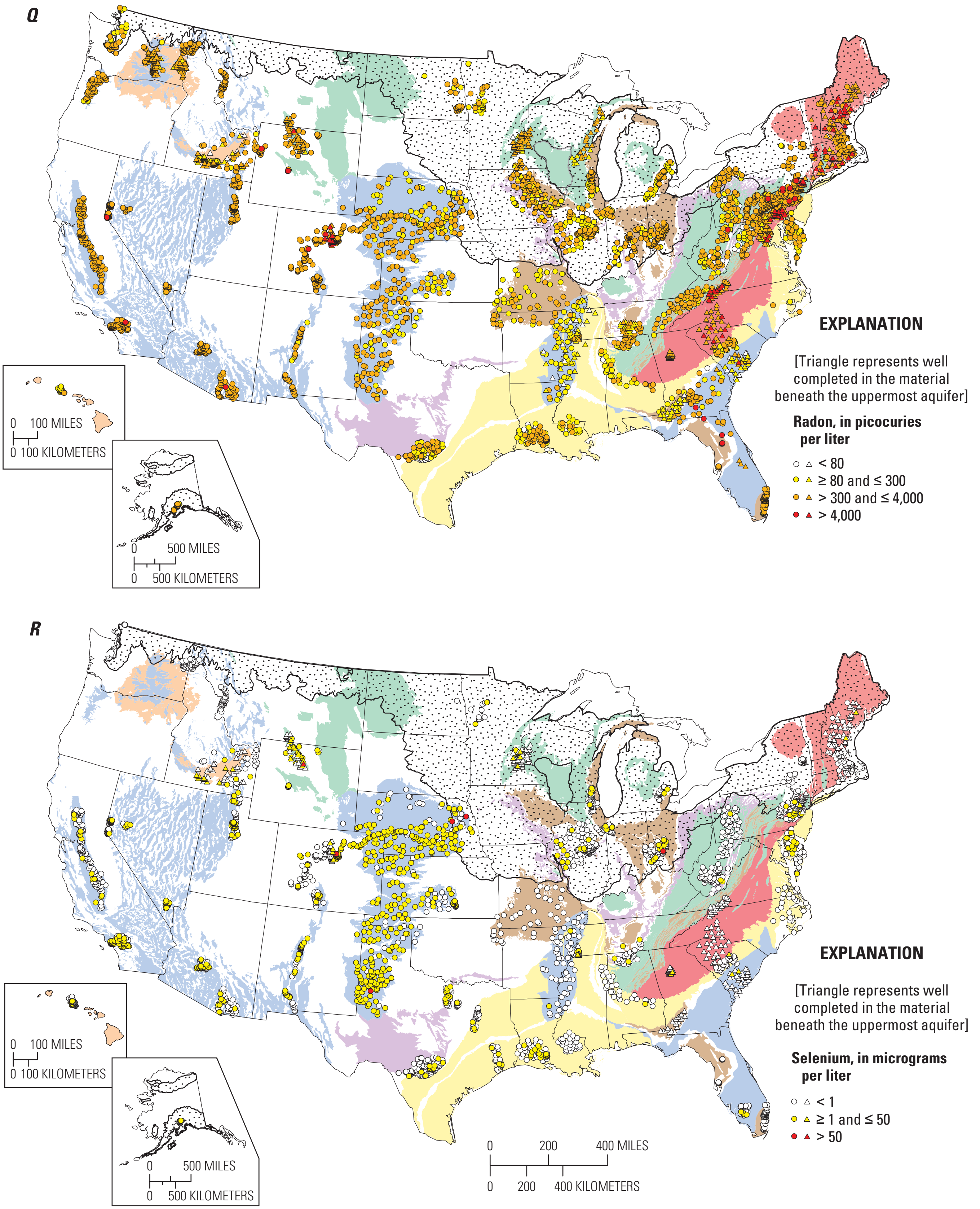


Figure 4. Geographic distribution of trace-element concentrations in groundwater collected from wells as part of the National Water-Quality Assessment Program, 1992–2003: *(A)* aluminum, *(B)* antimony, *(C)* arsenic, *(D)* barium, *(E)* beryllium, *(F)* boron, *(G)* cadmium, *(H)* chromium, *(I)* cobalt, *(J)* copper, *(K)* iron, *(L)* lead, *(M)* lithium, *(N)* manganese, *(O)* molybdenum, *(P)* nickel, *(Q)* radon, *(R)* selenium, *(S)* silver, *(T)* strontium, *(U)* thallium, *(V)* uranium, *(W)* vanadium, and *(X)* zinc.—Continued



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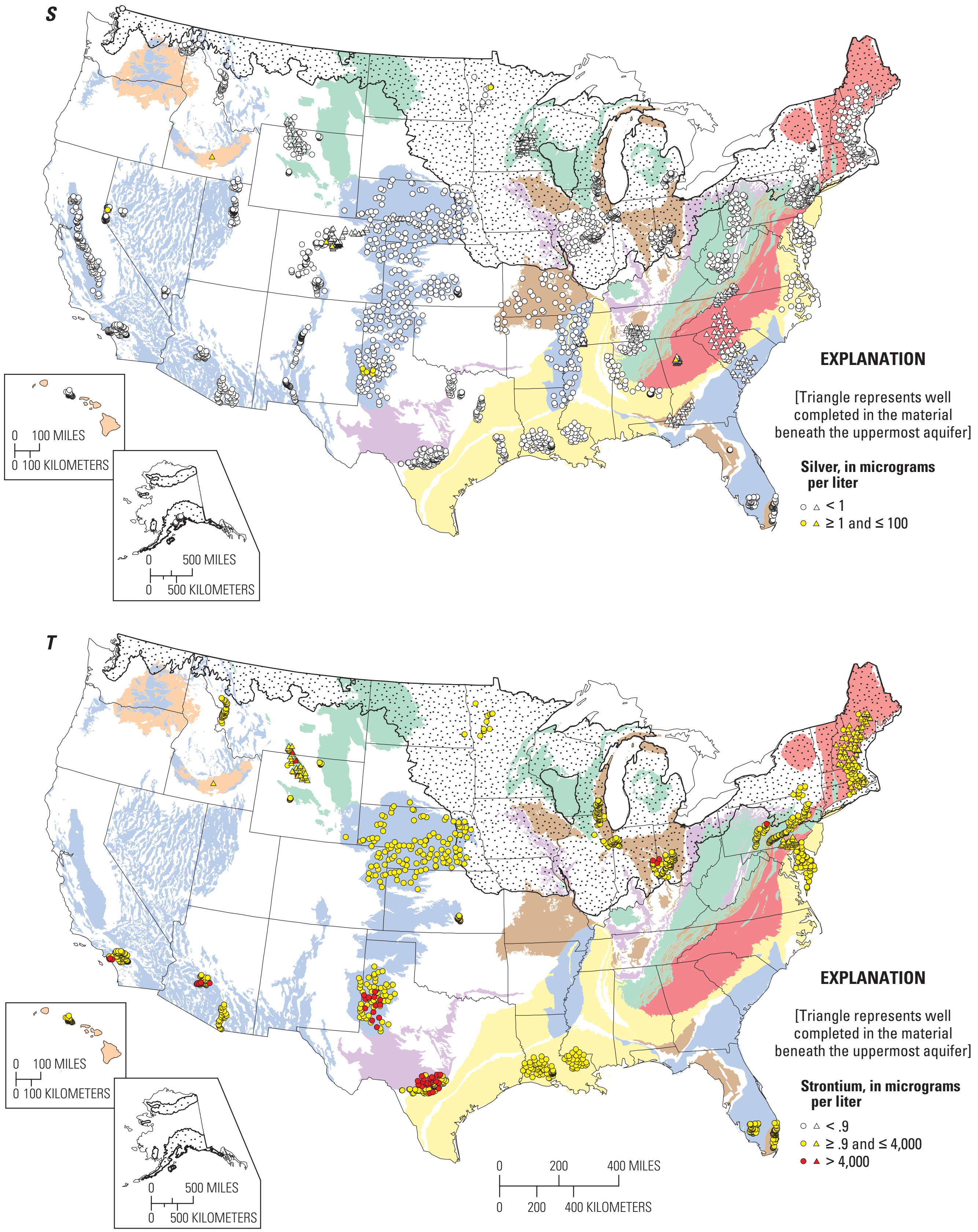

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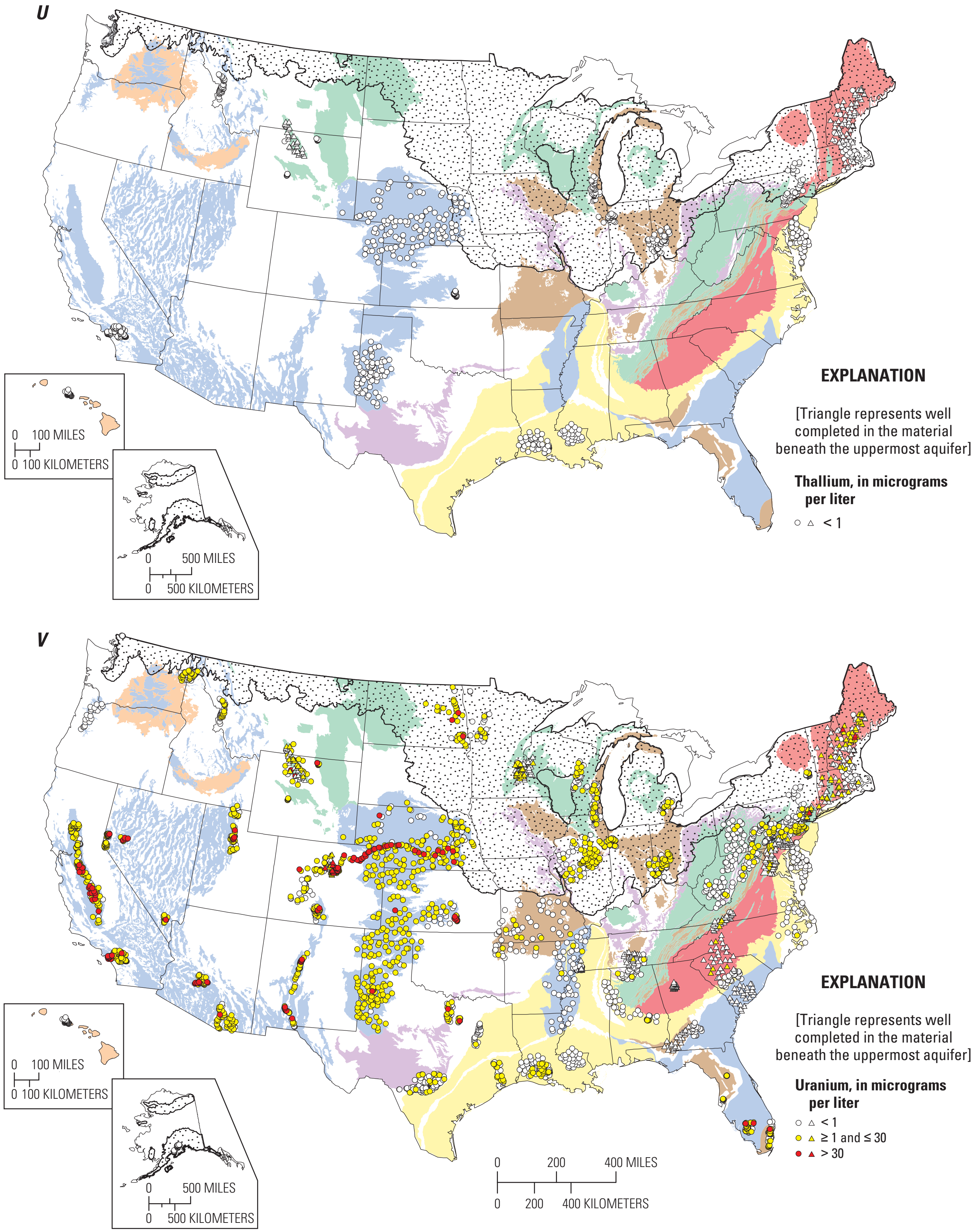

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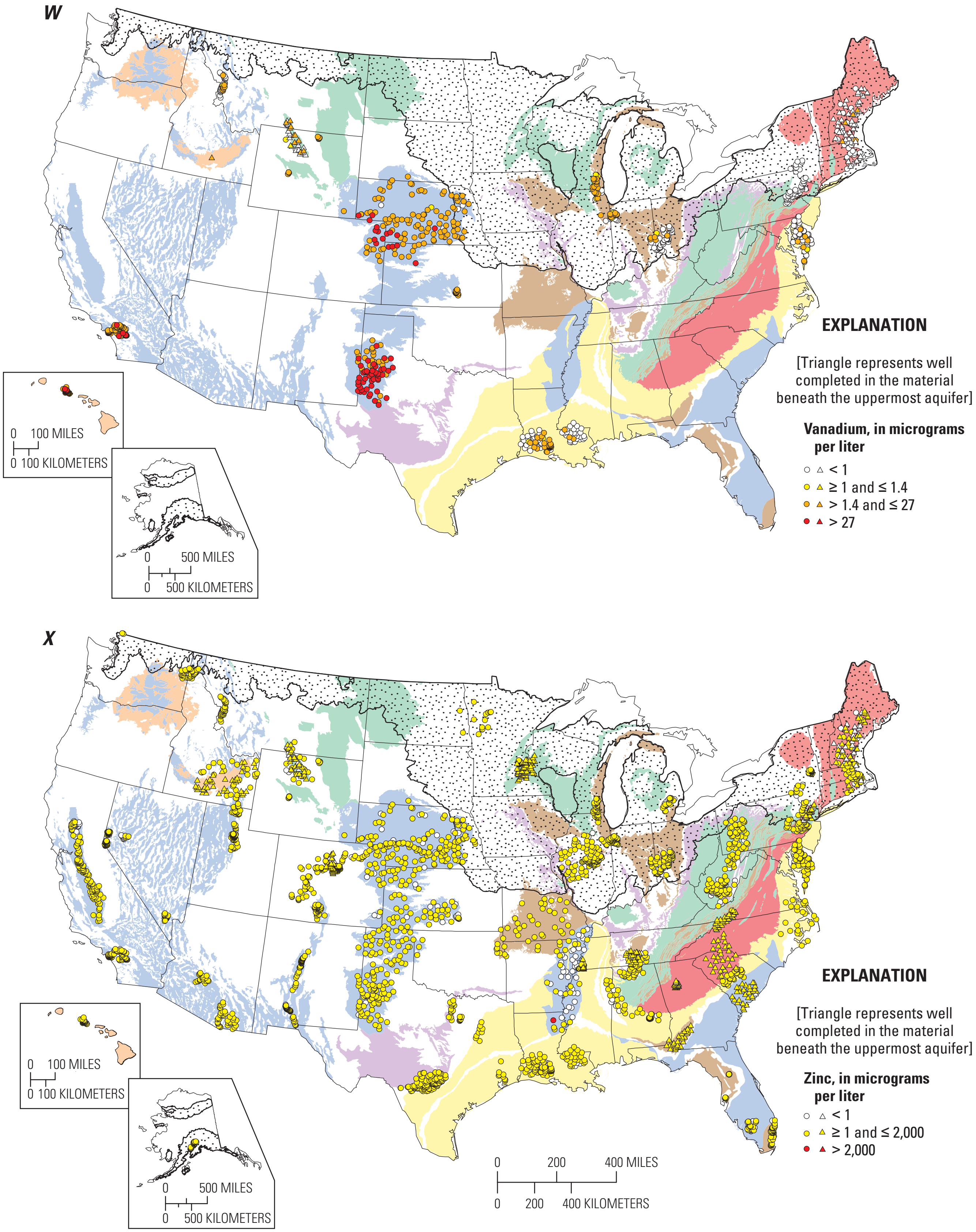

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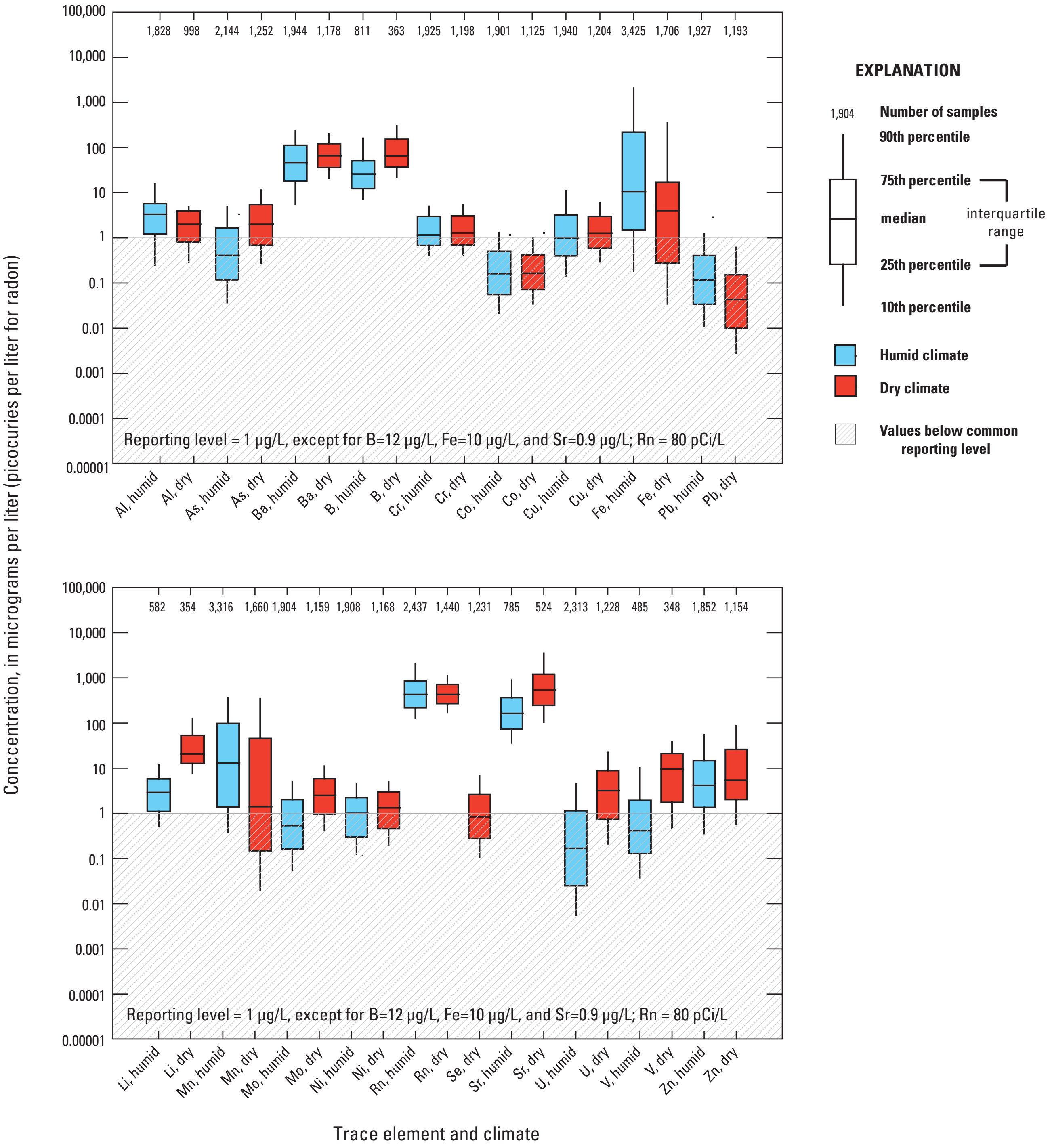


Figure 5. Trace-element concentrations in groundwater across the United States by climate region. [Concentrations below the common reporting level (1 µg/L, unless otherwise noted) were estimated by using regression-on-order statistics (see text for explanation). Elements with more than 80 percent of censored data (table 5) are not shown. µg/L, micrograms per liter; pCi/L, picocuries per liter (for radon)]

Table 7. Group-comparison statistics for concentrations of trace elements and selected field parameters in groundwater samples collected for the NAWQA Program by climate region and well type, 1992–2003, across the United States.

[Climate regions shown in figure 2A. Yellow shading indicates higher monitoring-well concentrations; blue shading indicates higher drinking-water well concentrations; concentrations of elements in the same Tukey group are not different significantly at alpha = 0.05. No shading indicates concentrations that do not differ significantly between well types. Reporting level is 1 microgram per liter except for boron (12 micrograms per liter), iron (10 micrograms per liter), radon (80 picocuries per liter), and strontium (0.9 micrograms per liter); N is the number of wells sampled; number of trace element samples varies with availability of grouping variable data; ≥, greater than or equal to; --, not applicable]

Element	Dry region							Humid region						
	Monitoring wells			Drinking-water wells				Monitoring wells			Drinking-water wells			
	N	Percentage ≥ reporting level	Tukey group	N	Percentage ≥ reporting level	Tukey group	*p*-value	N	Percentage ≥ reporting level	Tukey group	N	Percentage ≥ reporting level	Tukey group	*p*-value
Aluminum	422	70	A	523	58	A	0.2049	579	90	A	1,078	71	B	< 0.0001
Antimony	438	1.4	A	611	0.7	A	0.2427	598	2.3	A	1,122	0.5	B	0.0004
Arsenic	489	61	B	668	70	A	0.0028	616	37	A	1,344	33	A	0.0775
Barium	484	100	B	620	100	A	0.0301	618	100	A	1,151	97	B	0.0004
Beryllium	443	0.9	A	611	0.0	B	0.0189	602	1.0	A	1,128	0.6	A	0.3857
Boron	136	94	A	220	99	A	0.2918	262	87	A	515	70	B	< 0.0001
Cadmium	445	2.5	A	565	0.6	B	0.0093	602	1.2	A	1,158	0.4	A	0.0770
Chromium	464	49	A	645	62	A	0.1746	609	65	A	1,142	46	B	< 0.0001
Cobalt	447	19	A	612	1.3	B	< 0.0001	603	25	A	1,124	4.6	B	< 0.0001
Copper	469	79	A	649	51	B	< 0.0001	610	42	B	1,154	56	A	< 0.0001
Iron	677	39	A	914	28	B	< 0.0001	1,325	55	A	1,834	45	B	< 0.0001
Lead	447	2.9	B	657	13	A	< 0.0001	599	5.5	B	1,152	17	A	< 0.0001
Lithium	133	92	B	214	100	A	0.0039	166	85	A	348	75	B	0.0161
Manganese	629	78	A	916	35	B	< 0.0001	1,293	90	A	1,761	62	B	< 0.0001
Molybdenum	470	76	A	616	74	B	< 0.0001	607	48	A	1,123	36	B	< 0.0001
Nickel	479	83	A	616	46	B	< 0.0001	611	78	A	1,123	42	B	< 0.0001
Radon	491	100	A	847	97	B	< 0.0001	617	97	B	1,638	96	A	< 0.0001
Selenium	451	44	A	661	48	A	0.5767	614	12	A	1,099	8.6	B	0.0067
Silver	438	1.1	A	606	0.2	B	0.0402	584	0.3	A	1,125	0.2	A	0.5046
Strontium	177	100	B	316	99	A	0.0013	275	100	A	476	100	B	< 0.0001
Thallium	128	0.0	A	212	0.0	A	1.0000	170	0.0	A	326	0.0	A	1.0000
Uranium	524	72	A	631	72	B	< 0.0001	682	34	A	1,425	27	B	0.0075
Vanadium	129	71	B	212	88	A	< 0.0001	145	33	A	315	35	A	0.4239
Zinc	443	76	B	632	94	A	< 0.0001	587	68	B	1,089	90	A	< 0.0001
pH	667	--	B	926	--	A	< 0.0001	1,327	--	B	1,831	--	A	< 0.0001
Dissolved oxygen	661	--	B	858	--	A	< 0.0001	1,794	--	A	1,286	--	A	0.5481
Specific conductance	621	--	A	925	--	B	< 0.0001	1,329	--	A	1,828	--	B	< 0.0001

Trace-Element Occurrence and Concentrations in Wells in Agricultural and Urban Areas

Contaminants that are introduced at the land surface can affect water quality in underlying aquifers. Some trace elements have anthropogenic sources that are a direct result of land use. An example of this is the use of B in fertilizer in agricultural settings. Land use may not have a direct effect but can result in changes in groundwater pH, TDS, or redox conditions, which in turn can affect the solubility of naturally occurring trace elements. These changes can either enhance or inhibit the solubility of trace elements in groundwater. For example, Se can be concentrated by evaporation or by irrigation return flow (Seiler and others, 2003). Moreover, studies in agricultural areas in the northeastern United States show that organic As added to poultry feed is converted to inorganic As and loaded to the soil zone, where it may be soluble under favorable redox conditions (Rutherford and others, 2003; Stolz and others, 2007). Arsenic also has historically been used as a pesticide for orchard and row crops (D'Angelo and others, 1996; Hinkle and Polette, 1999; Loiselle and others, 2001). Many studies acknowledge that anthropogenic sources of As in groundwater cannot be ruled out, but most suggest that groundwater As sources are predominantly natural (Hinkle and Polette, 1999; Welch and others, 2000; Ayotte and others, 2003; Peters and Blum, 2003; Welch and Stollenwerk, 2003; Robinson and Ayotte, 2006; Robinson and Ayotte, 2007). Geochemical conditions near waste sites, such as landfills, however, may be altered sufficiently to allow Fe and Mn hydroxide dissolution, resulting in the mobilization of otherwise sequestered soil As and other metals (Stollenwerk and Colman, 2004; deLemos and others, 2006).

The concentrations of trace elements were compared between wells representing primarily agricultural and urban land uses (table 8). In this comparison, water samples from wells in agricultural settings have greater concentrations of some trace elements, such as As, Mo, and U, than samples from wells in urban settings, regardless of climate. Concentrations of DO and pH values also were greater in water samples from agricultural wells than in samples from urban wells. Significantly greater concentrations of B, Cr, Se, Ag, Sr, and V also were found in samples from agricultural wells in dry regions. Concentrations of Pb were greater in water samples from wells in agricultural settings than in samples from urban wells in humid regions, but the converse was true for dry regions.

Water sampled from urban wells in both climate regions generally had greater concentrations of Fe, Li, and Mn than water from agricultural wells, possibly because urban-well water also had lower pH and DO (table 8). Collectively, the urban-well samples were more anoxic than agricultural-well samples, and this result may partly explain why the urban-well samples had fewer HHB or guideline exceedences of oxyanion-forming elements, and why trace elements that are more mobile under anoxic conditions, such as Fe and Mn, were generally prevalent.

Comparisons of Trace-Element Concentrations in Groundwater to Human-Health Benchmarks

HHBs were defined for many trace elements to ensure that high-quality safe drinking water is provided to people using publicly supplied water. The results in this section are not intended to be interpreted as estimates of potential exposure, but rather as a simple comparison to identify geographic areas where concentrations of trace elements in groundwater were found by the NAWQA Program to be greater than established or proposed HHBs. Not all water samples collected for this study were from drinking-water wells; about 40 percent were monitoring wells. The trace elements with HHBs are Sb, As, Ba, Be, B, Cd, Cr, Cu, Pb, Mn, Mo, Ni, Se, Ag, Sr, Tl, U, and Zn; however, it is important to note that, for this summary, not all trace elements were analyzed in samples from all of the selected wells. Comparison of these data to HHBs is intended, in part, to provide a context for analysis of specific trace elements in specific areas of the United States.

For the analysis presented here, wells were selected irrespective of well type or land use (4,527 wells). In 19 percent of samples collected from those wells, at least one trace element exceeded an HHB (table 9). Wells with HHB exceedences were widespread across the United States; they occurred in all aquifer groups and in both humid and dry regions.

For trace elements, wells in urban settings had greater rates of HHB exceedences than agricultural wells or drinking-water wells in varied land-use settings (table 9). In addition, monitoring wells tended to have greater HHB-exceedence rates than drinking-water wells. For some contaminants in groundwater, such as nitrate and volatile organic compounds (VOCs), differences in land use (as an indicator of contaminant source) can have a profound effect on rates of HHB exceedences. For trace elements, however, the differences may be more related to redox, pH, and other conditions than to source indicators, although anthropogenic activities can change redox conditions and thereby can change concentrations of naturally occurring trace elements in groundwater. In general, the wells in the urban and agricultural categories (dominantly monitoring wells) are shallow water-table wells, where the pH in groundwater is commonly low and DO high. Water in a greater percentage of wells in major aquifers (dominantly drinking-water wells) was found to have a higher pH and lower DO than water sampled from the shallow wells. These differences may influence trace-element HHB exceedences, depending on the element.

An important finding from this analysis was that trace-element contamination in groundwater far outpaces contamination in most other commonly assessed groups, such as VOCs, pesticides, and nutrients. In drinking-water wells, one or more trace elements exceeded HHBs in untreated water from 13 percent of public-supply wells and 13 percent of domestic-supply wells (table 9); for pesticides, these rates were 2.2 and 0.76 percent, respectively (Gilliom and others, 2006). Similarly, about 2 percent of public-supply wells and

Table 8. Group-comparison statistics for concentrations of trace elements and selected field parameters in groundwater sampled for the NAWQA Program by climate region and land-use type, 1992–2003, across the United States.

[Yellow shading indicates higher agricultural land use well concentrations; blue shading indicates higher urban land use well concentrations; Concentrations of elements with same Tukey group do not differ significantly at alpha = 0.05. No shading indicates concentrations that do not differ significantly between well types. Reporting level is 1 microgram per liter except for boron (12 micrograms per liter), iron (10 micrograms per liter), radon (80 picocuries per liter), and strontium (0.9 micrograms per liter). N is the number of wells sampled; number of trace element samples varies with availability of grouping variable data; ≥, greater than or equal to; <, less than; --, not applicable]

Element	Dry region							Humid region						
	Agricultural land-use wells			Urban land-use wells				Agricultural land-use wells			Urban land-use wells			
	N	Percentage ≥ reporting level	Tukey group	N	Percentage ≥ reporting level	Tukey group	*p*-value	N	Percentage ≥ reporting level	Tukey group	N	Percentage ≥ reporting level	Tukey group	*p*-value
Aluminum	171	74	A	189	68	A	0.1080	258	92	A	341	90	A	0.5417
Antimony	161	1.9	A	211	1.4	A	0.7416	261	3.5	A	353	1.1	A	0.0513
Arsenic	191	77	A	225	56	B	< 0.0001	302	49	A	363	32	B	< 0.0001
Barium	190	100	A	225	100	A	0.0889	264	100	A	363	100	A	0.1237
Beryllium	163	0.0	A	213	1.9	A	0.0803	261	1.5	A	353	0.3	A	0.0886
Boron	38	100	A	58	100	B	< 0.0001	106	88	A	146	87	A	0.7145
Cadmium	164	2.4	A	212	3.3	A	0.6302	261	2.7	A	353	0.3	B	0.0099
Chromium	181	56	A	213	45	B	0.0009	263	65	A	357	63	A	0.9566
Cobalt	165	6.7	B	216	26	A	< 0.0001	262	21	A	357	28	A	0.0534
Copper	176	79	A	223	72	A	0.2735	263	48	A	362	48	A	0.6096
Iron	480	27	B	268	41	A	< 0.0001	922	42	B	540	56	A	< 0.0001
Lead	162	0.6	B	218	4.6	A	0.0235	261	14	A	353	4.0	B	< 0.0001
Lithium	40	98	B	58	98	A	< 0.0001	61	77	B	86	98	A	< 0.0001
Manganese	462	57	B	234	75	A	< 0.0001	895	75	B	541	90	A	< 0.0001
Molybdenum	185	90	A	217	67	B	< 0.0001	263	60	A	360	45	B	0.0001
Nickel	186	86	A	224	86	A	0.5004	263	72	B	362	78	A	0.0493
Radon	367	98	A	183	99	A	0.1939	425	96	A	300	99	A	0.1750
Selenium	176	52	A	219	38	B	0.0003	262	11	A	331	13	A	0.4383
Silver	163	3.1	A	210	0.0	B	0.0112	259	0.0	A	338	0.3	A	0.3836
Strontium	49	100	A	88	100	B	< 0.0001	163	100	B	154	99	A	< 0.0001
Thallium	37	0.0	A	57	0.0	A	1.0000	56	0.0	A	97	0.0	A	1.0000
Uranium	202	83	A	222	63	B	< 0.0001	455	42	A	377	30	B	0.0002
Vanadium	37	95	A	58	78	B	< 0.0001	58	28	A	70	36	A	0.4626
Zinc	177	84	A	195	69	A	0.0736	263	73	A	339	65	A	0.1179
pH	456	--	A	277	--	B	<0.0001	922	--	A	543	--	B	< 0.0001
Dissolved oxygen	475	--	A	253	--	B	< 0.0001	893	--	A	528	--	B	0.0005
Specific conductance	483	--	B	275	--	A	0.0029	925	--	A	542	--	A	0.4707

Table 9. Percentage of samples collected across the United States for the NAWQA Program from which one or more trace elements exceeded human-health benchmarks by primary water use and study type, 1992–2003.

[TE, trace elements; VOCs, volatile organic compounds; --, not applicable]

Study type	Public-supply wells		Domestic-supply wells		Monitoring wells		All wells	
	Number sampled	Percentage of samples exceeding benchmark	Number sampled	Percentage of samples exceeding benchmark	Number sampled	Percentage of samples exceeding benchmark	Number sampled	Percentage of samples exceeding benchmark
Trace-element studies								
Agricultural land use	0	--	402	9.5	904	26	1,306	21
Urban land use	9	33	17	29	740	28	766	28
Major aquifer study	372	12	1,895	13	188	26	2,455	14
All TE studies	381	13	2,314	13	1,832	27	4,527	19
Other contaminant groups								
All VOCs studies[1]	340	2.1	1,606	1.1	1,060	1.5	3,006	1.4
All pesticides studies[2]	364	2.2	2,356	0.76	2,293	2.5	5,013	1.7
All nitrate studies[3]	384	3.0	2,388	7.0	1,902	12	4,674	8.7

[1] Zogorski and others, 2006.

[2] Gilliom and others, 2006.

[3] Dubrovsky and others, 2010.

1 percent of domestic-supply wells had one or more VOCs greater than HBSLs (Zogorski and others, 2006). Nitrate exceeded its MCL in 3 percent of public-supply-well samples and 7 percent of domestic-supply-well samples (Dubrovsky and others, 2010), yet still did not approach the exceedence rate for trace elements.

HHB exceedences varied by element. Overall, 17 of 19 trace elements with defined HHBs had some exceedences (table 4). Seven of the 19 exceeded benchmarks in at least 1 percent of water samples (table 4). Mn occurred most often at concentrations greater than its HHB (12 percent), followed by As (7.0 percent), Sr (4.3 percent), U (4.0 percent), B (1.9 percent) and Mo (1.5 percent). Rn is a special case because it has a proposed two-tier benchmark that accommodates state-specific programs related to the mitigation of Rn in air. In the case of Rn, 65 percent of samples had concentrations greater than the USEPA-proposed MCL of 300 pCi/L, and 2.7 percent had concentrations greater than the USEPA-proposed AMCL of 4,000 pCi/L (table 4). For all other elements with defined HHBs, concentrations greater than those benchmarks occurred in fewer than 1 percent of samples. Similar rates of exceedence of HHBs for trace elements were found in a study that used only domestic wells sampled by the NAWQA Program (DeSimone, 2009). Radionuclides, As, Mn, Sr, and B were the contaminants exceeding HHBs most frequently in a national study of source-water samples from public wells (Toccalino and others, 2010).

Because trace elements tend to occur at different concentrations in dry and humid climates, the rates of HHB exceedence also vary by climate. For example, in dry regions, concentrations of As exceeded the MCL of 10 µg/L in 11 percent of samples compared to fewer than 5 percent in humid regions (table 5). Sr concentrations were greater than the HBSL of 4,000 µg/L in about 9 percent of dry-region samples compared to 1 percent in humid regions. U exceeded the 30 µg/L MCL in 7.5 percent of dry-region samples and in only 2.1 percent of humid-region samples (table 5). Se concentrations in groundwater were not commonly greater than the USEPA MCL of 50 µg/L but were greater than the MCL about 8 times more frequently in the dry-region samples than in the humid-region samples (0.4 and 0.05 percent, respectively). As discussed previously, these differences may reflect the generally high mobility of some of these elements (As, Se, U) in high-pH, high-TDS groundwater.

Trace-Element Occurrence and Concentrations in Groundwater by Major Aquifer Group

Groundwater trace-element occurrences in relation to aquifer geology are described for eight major groups of aquifers in the United States. Most wells in aquifers sampled in this study were in humid regions, although the basaltic- and other volcanic-rock (BAV) aquifers were in predominantly dry regions. Only aquifers in unconsolidated sand and gravel (USG) and in sandstone and carbonate rock (SCR) had fewer than 85 percent of wells in one climate region. For samples from the SCR group, 79 of the 222 (36 percent) were in humid regions. Groundwater samples in the USG aquifer group (the largest group of samples in this study) were more evenly split between dry and humid regions, with 723 of the 1,801 wells (40 percent) in humid regions.

Dominant water types, based on major-ion chemistry, were determined to provide a description of each major aquifer group (fig. 6). Because some ions are geochemically active or redox sensitive, water type is useful in analyzing the occurrence of some trace elements. Trace-element and Rn concentrations in groundwater were compared to current and proposed HHBs. In many cases, median concentrations of a trace element in the aquifer groups were less than the corresponding HHBs, so higher percentiles, such as the 75th or 95th percentiles, were compared. In selected cases, sources and processes controlling trace-element concentrations and, if applicable, unusually high or low concentrations were examined.

Summary statistics (percentiles) of the concentrations of trace elements and Rn and the percentages of samples in which concentrations exceeded current and proposed HHBs and nonhealth guidelines for each major aquifer group are shown in appendix 3. The median concentrations for all trace elements in all of the major aquifer groups were less than established HHBs and nonhealth guidelines (table 10). Radon concentrations, however, were greater than the USEPA-proposed MCL of 300 pCi/L in more than 50 percent of wells in five of the eight aquifer groups (table 10).

Groundwater concentrations of 12 different elements were above current or proposed HHBs (or nonhealth guidelines) in at least 1 percent of samples in at least one aquifer group (table 10, blue shading). Fe, Mn, and Rn exceeded HHBs (or nonhealth guidelines) in some water samples in all aquifer groups. The USG, GLA, and SAN aquifer groups had at least eight elements that exceeded current or proposed HHBs or nonhealth guidelines in at least 1 percent of water samples, and Al, As, Fe, Mn, Rn, and Sr concentrations exceeded HHBs or nonhealth guidelines in all three aquifer groups. The SCS, SCR, CAR, and BAV groups had five or fewer elements that exceeded current or proposed HHBs or nonhealth guidelines in at least 1 percent of water samples (combinations of As, Fe, Pb, Mn, Rn, or Sr). The CRL aquifer group was similar but also included HHB or nonhealth-guideline exceedences of U and Al. Sr exceeded HHBs or nonhealth guidelines in at least 1 percent of the water samples from the USG, GLA, SAN, and SCR aquifer groups, but in the SCR, more than 26 percent exceeded the HHBs or nonhealth guidelines. Mo exceeded HHBs or nonhealth guidelines in more than 1 percent of the samples in the USG and GLA aquifer groups (table 10).

Unconsolidated Sand and Gravel Aquifers (USG)

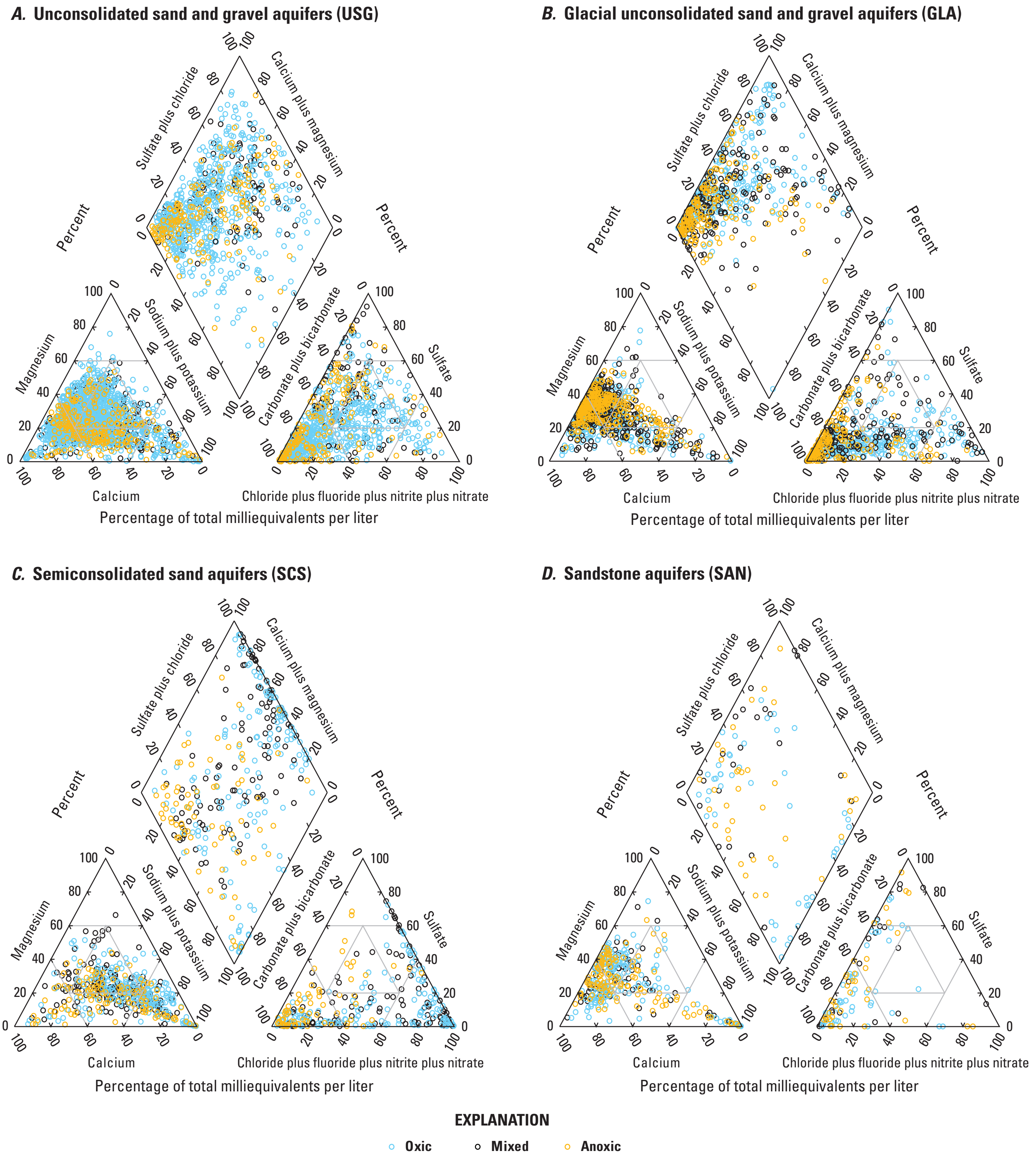
Groundwater samples from the USG aquifer group were predominantly of the calcium-magnesium-bicarbonate (Ca-Mg-bicarbonate or mixed bicarbonate) type (fig. 6A) with a median pH of 7.3 (fig. 7). These samples had the largest variability in water type, however, with many samples in the sodium-chloride (Na-Cl) and Ca-Mg-sulfate fields; this variability may be related to differences in the lithologic compositions of the original source materials from which the sand and gravel was derived, as well as climate differences between the sampling locations.

Generally, trace-element concentrations in groundwater samples from USG wells are among the highest of any of the aquifer groups described in this report. Concentrations of As, B, Li, Mo, Se, U, and V (and HHB exceedences) were generally greater in the USG than in any other aquifer groups (table 10).

About 9 percent of water samples in the USG have U concentrations above the USEPA drinking water MCL (table 10). This is the greatest rate among all of the aquifer groups for U and accounts for about 95 percent of all U HHB exceedences. Sr exceeded the HHB of 4,000 µg/L in 5.2 percent of samples (mostly in western aquifers), which accounts for about 45 percent of Sr benchmark exceedences for all aquifer groups combined.

Concentrations of As and U in all groundwater samples in the USG aquifer group were most often above the USEPA drinking water MCLs of 10 and 30 µg/L, respectively, in the western principal aquifers, such as the Basin and Range basin-fill aquifers, California Coastal Basin aquifers, Central Valley aquifer system, Rio Grande aquifer system, and High Plains aquifer (figs. 3, 4C and V). In many cases, several oxyanion- and ion-complex-forming trace elements are correlated (rho > 0.5) with each other and also with bicarbonate, sulfate, and TDS. Many of these samples had relatively high groundwater pH, which can enhance the solubility of trace elements such as As, B, Mo, Se, and U (Dubrovsky and others, 1991; Fujii and Swain, 1995; Welch and others, 2000; Focazio and others, 2001; Smedley and Kinniburgh, 2002; Welch and Stollenwerk, 2003).

In the generally humid eastern regions, As concentrations were greatest in groundwater samples from the Mississippi River Valley alluvial aquifer and the surficial aquifer system (southern Florida). In the Mississippi River Valley alluvial aquifer, the occurrence of As appears to be associated with the reductive dissolution of Fe oxide coatings on aquifer materials possibly coupled with the oxidation of lignite and peat (Kresse and Fazio, 2003). Uranium occurs in groundwater in the surficial aquifer system (Florida) and may be related to phosphate deposits containing U in the limestone-derived sediments of the Tamiami Formation (Meyer, 1989). U in shallow oxic groundwaters may form soluble complexes with bicarbonate and phosphate in the aquifer (Meyer, 1989).



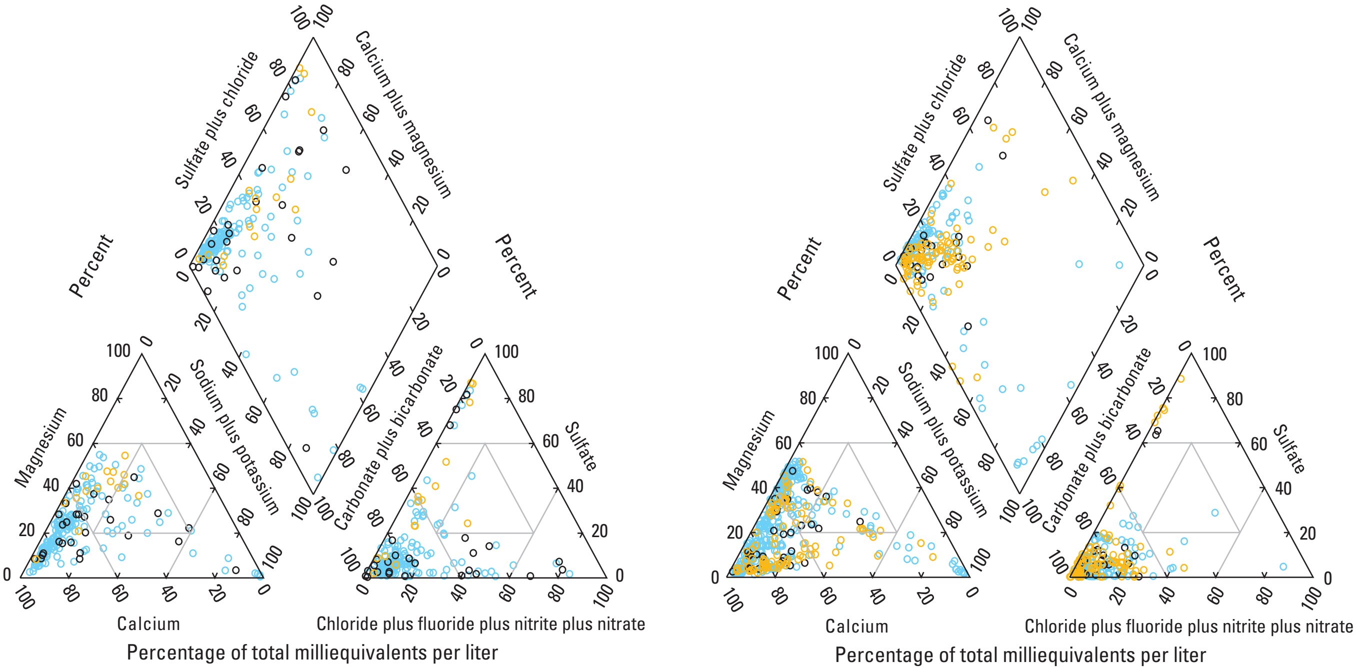
A. Unconsolidated sand and gravel aquifers (USG)

B. Glacial unconsolidated sand and gravel aquifers (GLA)

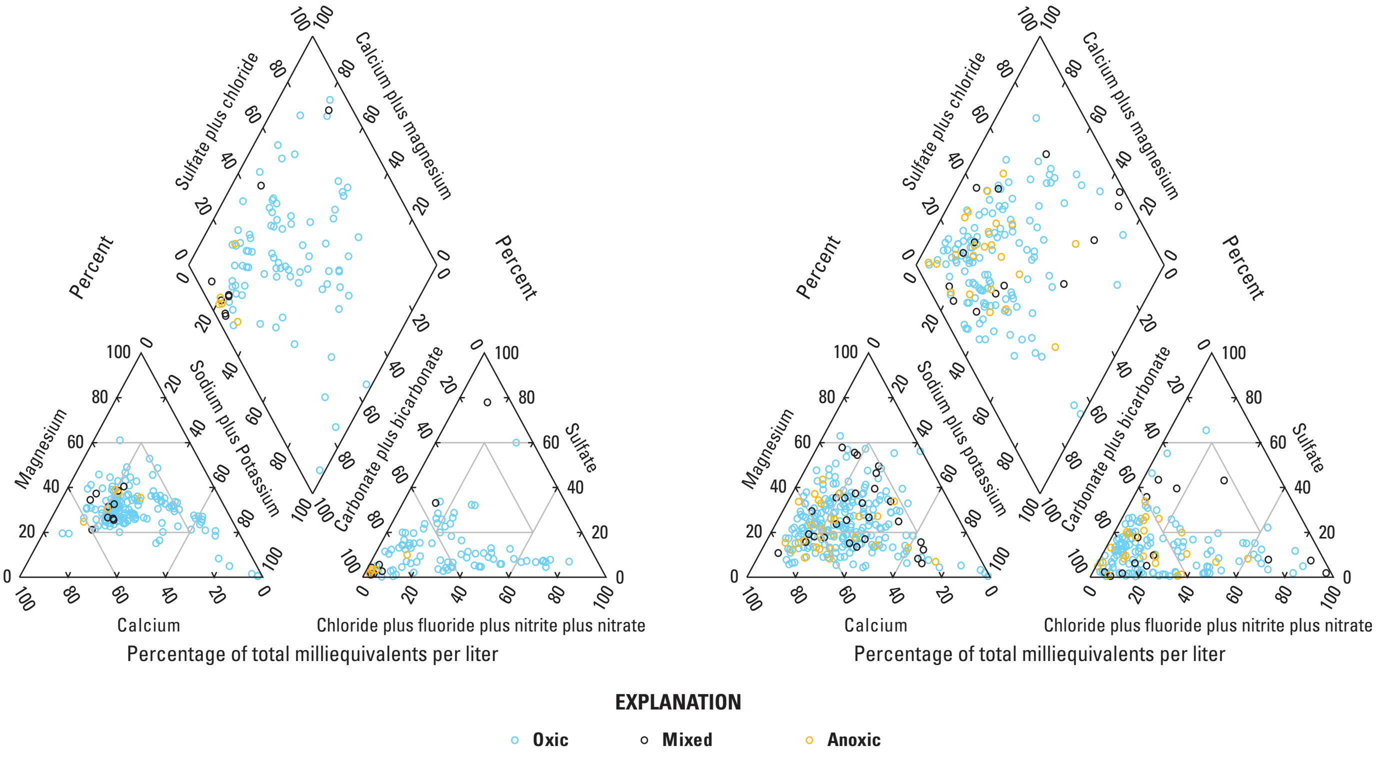
C. Semiconsolidated sand aquifers (SCS)

D. Sandstone aquifers (SAN)

Figure 6. Major-ion chemistry by redox class for *(A)* unconsolidated sand and gravel aquifers, *(B)* glacial unconsolidated sand and gravel aquifers, *(C)* semiconsolidated sand aquifers, *(D)* sandstone aquifers, *(E)* sandstone and carbonate-rock aquifers, *(F)* carbonate-rock aquifers, *(G)* basaltic- and other volcanic-rock aquifers, and *(H)* crystalline-rock aquifers.


***E.* Sandstone and carbonate-rock aquifers (SCR)**

***F.* Carbonate-rock aquifers (CAR)**


***G.* Basaltic- and volcanic-rock aquifers (BAV)**

***H.* Crystalline-rock aquifers (CRL)**

Figure 6. Major-ion chemistry by redox class for *(A)* unconsolidated sand and gravel aquifers, *(B)* glacial unconsolidated sand and gravel aquifers, *(C)* semiconsolidated sand aquifers, *(D)* sandstone aquifers, *(E)* sandstone and carbonate-rock aquifers, *(F)* carbonate-rock aquifers, *(G)* basaltic- and other volcanic-rock aquifers, and *(H)* crystalline-rock aquifers.—Continued

Table 10. Summary of the percentages of exceedences of human-health benchmarks or nonhealth guidelines in samples collected for the NAWQA Program across the United States, 1992–2003, by major aquifer group.

[Elements in which at least 1 percent of samples exceeded guidelines are shown with blue shading; the total number of these elements is shown at the bottom of the table; USG, unconsolidated sand and gravel; GLA, glacial unconsolidated sand and gravel; SCS, semiconsolidated sand; SAN, sandstone; SCR, sandstone and carbonate rock; CAR, carbonate rock; BAV, basaltic and other volcanic rock; CRL, crystalline rock; --, no data; N is the number of wells sampled; %, percentage; ≥, more than or equal to; benchmark units are in micrograms per liter except radon, for which the proposed benchmark is in picocuries per liter]

Element	Bench-mark or guideline	Major aquifer group															
		USG		GLA		SCS		SAN		SCR		CAR		BAV		CRL	
		N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Aluminum	200	1,226	1.0	485	1.0	301	3.0	229	1.7	166	0.60	195	0.00	31	0.00	193	1.0
Antimony	6	1,318	0.00	498	0.00	338	0.00	256	0.39	186	0.00	189	0.00	30	0.00	194	0.00
Arsenic	10	1,507	12	512	6.8	373	0.80	282	1.4	189	1.1	229	1.3	81	6.2	223	5.4
Barium	2,000	1,376	0.07	513	0.00	343	0.29	283	0.35	189	0.00	189	0.00	35	0.00	194	0.00
Beryllium	4	1,318	0.00	511	0.00	338	0.29	258	0.78	186	0.00	189	0.00	31	0.00	194	0.52
Boron	1,000	552	3.4	274	1.1	181	0.00	86	0.00	--	--	--	--	30	0.00	51	0.00
Cadmium	5	1,351	0.37	511	0.00	338	0.00	274	1.1	186	0.00	189	0.00	81	0.00	194	0.00
Chromium	100	1,367	0.07	491	0.00	338	0.00	275	0.00	188	0.00	190	0.00	80	0.00	194	0.00
Copper	1,300	1,372	0.07	501	0.00	339	0.00	280	0.00	189	0.00	189	0.00	80	0.00	194	0.00
Iron	300	1,769	12	1,190	29	570	29	389	32	222	7.7	480	19	232	3.4	279	9.3
Lead	15	1,355	0.00	498	0.00	339	1.2	277	0.36	187	0.00	189	0.00	81	0.00	194	0.00
Manganese	300	1,700	12	1,148	20	564	9.8	376	17	219	3.2	463	1.9	228	2.6	278	3.6
Molybdenum	40	1,368	2.4	499	2.0	339	0.00	257	0.78	188	0.53	189	0.00	30	0.00	194	0.00
Nickel	100	1,369	0.00	502	0.00	341	0.29	262	2.3	189	0.00	189	0.00	30	0.00	194	0.00
Radon	300	1,481	77	763	54	243	39	358	65	136	44	431	61	192	43	273	92
Selenium	50	1,395	0.29	511	0.20	342	0.00	282	0.35	189	0.00	183	0.00	74	0.00	190	0.00
Silver	100	1,297	0.00	507	0.00	339	0.00	264	0.00	184	0.00	169	0.00	35	0.00	194	0.00
Strontium	4,000	483	5.2	259	1.2	155	0.00	59	3.4	98	26	140	0.71	31	0.00	84	0.00
Thallium	2	366	0.00	202	0.00	154	0.00	57	0.00	--	--	--	--	--	--	58	0.00
Uranium	30	1,409	8.7	640	0.47	339	0.00	336	0.30	187	0.53	318	0.31	33	0.00	279	3.9
Zinc	2,000	1,335	0.07	494	0.00	308	0.00	238	0.00	178	0.00	190	0.00	70	0.00	193	0.00
Number of elements with ≥ 1% exceedence			9		8		5		8		5		4		4		6

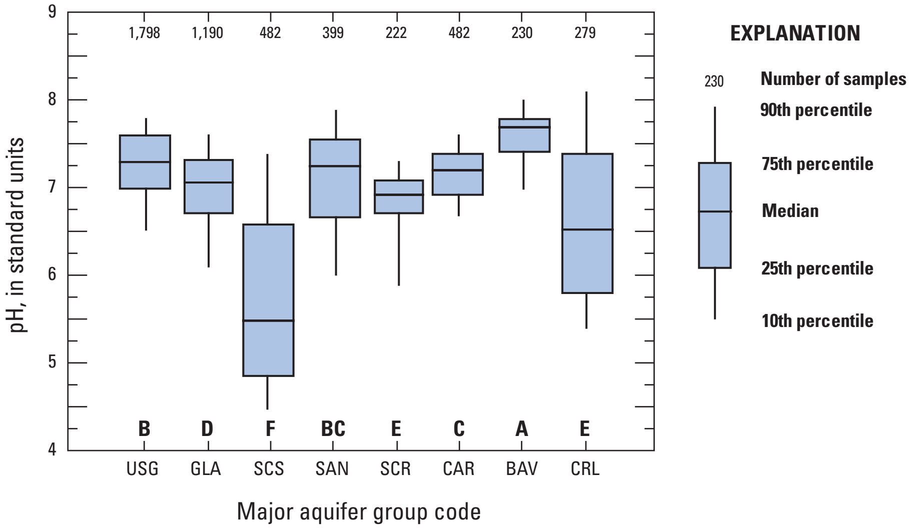


Figure 7. Distributions of pH by major aquifer group. Letters representing nonparametric Tukey group are shown below boxes. Groups with different letters are significantly different (alpha = 0.05). USG, unconsolidated sand and gravel aquifers; GLA, glacial unconsolidated sand and gravel aquifers; SCS, semiconsolidated sand aquifers; SAN, sandstone aquifers; SCR, sandstone and carbonate-rock aquifers; CAR, carbonate-rock aquifers; BAV, basaltic- and other volcanic-rock aquifers; and CRL, crystalline-rock aquifers.

Glacial Unconsolidated Sand and Gravel Aquifers (GLA)

The water type of the GLA groundwater samples was predominantly Ca-Mg bicarbonate but with some samples having a Na-Cl influence (fig. 6B). The median pH of samples from this aquifer group was 7.1 (fig. 7). The GLA aquifer group had the greatest percentage of mixed and anoxic samples (and the lowest percent of oxic) of all of the categories in this report (fig. 6B; table 1). Some of the GLA groundwater samples had relatively high percentages of Na and Cl, and most of those samples were oxic, possibly because of shallow groundwater that had been affected to some extent by land use (deicing chemicals, septic use, urbanization, and agriculture). The sources of trace elements, aquifer geochemistry, and redox varied greatly within this aquifer group, in part because of the wide array of source rocks that affected the composition of the glacial sediments.

Mn exceeded the HBSL (300 µg/L) in about 20 percent of all water samples in the GLA—more than in samples from any other major aquifer group (table 10). This rate of exceedence may be related to the relatively high percentage of mixed and anoxic samples in the GLA as well as commonly low pH conditions (compare figs. 2, 3A, 6B, and 4N). Arsenic also is a common trace element with concentrations above HHBs in water samples from the GLA aquifer group, as are Al, B, Fe, Mo, Rn, and Sr. Arsenic occurred at concentrations above 10 µg/L in nearly 7 percent of 512 samples (table 10). U was greater than 30 µg/L in 0.5 percent of 640 samples, and most of these samples came from the west-central region, especially North Dakota (table 10; fig. 4V). U concentrations in groundwater in this region may be related to the incorporation of uraniferous Cretaceous-age shale in the glacial sediments (Tourtelot, 1956; Seiler and others, 2003; Ayotte and others, 2007; Groschen and others, 2008). Groundwater samples from glacial sediments derived in part from crystalline rocks, primarily in Minnesota, had comparatively low U concentrations. Arsenic, by contrast, appears to be more strongly related to geochemical controls such as redox and pH (Warner, 2001; Thomas, 2003, 2007).

Mo and Sr concentrations in water from wells in the GLA were above HBSLs in 2 and 1.2 percent of samples, respectively (table 10). These Mo samples were from groundwater primarily in the central portion of the GLA, including Illinois and Indiana (fig. 4O). Mo correlates most strongly with bicarbonate (rho equal to 0.58, *p* less than 0.001, *N* equal to 149), Sr (rho equal to 0.53, *p* less than 0.0001, *N* equal to 245), and As (rho equal to 0.47, *p* less than 0.0001, *N* equal to 470). Arsenic and Mo commonly occur as oxyanions in water and, as such, may be released by redox- or pH-driven desorption from mineral oxides. The correlation of As with Mo concentrations has been noted in studies of other areas in Illinois and Canada (Warner, 2001; Thomas, 2003). Sr concentrations were greatest in water samples in the east-central part of the GLA, primarily in Illinois, Indiana, and Ohio (fig. 4T). Sr is relatively insoluble in water except when it forms complexes with anions, such as sulfate or carbonate; in water samples from the GLA, Sr was correlated with bicarbonate (rho equal to 0.64, *p* less than 0.0001, *N* equal to 95) and sulfate (rho equal to 0.44, *p* less than 0.0001, *N* equal to 256).

Semiconsolidated Sand Aquifers (SCS)

Groundwater samples from the SCS aquifer group consisted of a wide mix of water types (fig. 6C). Most samples from the SCS had either bicarbonate or Cl as the predominant anion, but some waters had a strong sulfate component. The bicarbonate-chloride-sulfate signature of these waters may be a reflection of the marine depositional history of these eastern and southern coastal plain sediments. Groundwater samples from the Northern Atlantic Coastal Plain aquifer system were predominantly of the sulfate type, whereas samples from the Mississippi Embayment aquifer system, Coastal Lowlands aquifer system, and the Texas Coastal uplands aquifer system were predominantly of the bicarbonate type.

The median pH of water samples from this aquifer group (5.5) was the lowest among all the aquifer groups (fig. 7); however, there was variability within this aquifer group. For example, the water samples from the Northern Atlantic Coastal Plain aquifer system and the Southeastern Coastal Plain aquifer system collectively had a median pH of 5.1, whereas the samples from the Coastal Lowlands aquifer system, Mississippi embayment aquifer system, and Texas coastal uplands aquifer system had median pH values of 6.6, 6.3, and 7.6, respectively. Differences in pH may affect the solubility of certain trace elements.

In water samples from the SCS aquifer group, Al, Fe, Pb, Mn, and Rn concentrations were above current or proposed HHBs or nonhealth guidelines in 1 percent or more of samples (table 10). The greatest concentrations of Al, Fe, Pb, and Mn were measured in water samples from the Northern Atlantic Coastal Plain and Southeastern Coastal Plain aquifer systems, where low pH values were likely to be a factor in their mobility (figs. 4A, K, L, and N). Concentrations of Co also were greatest in the water samples from the Northern Atlantic Coastal Plain aquifer system. The same was true for Ni and Zn; these results were consistent with the low pH of the water in this aquifer (figs. 4I, P, and X).

Concentrations of As were greatest in water samples from the Coastal Lowlands and Northern Atlantic Coastal Plain aquifer systems of the SCS (figs. 3, 4C). Concentrations of U were below HHBs in all water samples from the SCS aquifers, but concentrations above 5 µg/L were found in water samples from the Coastal Lowlands, Southeastern Coastal Plain, and the Texas Coastal Uplands aquifer systems (figs. 3, 4V). Concentrations of U were correlated with concentrations of many dissolved ions; this correlation is consistent with mobilization by ion complexation, which occurs in other aquifer groups.

Sandstone Aquifers (SAN)

The sandstone aquifer group covers large areas of the east- and west-central parts of the United States (fig. 3A). The water type of samples from the SAN aquifers was variable but predominantly of the Ca-Mg-bicarbonate type. Some samples had a substantial percentage of Na and proportionally more sulfate (fig. 6D). Differences in water type may reflect differences in climate and (or) local differences in aquifer chemistry. The Na-dominated samples, for example, were mainly from the Lower Tertiary sandstone aquifers in Wyoming, where processes involving ion exchange of Ca for Na on aquifer materials and sulfate reduction may have been responsible for differences in water type (Bartos and others, 2005).

The pH of water samples from the SAN aquifers also varied locally with a median value of 7.3. Groundwater samples from Pennsylvanian aquifers and from the Woodbine aquifer (Dallas-Fort Worth metropolitan area) (fig. 3A) had substantially lower pH values (medians of 6.3 and 6.8, respectively) than other SAN water samples. Groundwater samples from the Lower Tertiary aquifers (primarily in the Bighorn Basin) had a median pH of 8.1 and tended to be of the Na-bicarbonate type, which transitioned to Na-sulfate type as TDS increased (Bartos and others, 2005). The median TDS value for all of the water samples from the Lower Tertiary aquifers and the Woodbine aquifer was more than 1,300 mg/L (compared to less than 300 mg/L for all other SAN water samples).

Groundwater samples from the SAN aquifer group had eight elements (Al, As, Cd, Fe, Mn, Ni, Rn, and Sr) with more than 1 percent of concentrations above current and proposed HHBs and nonhealth guidelines; however, percentages were less than 2 percent, except for Fe, Mn, Ni, Rn, and Sr (table 10). Concentrations of As were greatest in groundwater samples from the northeastern parts of the Early Mesozoic basin aquifers and the Valley and Ridge aquifers (75th-percentile value greater than 3 µg/L) and also in the Woodbine aquifer and Lower Tertiary aquifers (75th-percentile value greater than 1 µg/L). Concentrations of As from all samples were most strongly correlated with Mo (rho equal to 0.41, *p* less than 0.001, *N* equal to 256).

Concentrations of U were greatest in the Woodbine aquifer, Early Mesozoic basin aquifers, and Lower Tertiary aquifers (75th-percentile value greater than 3 µg/L). At the principal aquifer scale, sulfate, alkalinity, bicarbonate, specific conductance, and Mo are among the most significant correlates with U.

Sandstone and Carbonate-Rock Aquifers (SCR)

Groundwater samples from the SCR aquifer group—the Edwards-Trinity aquifer system in south-central Texas and the Mississippian aquifers primarily in Tennessee and Alabama were predominantly of the Ca-Mg-carbonate type (figs. 3A, 6E). A few water samples, mostly from the Mississippian aquifers, had a Na-Cl component. The pH of waters from the SCR aquifers is variable, with the median from the Edwards-Trinity aquifer system (dry climate) equal to 7.0 and that from the Mississippian aquifers (humid climate) equal to 6.6 (fig. 7).

Sr exceeded the HBSL of 4,000 µg/L (table 10) in more than 25 percent of samples from the aquifers in SCR—much greater than in other aquifer groups—however, these Sr concentrations were not evenly distributed across this aquifer group. For example, Sr concentrations exceeded the

HBSL in about 10 percent of water samples from wells in the Edwards aquifer and in about 50 percent of water samples from the Trinity aquifer in south-central Texas (figs. 3, 4T). The source of the Sr is likely the argillaceous carbonate rocks that underlie the aquifer system (Oetting and others, 1996; Musgrove and Banner, 2004). Sr in groundwater samples from the Trinity aquifer correlated most strongly with specific conductance, sulfate, TDS, and K (rho equal to 0.64 to 0.55, p less than 0.001, N equal to 29). Median concentrations of Rn were near the USEPA-proposed MCL of 300 pCi/L in groundwater samples from the Trinity aquifer and about 150 pCi/L in groundwater samples from the Edwards aquifer. Median Rn concentrations groundwater samples from the Mississippian aquifers were about 600 pCi/L.

Carbonate-Rock Aquifers (CAR)

Groundwater samples from wells in carbonate-rock aquifer group were predominantly of the Ca-Mg bicarbonate type (fig. 6F). The chemistry of most samples indicated recharging groundwater (Ca bicarbonate) to evolved groundwater (dissolution of dolomite and gypsum) (Hanshaw and Back, 1979; Back and others, 1988).

Most of the groundwater samples were collected from these aquifers in humid parts of the United States, and very few elements (As, Fe, Mn, Rn) above current or proposed HHBs or nonhealth guidelines were detected (table 10). Al, As, Rn, Sr, and U concentrations were elevated locally in the carbonate-rock aquifers. Al, for example, was above 50 µg/L in samples from only the Ozark Plateaus aquifer system, whereas As concentrations were greatest in the samples from the Biscayne aquifer and Floridan aquifer system. Rn was above the USEPA-proposed AMCL of 4,000 pCi/L in only one groundwater sample from the Floridan aquifer system, but median concentrations exceeded the USEPA-proposed MCL of 300 pCi/L in most of the samples from this aquifer group.

Sr, a common element in carbonate-aquifer waters, was analyzed in water samples from the carbonate rocks of only the Valley and Ridge aquifers and Biscayne aquifers. The 95th-percentile value for Sr in these samples exceeded 1,000 µg/L, and the median in water samples from the Biscayne aquifer was greater than 750 µg/L. U also occurred in some water samples in the Biscayne aquifer, with the 95th-percentile value exceeding 24 and 15 µg/L in samples collected from shallow and deep positions in the aquifer, respectively.

By contrast, As concentrations in 30 groundwater samples from a dry-region carbonate aquifer in the Great Basin (Nevada and Utah) ranged from 0.7 to 45.7 µg/L with a median value of 9.7 µg/L (Schaefer and others, 2006). Processes identified as leading to the mobilization of As in groundwater include geothermal heating and long time of travel along a flow path. For example, in the central part of this carbonate-rock aquifer, groundwater flow is generally from north to south, and As concentrations also increase in this direction (Schaefer and others, 2006).

Basaltic- and other Volcanic-Rock Aquifers (BAV)

The fewest groundwater samples were collected from the BAV aquifer group, partly because of the smaller areal distribution of these deposits. Fewer than 100 water samples were collected for each trace element except Fe (N equal to 232) and Mn (N equal to 228) (table 10). The water type of the groundwater samples from BAV aquifer group was mixed but tended toward either Ca-Mg bicarbonate or Ca-Mg chloride (fig. 6G). The median pH of water samples from this aquifer group (7.7) was the highest among the aquifer groups in this report (fig. 7). The pH of water in these aquifers may be increased by processes such as silicate hydrolysis and carbonic acid weathering (Wood and Fernandez, 1988). The former process results in the addition of hydroxyl ions to the water, raising the pH, whereas in the latter, bicarbonate ions are added. Ion exchange of Na for Ca can further increase the dissolution of calcite, resulting in still higher pH (Wood and Fernandez, 1988). The water samples from the BAV aquifer group had only four elements above HHBs or nonhealth guidelines (table 10), although As was found above 10 µg/L in 6.2 percent of water samples (all from the Upper Snake River basin), and Rn was above the USEPA-proposed MCL of 300 pCi/L in 43 percent of water samples (table 10).

Crystalline-Rock Aquifers (CRL)

The water type of samples from the CRL aquifer group was predominantly Ca bicarbonate to mixed Ca-Mg-Na bicarbonate, but with some samples having a stronger Na-Cl influence (fig. 6H). The median pH of water samples from crystalline-rock aquifers was about 6.5 (fig. 7); however, pH was slightly alkaline (7.3) in New York and New England and the Rocky Mountain Front Range crystalline-rock aquifers, and somewhat acidic (5.9) for the Piedmont and Blue Ridge crystalline-rock aquifers. This variation was evident from the large interquartile range for pH (1.6 pH units) for the CRL water samples (fig. 7). Concentrations of six elements (Al, As, Fe, Mn, Rn, and U) were greater than HHBs and nonhealth guidelines in at least 1 percent of the groundwater samples from the CRL aquifer group (table 10). Arsenic exceedences of HHBs in the CRL were 5.4 percent but jumped to 17 percent in samples from the CRL aquifers in the eastern part of New England. U was greatest in groundwater from CRL aquifers in the Northeast (New York and New England) and the Rocky Mountain Front Range (95th-percentile values of 18 and 220 µg/L, respectively), whereas 95th-percentile concentrations in samples from the Piedmont and Blue Ridge CRL aquifers ranged from 1.9 to 6.7 µg/L. Water from the CRL aquifers had the greatest Rn concentrations of any aquifer group. For example, 92 percent of Rn concentrations from this aquifer group were greater than the USEPA-proposed MCL of 300 pCi/L, and 28 percent of concentrations from CRL samples were greater than the USEPA-proposed AMCL of

4,000 pCi/L (table 10; appendix 3). Rn concentrations were, by far, greater in the water samples from CRL aquifers in New York and New England (fig. 4Q).

Concentrations of As in water samples from the CRL were correlated most strongly with pH (rho equal to 0.32, *p* less than 0.0001, *N* equal to 223) and redox as indicated by DO concentration (rho equal to -0.34, *p* less than 0.0001, *N* equal to 221). U in the samples from the CRL aquifers was correlated with many water-quality and well-construction parameters, including Mo, Ca, pH, specific conductance, TDS, Na, and well depth, collectively indicating possible complexation of U with bicarbonate. U concentrations were also correlated with Rn in the CRL aquifers, but Rn was correlated with no other elements at the aquifer-group level. In water from the CRL aquifers in New York and New England, however, Rn correlated weakly with Pb (rho equal to 0.38, *p* less than 0.0005, *N* equal to 82).

Relation of Selected Trace Elements to pH and Redox State

The effects of redox and pH account for substantial additional variability in the concentrations of trace elements in groundwater among the major aquifer groups. Other factors such as water type, TDS, organic matter, and biological activity also may influence trace-element concentrations and may account for unexplained variability in the expected redox- and pH-related behavior of some trace elements. Most trace elements are sensitive to redox conditions in groundwater, either because that element can occupy multiple redox states in natural waters, or because the redox state controls the concentration of soluble complexes. Variation in pH has an effect on the adsorption of many trace elements, as well as on the solubility of some concentration-limited hydroxide solid phases (such as Fe and Mn). Some redox-sensitive trace elements are more mobile under low pH and oxic conditions. For example, Cd, Cu, Pb, and Zn can increase from 0 to 100 percent adsorption on oxide-hydroxides over a pH range of 2 standard units (Salbu and Steinnes, 1994). Other elements, such as Fe and Mn, are mobile under low pH and (or) anoxic conditions. Some oxyanion-forming trace elements, by contrast, are generally more mobile under high pH conditions and include As, Cr, Mo, Se, and V. Arsenic sorption, for example, decreases as pH increases (Smedley and Kinniburgh, 2002; Stollenwerk, 2003).

In this report, groundwater samples are classified into three simplified redox states: oxic, mixed, and anoxic (table 2) based on a scheme that uses commonly measured ions and properties of the water sample to assess the redox state (Chapelle and others, 1995; Chapelle and others, 2002; Paschke, 2007; McMahon and Chapelle, 2008; McMahon and others, 2009). Most samples were oxic according to this scheme (fig. 2A). About 70 percent or more of the water samples in the USG, SCR, CAR, BAV, and CRL aquifer groups were classified as oxic. By contrast, more than 50 percent of groundwater samples in the GLA, SCS, and SAN aquifer groups were classified as mixed or anoxic (table 1). Generally, anoxic and mixed redox conditions were more common in well water in the humid parts of the United States, whereas oxic conditions were more common in well water in the dry regions (fig. 2A). Additional information on Fe and other trace-element guideline exceedences for categories of pH and redox are shown in appendix 4.

The median pH varies by aquifer group and is above or equal to 7 for the samples from the USG, GLA, SAN, CAR, and BAV groups and below 7 for the samples from the SCS, SCR, and CRL groups (fig. 7). The pH of precipitation is lower in the eastern part of the United States than in the west (fig. 2B), and acidification of groundwater from external factors, such as acid deposition related to increased fossil-fuel burning, can be associated with the mobility of trace metals in recently recharged (post-1960) groundwater (Jacks, 1993).

Iron and Manganese

Based on the redox classification scheme used in this report, samples with high Fe or Mn (concentrations greater than 0.1 or 0.05 mg/L, respectively) were considered to be anoxic (table 2). Therefore, Fe and Mn occurred most often in mixed and anoxic samples and least often in oxic samples (figs. 8K, N). For samples with data sufficient for the inference of redox status, 19 percent had DO less than or equal to 0.5 mg/L and high Fe/Mn, 62 percent had low Fe/Mn and DO greater than 0.5 mg/L, and 19 percent had high Fe/Mn and DO greater than 0.5 mg/L. Thus, 81 percent of the time, Fe/Mn and DO were mutually exclusive under the above conditions.

Aluminum, Copper, Lead, and Zinc

Al, Cu, Pb, and Zn are common elements in the environment and are found in materials and products used in drinking-water-well construction and plumbing. It is therefore difficult to determine the extent to which the concentrations of these elements in water samples from drinking-water wells are related to these materials or to other sources. Additionally, bias caused by systematic contamination of samples was identified for Al and Zn through analysis of water initially free of these elements (Apodaca and others, 2006). Thus, results from analyses of these elements at concentrations near the reporting levels must be considered in light of the potential bias.

Redox effects on trace-element occurrence and distribution are often, but not always, similar among the major aquifer groups. In groundwater samples from the USG, Al occurrence generally increased as samples became more anoxic in both pH categories (figs. 8A and 9A). Al exceeded the nonhealth guideline in up to 3 percent of water samples from the major aquifer groups and most commonly exceeded guidelines under low-pH and mixed or anoxic conditions (table 10). Cu also was sensitive to redox and pH, occurring more frequently under low-pH and oxic conditions in about half of the aquifer groups (fig. 8J). Pb, based on solubility considerations, is more mobile under low-pH conditions (Hem, 1985), and this was true for most water samples (figs. 9B and 8L).

Additional variation in redox and pH effects within the same aquifer group may be related to climate. For example, in the humid-region USG aquifers, Pb in groundwater occurred more frequently and was more strongly redox controlled in the high-pH samples than in the low-pH samples (fig. 10B). In the dry-region USG aquifers, redox and pH effects for groundwater Pb occurrence were less discernible. Further, Cu occurrence in groundwater was not sensitive to pH in either region but was redox sensitive in humid-region samples (fig. 10C). Zn occurrence in groundwater showed a clear sensitivity to redox in the humid-region USG aquifers but not in dry-region aquifers (fig. 10D).

Arsenic, Chromium, Molybdenum, and Selenium

As, Cr, Mo, and Se commonly form oxyanions in groundwater that are affected by redox and pH, and thus the chemical behavior of these elements is somewhat predictable. The percentage of samples with As, for example, generally increased from oxic to anoxic redox conditions when pH was less than 7, but was consistently greater than 50 percent when pH was greater than or equal to 7 (fig. 11A). A similar pattern was seen for Mo (fig. 11C) and, to a lesser extent, Cr (fig. 11B). The pattern was opposite and applied in both pH categories for Se, which is more soluble under oxic conditions (fig. 11D). For As, Cr, and Mo, the lack of redox sensitivity at high pHs may be related to pH-driven desorption or ion competition, which either obscures or reduces the redox effects that were seen in the low-pH samples.

Some deviation from these general patterns occurred by aquifer group and by aquifer, but the general patterns may indicate the relative importance of different processes in specific aquifer settings. For example, in the GLA aquifer group, As concentrations and occurrence increased significantly as samples became increasingly anoxic and as pH increased (figs. 12A and B). These results are similar to findings from other regional studies (Thomas, 2007). For groundwater samples from the USG aquifer group, however, As occurrence increased significantly as pH increased, but only for oxic and mixed conditions (figs. 12C and D). In the high-pH USG samples, there were no differences in the groundwater As concentrations or occurrence rates among redox categories. This result suggests that As mobility in some settings may be less controlled by redox when pH is greater than 7.

Occurrences of Mo and to some extent Cr in groundwater from the GLA aquifer group also increased as the water became more anoxic for both low- and high-pH samples (figs. 8H, O, 11B and C). Se occurrence, by contrast, dropped off sharply from oxic and mixed to anoxic water samples (figs. 8R, 11D). Se occurred at concentrations greater than 1 µg/L in fewer than 30 percent of water samples from most aquifer groups except the USG group, from which concentrations in as many as half of the samples in the oxic or mixed categories were greater than 1 µg/L (fig. 8R). This result is consistent with results from studies in the San Joaquin Valley in California, where Se mobility was greater under oxic conditions (Dubrovsky and others, 1993; Fujii and Swain, 1995). These studies showed that Se was controlled by redox conditions, with only selenate (SeO_4^{2-}) being mobile under oxic conditions. B, and to some extent V, appeared redox sensitive (figs. 8F, W) and generally followed the behavior of As and Mo (figs. 8C, O).

Uranium and Radon

U occurrence in groundwater was redox and pH dependent, occurring most frequently in samples with oxic or mixed redox conditions and generally under high-pH conditions (fig. 8V). However, because U can form soluble complexes under a wide range of redox and pH conditions that are common in groundwater across the United States, U also is sometimes found in water samples that are characterized as anoxic and low pH, possibly because of ion complexation or competition.

Concentrations of Rn, a nonreactive gas, showed relations to redox and (or) pH conditions in the water samples from several aquifer groups. In general, Rn occurred most often in low-pH, oxic water samples. In groundwater from the CRL aquifer group, Rn occurrence was nearly ubiquitous, owing to the abundant U-bearing minerals in the rocks of the region and to the associated presence of radium (^{226}Ra, which decays directly to Rn) on or near fracture surfaces. In groundwater samples from the GLA aquifer group, however, both redox and pH were related to occurrence (fig. 8Q). The apparent redox relation may be due in part to the decreased solubility of ^{226}Ra in oxic groundwater conditions. This suggests that the source strength and (or) emanation efficiency for radon is possibly enhanced in the shallow part of the aquifer, perhaps due to greater weathering of radionuclides from aquifer materials or the flushing or depletion of sources of radon (^{226}Ra) in the deeper parts of the aquifer. Oxic, low-pH groundwater conditions are consistent with the relative immobility of ^{226}Ra in the shallow aquifer and the possible depletion of ^{226}Ra in the deeper, anoxic parts of the aquifer. Decreased solubility would favor adsorption of ^{226}Ra and provide a source for the generation of Rn (Focazio and others, 2001).

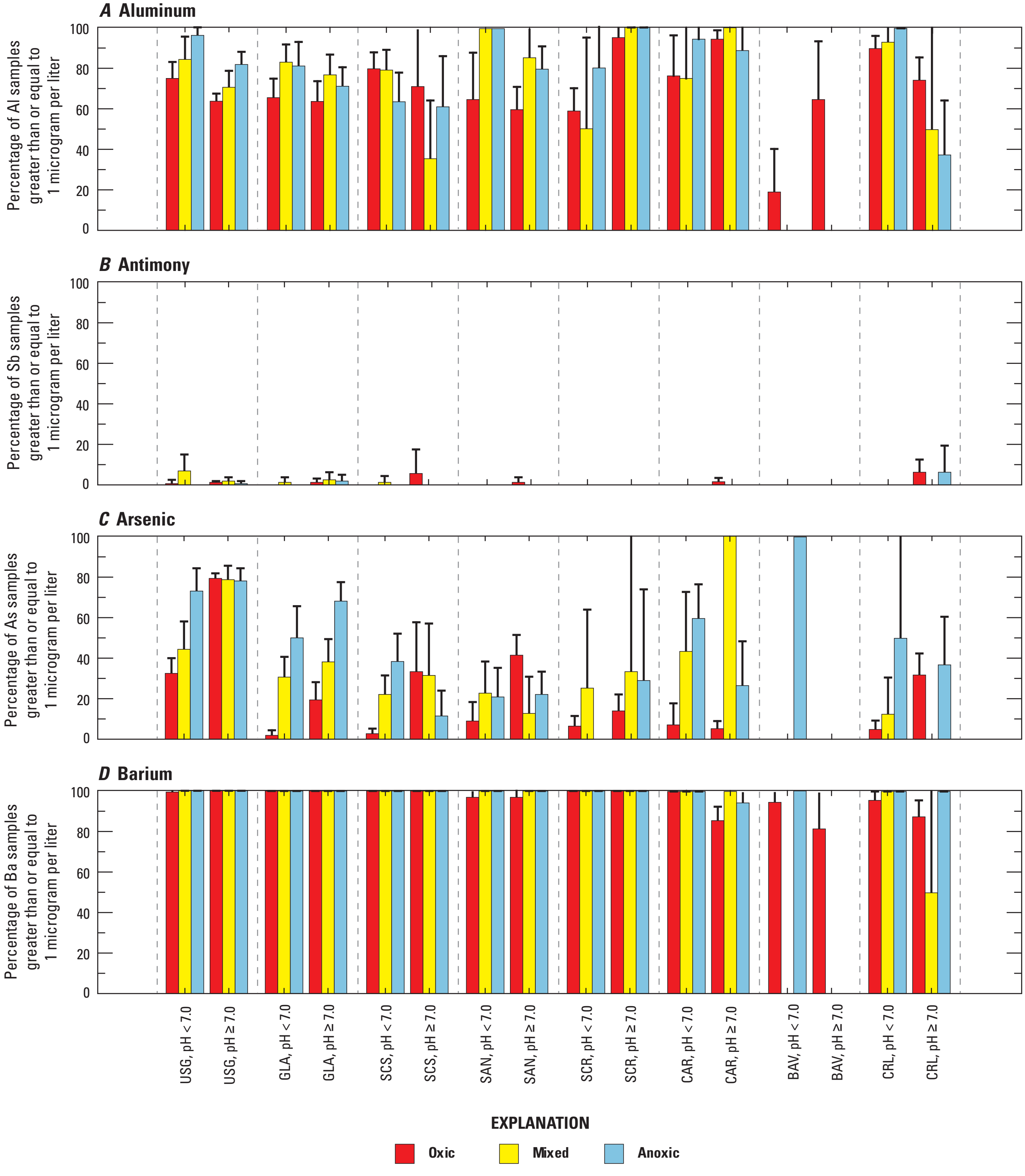
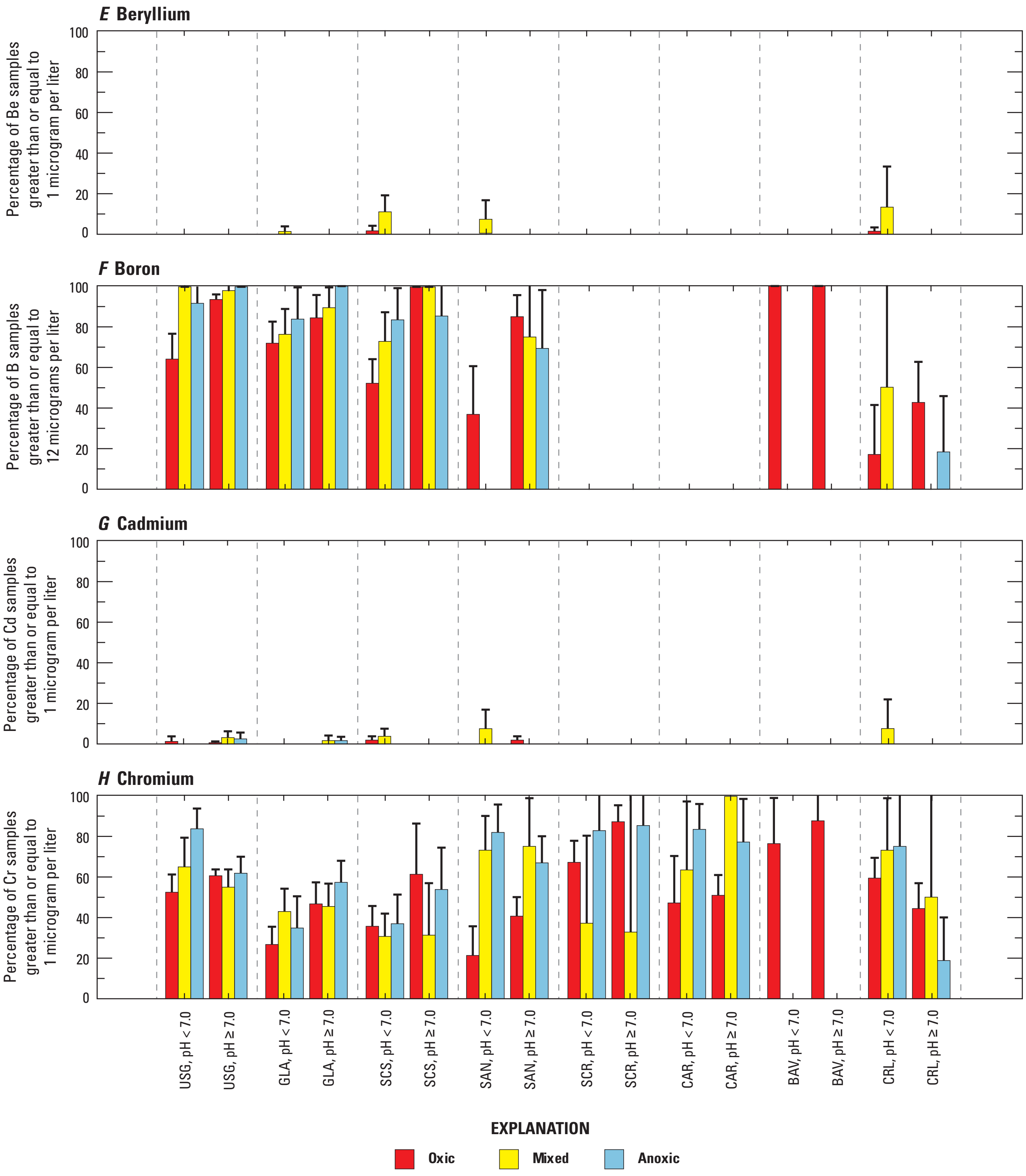


Figure 8. The percentage of groundwater samples with trace-element concentrations greater than or equal to the reporting level, by redox and pH categories, for the major aquifer groups: *(A)* aluminum, *(B)* antimony, *(C)* arsenic, *(D)* barium, *(E)* beryllium, *(F)* boron, *(G)* cadmium, *(H)* chromium, *(I)* cobalt, *(J)* copper, *(K)* iron, *(L)* lead, *(M)* lithium, *(N)* manganese, *(O)* molybdenum, *(P)* nickel, *(Q)* radon, *(R)* selenium, *(S)* silver, *(T)* strontium, *(U)* thallium, *(V)* uranium, *(W)* vanadium, and *(X)* zinc. Reporting level is 1 microgram per liter unless otherwise noted. USG, unconsolidated sand and gravel aquifers; GLA, glacial unconsolidated sand and gravel aquifers; SCS, semiconsolidated sand aquifers; SAN, sandstone aquifers; SCR, sandstone and carbonate-rock aquifers; CAR, carbonate-rock aquifers; BAV, basaltic- and other volcanic-rock aquifers; and CRL, crystalline-rock aquifers. Error bars represent the 95-percent confidence interval of the mean (binomial distribution). See appendix 4 for the number of samples in each category.



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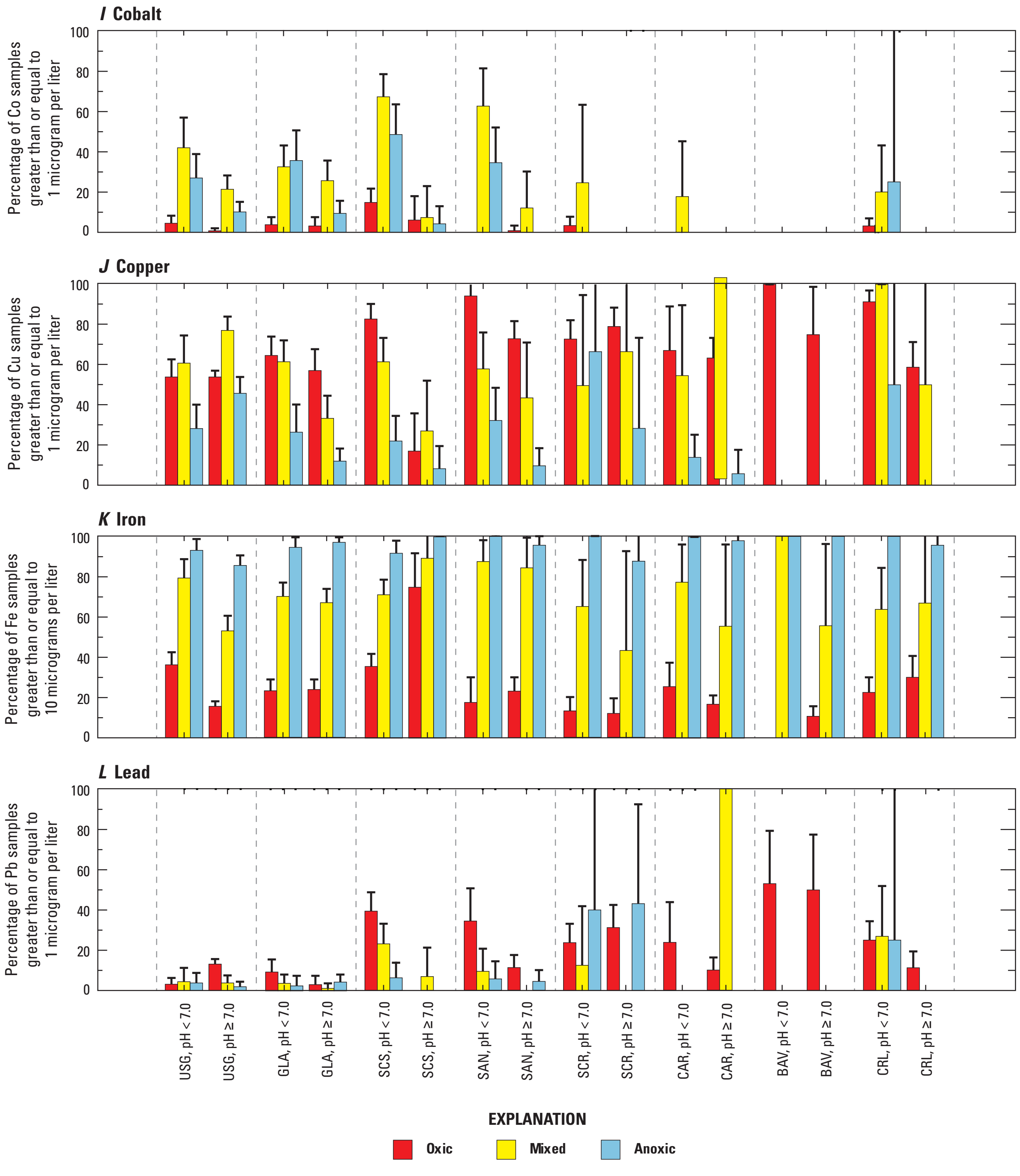

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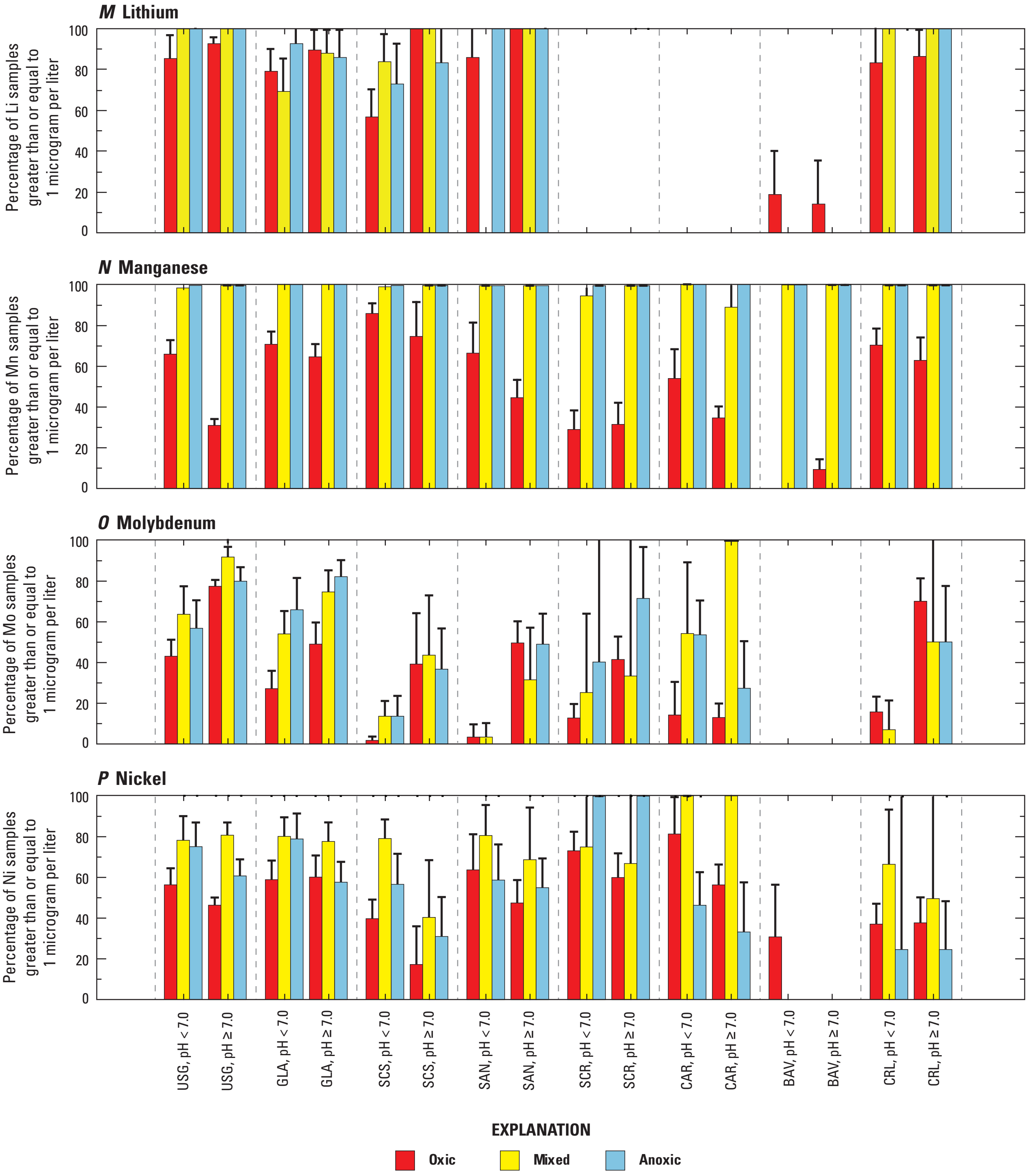

Figure 8. The percentage of groundwater samples with trace-element concentrations greater than or equal to the reporting level, by redox and pH categories, for the major aquifer groups: *(A)* aluminum, *(B)* antimony, *(C)* arsenic, *(D)* barium, *(E)* beryllium, *(F)* boron, *(G)* cadmium, *(H)* chromium, *(I)* cobalt, *(J)* copper, *(K)* iron, *(L)* lead, *(M)* lithium, *(N)* manganese, *(O)* molybdenum, *(P)* nickel, *(Q)* radon, *(R)* selenium, *(S)* silver, *(T)* strontium, *(U)* thallium, *(V)* uranium, *(W)* vanadium, and *(X)* zinc. Reporting level is 1 microgram per liter unless otherwise noted. USG, unconsolidated sand and gravel aquifers; GLA, glacial unconsolidated sand and gravel aquifers; SCS, semiconsolidated sand aquifers; SAN, sandstone aquifers; SCR, sandstone and carbonate-rock aquifers; CAR, carbonate-rock aquifers; BAV, basaltic- and other volcanic-rock aquifers; and CRL, crystalline-rock aquifers. Error bars represent the 95-percent confidence interval of the mean (binomial distribution). See appendix 4 for the number of samples in each category.—Continued

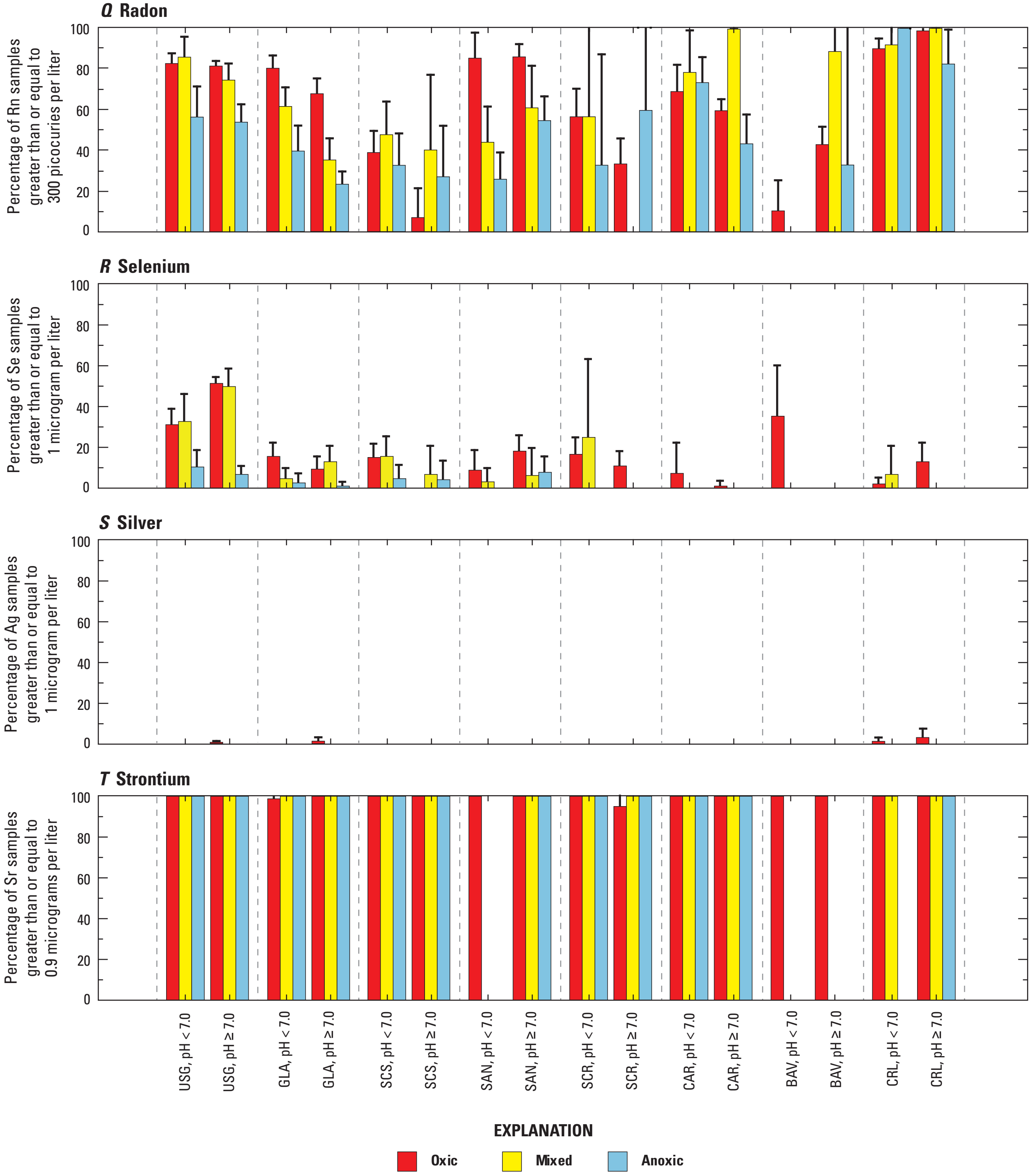

Figure 8. The percentage of groundwater samples with trace-element concentrations greater than or equal to the reporting level, by redox and pH categories, for the major aquifer groups: *(A)* aluminum, *(B)* antimony, *(C)* arsenic, *(D)* barium, *(E)* beryllium, *(F)* boron, *(G)* cadmium, *(H)* chromium, *(I)* cobalt, *(J)* copper, *(K)* iron, *(L)* lead, *(M)* lithium, *(N)* manganese, *(O)* molybdenum, *(P)* nickel, *(Q)* radon, *(R)* selenium, *(S)* silver, *(T)* strontium, *(U)* thallium, *(V)* uranium, *(W)* vanadium, and *(X)* zinc. Reporting level is 1 microgram per liter unless otherwise noted. USG, unconsolidated sand and gravel aquifers; GLA, glacial unconsolidated sand and gravel aquifers; SCS, semiconsolidated sand aquifers; SAN, sandstone aquifers; SCR, sandstone and carbonate-rock aquifers; CAR, carbonate-rock aquifers; BAV, basaltic- and other volcanic-rock aquifers; and CRL, crystalline-rock aquifers. Error bars represent the 95-percent confidence interval of the mean (binomial distribution). See appendix 4 for the number of samples in each category.—Continued

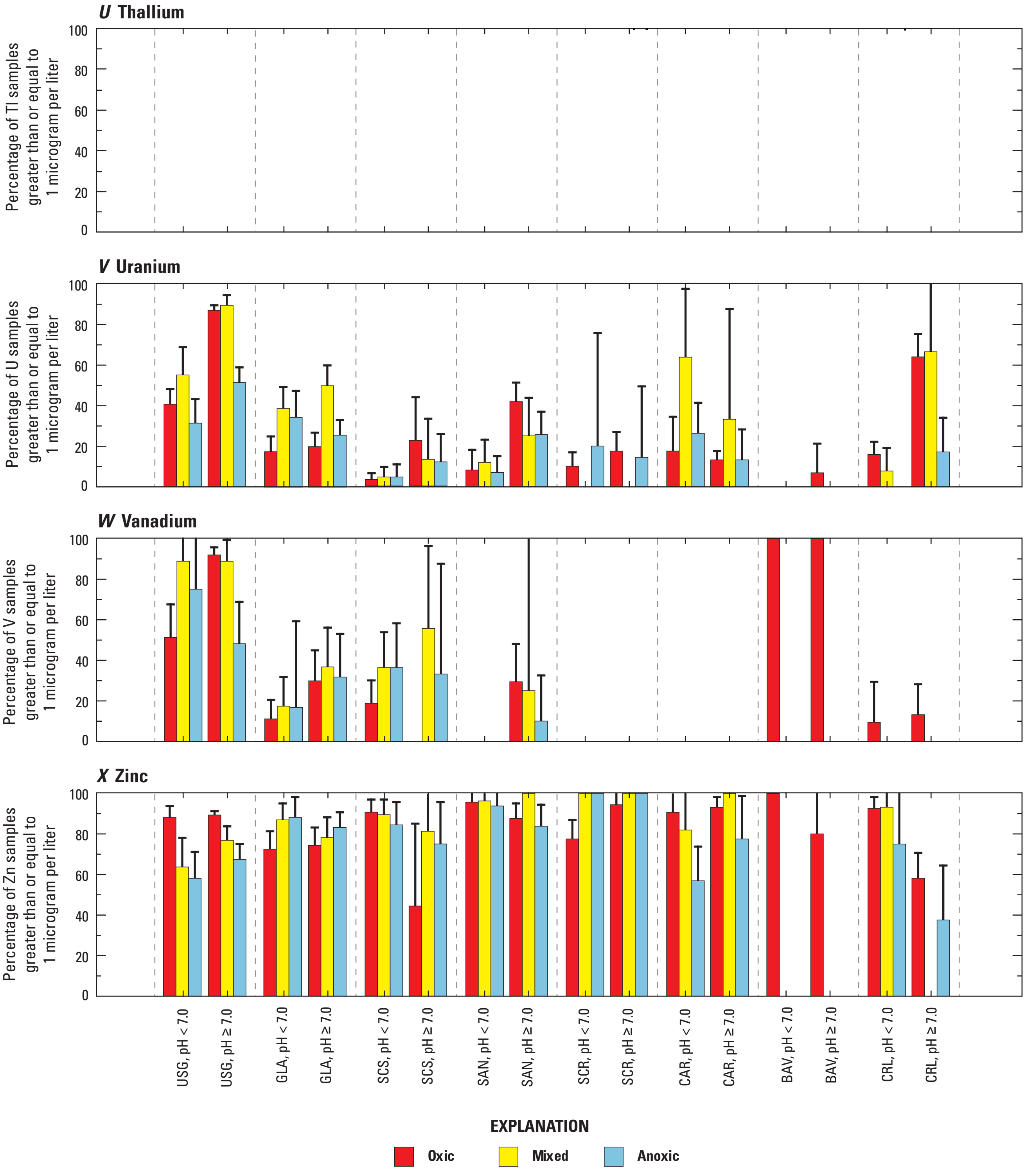

Figure 8. The percentage of groundwater samples with trace-element concentrations greater than or equal to the reporting level, by redox and pH categories, for the major aquifer groups: *(A)* aluminum, *(B)* antimony, *(C)* arsenic, *(D)* barium, *(E)* beryllium, *(F)* boron, *(G)* cadmium, *(H)* chromium, *(I)* cobalt, *(J)* copper, *(K)* iron, *(L)* lead, *(M)* lithium, *(N)* manganese, *(O)* molybdenum, *(P)* nickel, *(Q)* radon, *(R)* selenium, *(S)* silver, *(T)* strontium, *(U)* thallium, *(V)* uranium, *(W)* vanadium, and *(X)* zinc. Reporting level is 1 microgram per liter unless otherwise noted. USG, unconsolidated sand and gravel aquifers; GLA, glacial unconsolidated sand and gravel aquifers; SCS, semiconsolidated sand aquifers; SAN, sandstone aquifers; SCR, sandstone and carbonate-rock aquifers; CAR, carbonate-rock aquifers; BAV, basaltic- and other volcanic-rock aquifers; and CRL, crystalline-rock aquifers. Error bars represent the 95-percent confidence interval of the mean (binomial distribution). See appendix 4 for the number of samples in each category.—Continued

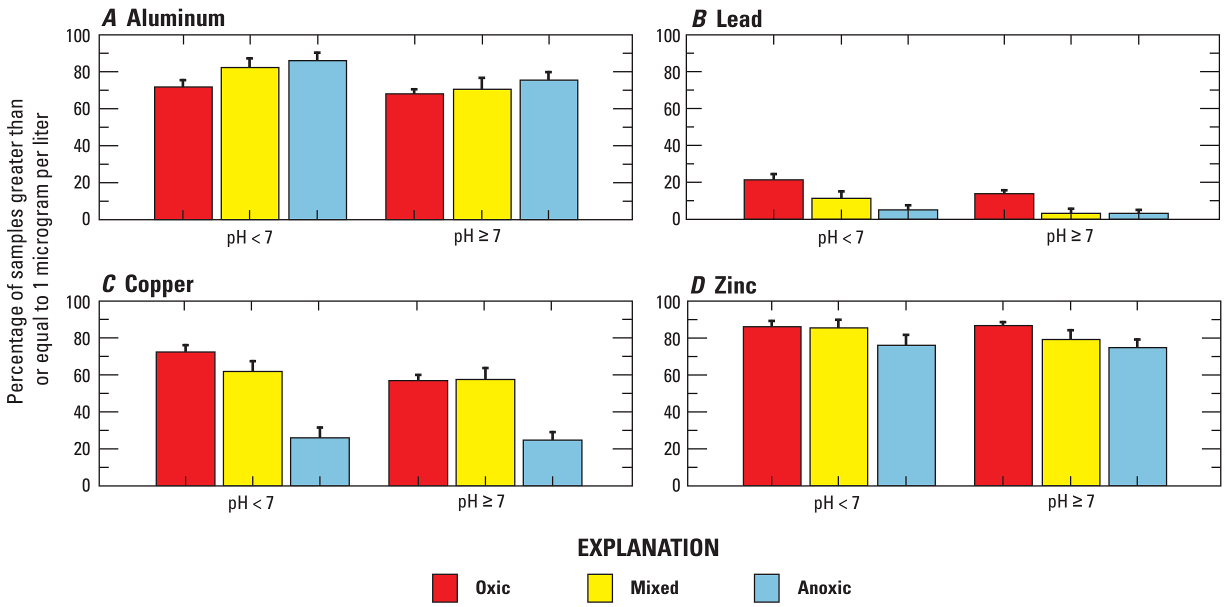

Figure 9. The percentages of groundwater samples with trace-element concentrations greater than or equal to 1 microgram per liter for *(A)* aluminum, *(B)* lead, *(C)* copper, and *(D)* zinc, by pH and redox category. Error bars represent the 95-percent confidence interval of the mean (binomial distribution). <, less than; ≥, greater than or equal to.

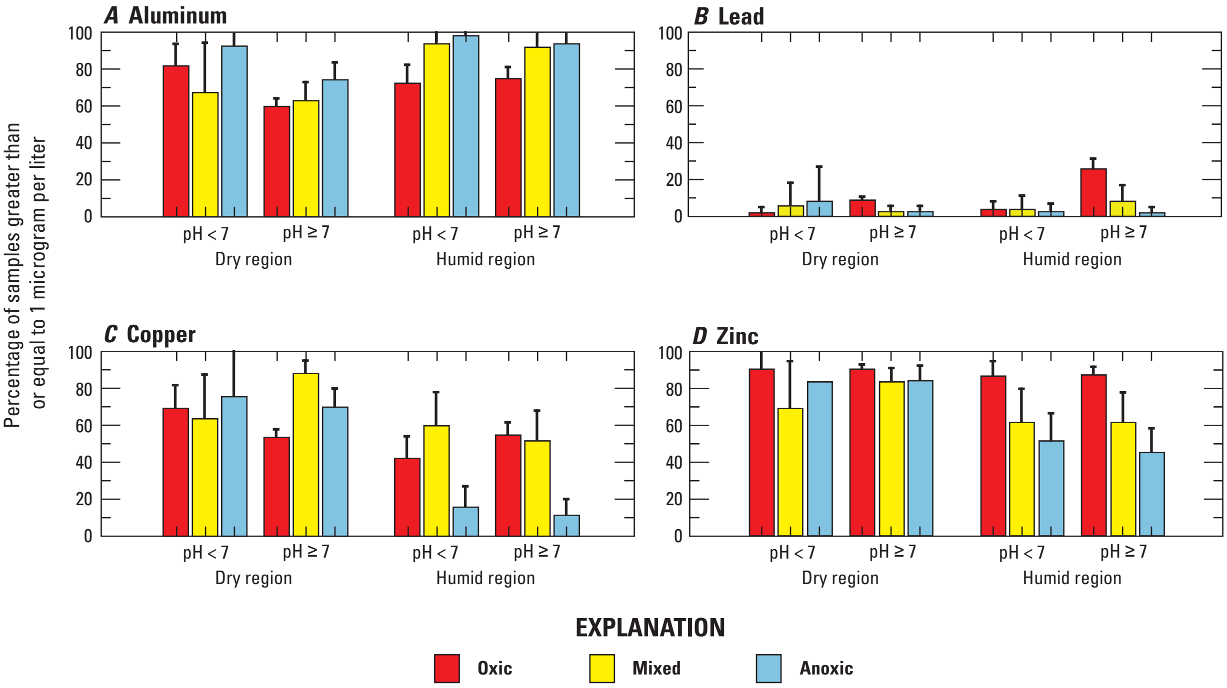

Figure 10. The percentages of groundwater samples with trace-element concentrations greater than or equal to 1 microgram per liter for *(A)* aluminum, *(B)* lead, *(C)* copper, and *(D)* zinc in dry- and humid-region unconsolidated sand and gravel aquifers. Error bars represent the 95-percent confidence interval of the mean (binomial distribution). <, less than; ≥, greater than or equal to.

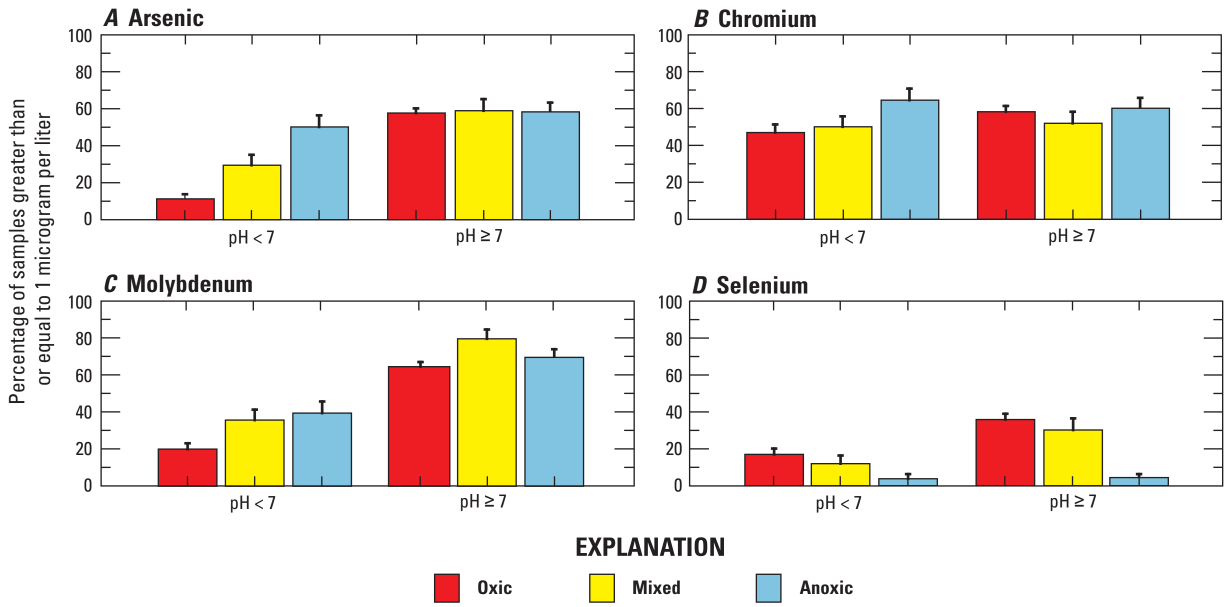

Figure 11. The percentages of samples with trace-element concentrations greater than or equal to 1 microgram per liter for *(A)* arsenic, *(B)* chromium, *(C)* molybdenum, and *(D)* selenium, by pH and redox category. Error bars represent the 95-percent confidence interval of the mean (binomial distribution). <, less than; ≥, greater than or equal to.

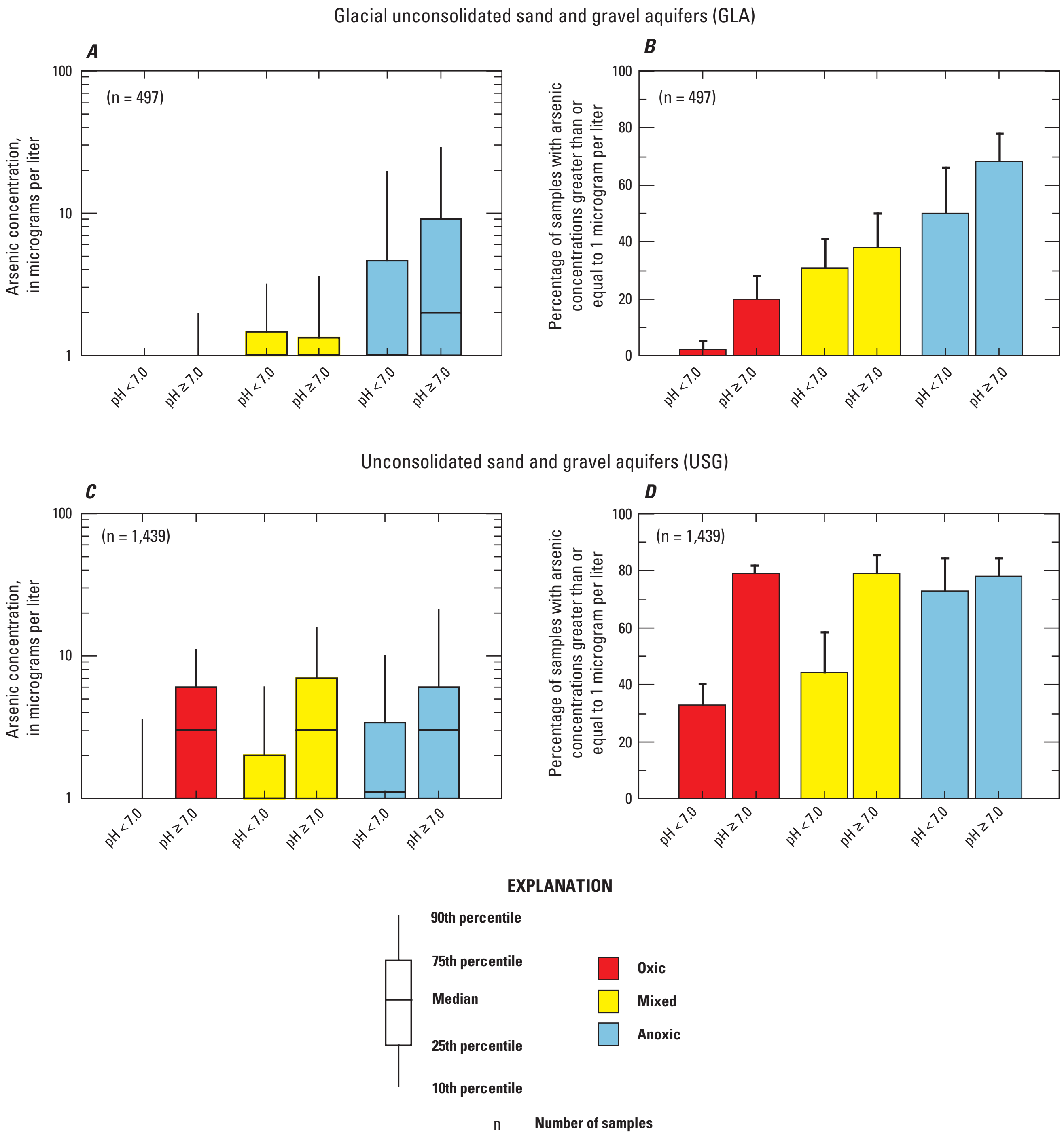

Figure 12. *(A)* Concentrations of arsenic in glacial unconsolidated sand and gravel aquifers (GLA), *(B)* percentages of samples with arsenic concentrations greater than or equal to 1 microgram per liter in GLA aquifers, *(C)* concentrations of arsenic in unconsolidated sand and gravel aquifers (USG), and *(D)* percentages of samples with arsenic concentrations greater than or equal to 1 microgram per liter in USG aquifers. Error bars represent the 95-percent confidence intervals of the mean (binomial distribution).

Relation to Groundwater Age

The occurrence of trace elements in groundwater is related to the length of time that the water has been in contact with the soil and underlying aquifer materials—that is, the time elapsed since recharge. In this analysis, the presence of tritium above the common reporting level of 2.5 pCi/L was considered to indicate that at least some young groundwater was present in the sample. Groundwater samples with tritium activities less than or equal to 2.5 pCi/L are interpreted as containing water predominantly recharged before 1953. In general, old groundwater tends to come from deeper wells with higher pH and lower DO (figs. 13A–C). These factors are generally associated with deep, long flow paths and long contact time between groundwater and aquifer materials.

Most oxyanion-forming trace elements have greater rates of occurrence in old waters (fig. 14) and can serve as markers of chemical evolution. Fe and Mn also occurred more frequently in older waters, although their occurrence was greater in samples collected from humid-region aquifers. U, which commonly forms soluble complexes under oxic and variable-pH conditions, occurred more frequently in samples collected from older water in the dry-region aquifers, but in humid-region aquifers, U occurred more often in young water. This may be indicative of processes that favor U solubility and mobility, such as oxic conditions. In dry regions, ion competition, evaporative concentration, and complexation with bicarbonate and sulfate may be controlling factors (Seiler and others, 2003), whereas in humid regions, deeper, older waters are more often anoxic and may inhibit U mobility. Alternatively, in humid regions, the generally low-pH recharge may more readily dissolve U-bearing minerals in the aquifer matrix.

Al and Ni behave as expected for metals soluble at low pH and under oxic conditions and occurred more frequently in samples of young groundwater, especially in the dry-region aquifers. Based on a small number of samples from the USG aquifer group, B occurrence appeared independent of groundwater age.

Analysis of Multiple Factors Affecting Trace-Element Occurrence

Potential factors affecting the distribution of selected trace elements, most of which are known to have human-health implications, were investigated by using logistic regression. Elements were selected for logistic regression analyses on the basis of the rates of exceedences of HHBs and nonhealth guidelines; in most cases, models were developed for elements that occurred at concentrations greater than benchmarks or guidelines in at least 1 percent of the samples in any given aquifer group (table 10). The elements modeled (as a dependent variable) included Al, As, B, Fe, Mn, Mo, Ni, Rn, Se, Sr, and U (table 11). The number of modeled elements differed among aquifer groups because the occurrence of some elements may have been too low to model, as was the case for B in the SCR, CAR, and CRL aquifer groups. Independent variables used in this analysis included other trace elements, DO, nitrate, ammonia, Mn, Fe, sulfate, pH, phosphate, major-ion chemistry, and well depth.

The analysis was designed to identify factors related to trace-element occurrence and mobility and to identify co-occurrence and nonoccurrence among selected trace elements. Trace-element concentrations were modeled as binary variables because a large proportion of samples for most trace elements had concentrations reported as less than the LRL (or multiple LRLs). This approach allowed the data to be used directly without modification.

In general, the models corroborate the findings comparing trace-element occurrence with redox and pH. For some elements, only the pH or the redox variable was significant, possibly indicating the dominance of one control over another. Some variation in the number of variables also is likely among aquifer groups because of the number of samples collected from any given aquifer group. Variation in the identified explanatory variables also may be influenced to some degree by which trace elements were measured for any given sample.

Several explanatory variables were either positive or negative covariates with the modeled dependent variables, indicating that these covariates tended to co-occur or not co-occur with the modeled trace element. In some cases, different variables representing similar processes (for example, low DO compared to the presence of Fe) were selected for a given model on the basis of model-performance statistics. Because of the effect of climate, separate models were generated for humid-region unconsolidated sand and gravel samples (USGH) and dry-region unconsolidated sand and gravel samples (USGD). The variables associated with occurrence for the selected trace elements are shown by aquifer group in table 11. The models are summarized by the type of independent variable, and independent variables are arranged by groups (anions and ion complexes, cations, and other); correlations are indicated as positive or negative. More quantitative results for these models by aquifer group are shown in appendix 5.

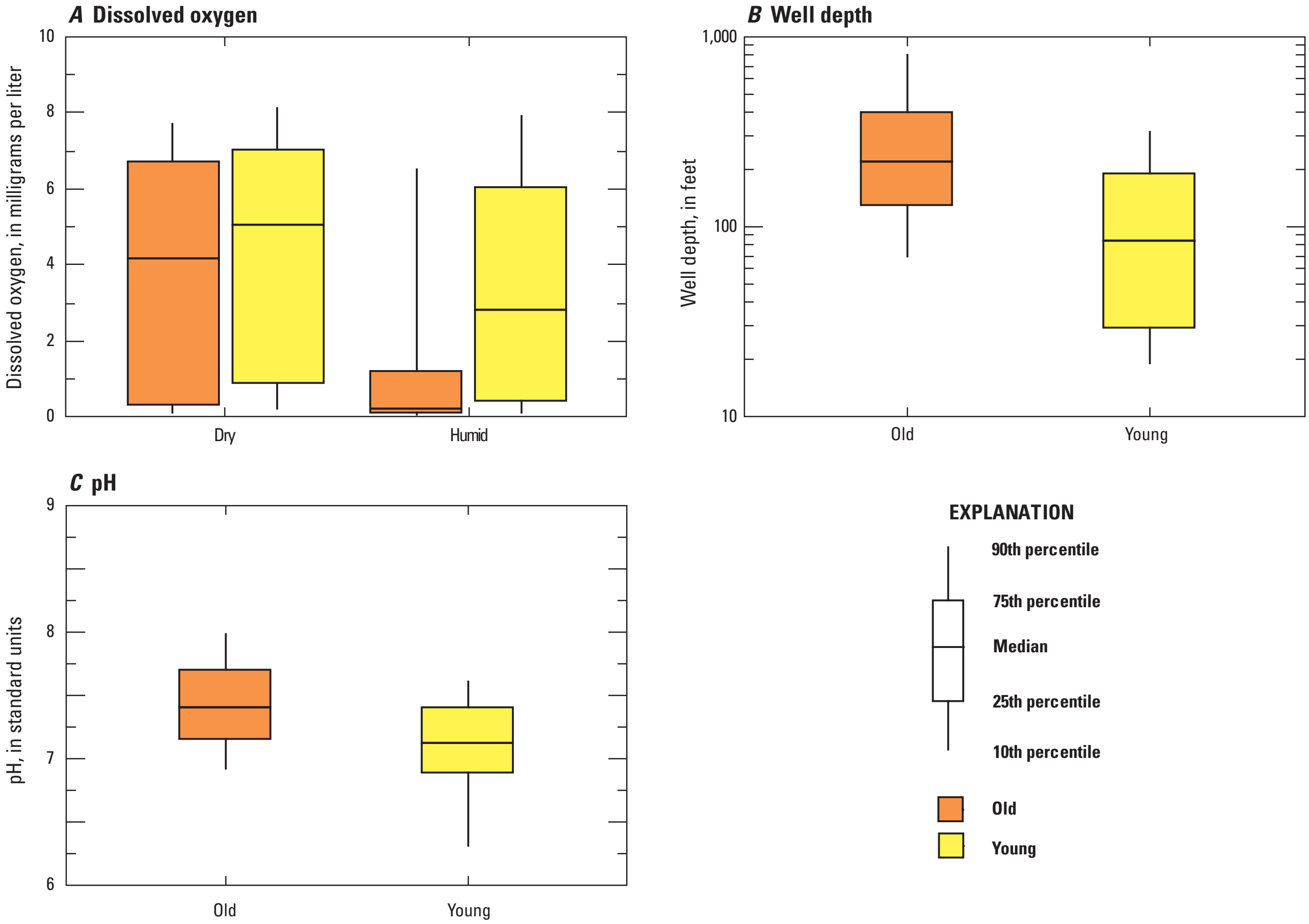

Figure 13. The distribution of *(A)* dissolved oxygen, *(B)* well depth, and *(C)* pH in groundwater samples by category of age of recharge. "Old" refers to water samples recharged prior to 1953 (tritium activity less than or equal to 2.5 picocuries per liter), and "Young" refers to samples with at least some fraction of water recharged after 1953 (tritium activity greater than 2.5 picocuries per liter).

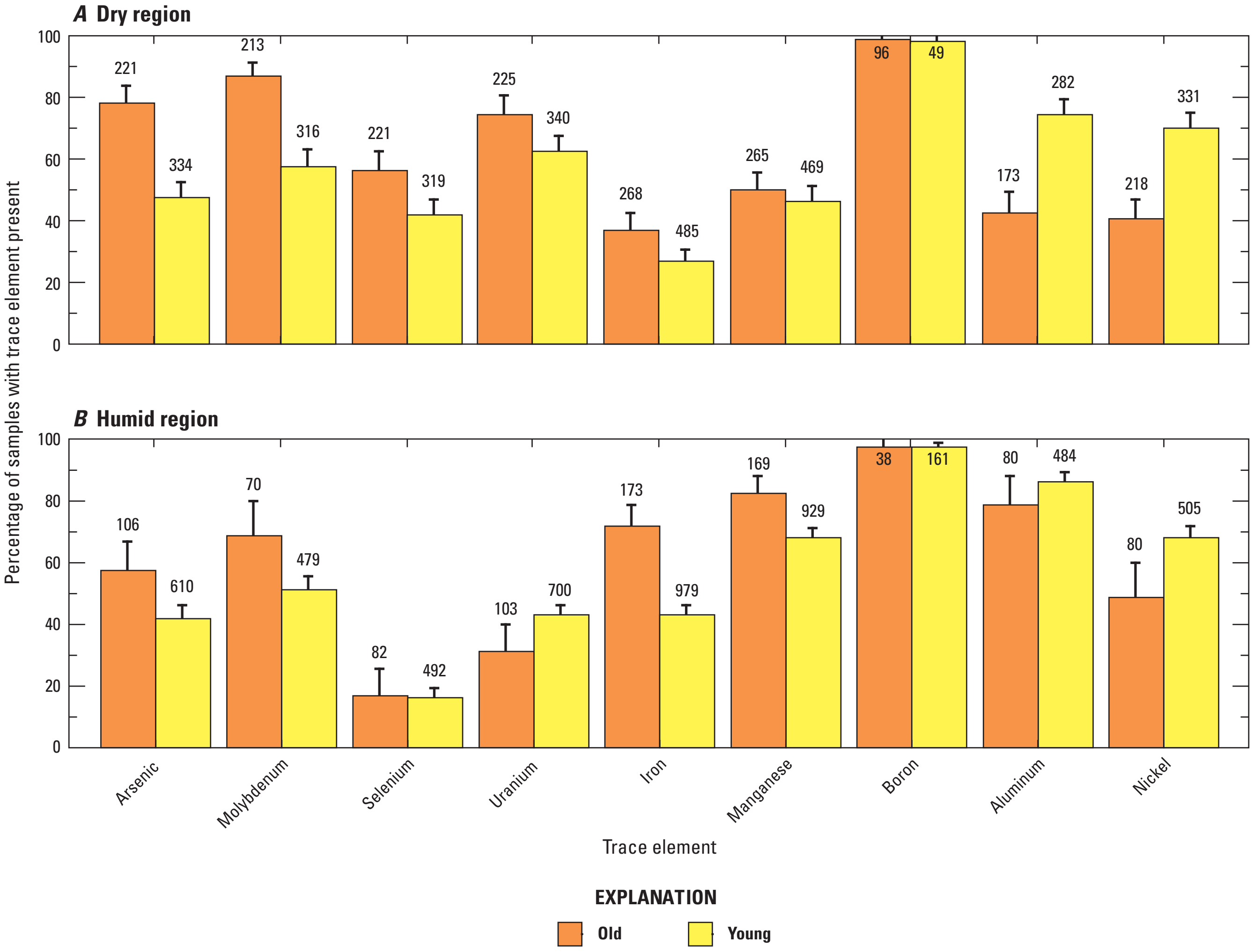

Figure 14. Percentages of groundwater samples with trace-element concentrations greater than or equal to 1 microgram per liter (µg/L) (300 µg/L for iron and 50 µg/L for manganese) by category of age of recharge for samples from *(A)* dry and *(B)* humid regions. Number above bar is number of samples. "Old" refers to water recharged prior to 1953 (tritium activity less than or equal to 2.5 picocuries per liter), and "Young" refers to water with at least some fraction of water recharged after 1953 (tritium activity greater than 2.5 picocuries per liter). Error bars represent the 95-percent confidence interval of the mean (binomial distribution).

Table 11. Summary of logistic regression models for selected trace elements in groundwater sampled for the NAWQA Program across the United States by element and major aquifer group, 1992–2003.

[USG, unconsolidated sand and gravel; GLA, glacial unconsolidated sand and gravel; SCS, semiconsolidated sand; SAN, sandstone; SCR, sandstone and carbonate rock; CAR, carbonate rock; BAV, basaltic and volcanic rock; CRL, crystalline rock; B, binary; N, continuous; +, positive covariate; -, negative covariate; yellow shading indicates anions and ion complexes; blue shading indicates cations; green shading indicates other correlates]

Dependent variable	Explanatory variable	Type of variable	Major aquifer group								
			USG dry	USG humid	GLA	SCS	SAN	SCR	CAR	BAV	CRL
Aluminum	Chromium	B	+	+	+		+	+			+
	Phosphate	B	+				-				
	Arsenic	B		+							
	Bromide	B					-				
	Fluoride	B		-							
	Selenium	B	-								
	Sulfate	N							-		
	Nickel	B	+	+	+	+	+				
	Calcium	N		-				-	+		
	Nitrogen as ammonia	B		+		+	+				
	Silica	N	-			-					-
	Copper	B						+	+		
	Iron	B			-	+					
	Manganese	B			+			+			
	Lead	B	+								
	Magnesium	N							-		
	Sodium	N						+			
	Zinc	B						+			
	pH	N			-	-				-	-
	Dissolved oxygen	N	-	-						+	
	Well depth	N				-					
	Radon	B	+								
	Temperature	N									+
Arsenic	Molybdenum	B			+	+	+	+	+		
	Uranium	B		+	+		-				
	Phosphate	B		+							
	Sulfate	N								+	
	Silica	N	+	+	+	+	+				
	Aluminum	B		+							
	Barium	B									-
	Boron	B	+								
	Cobalt	B				+					
	Copper	B		-							
	Nickel	B									+
	Potassium	N		+							
	Zinc	B						-			
	pH	N	+	+	+					+	+
	Dissolved oxygen	N			-	-					-
	Temperature	N						-	+		
	Radon	B								+	
	Well depth	N			+						

Table 11. Summary of logistic regression models for selected trace elements in groundwater sampled for the NAWQA Program across the United States by element and major aquifer group, 1992–2003.—Continued

[USG, unconsolidated sand and gravel; GLA, glacial unconsolidated sand and gravel; SCS, semiconsolidated sand; SAN, sandstone; SCR, sandstone and carbonate rock; CAR, carbonate rock; BAV, basaltic and volcanic rock; CRL, crystalline rock; B, binary; N, continuous; +, positive covariate; -, negative covariate; yellow shading indicates anions and ion complexes; blue shading indicates cations; green shading indicates other correlates]

Dependent variable	Explanatory variable	Type of variable	Major aquifer group								
			USG dry	USG humid	GLA	SCS	SAN	SCR	CAR	BAV	CRL
Boron	Molybdenum	B		+	+						
	Arsenic	B	+								
	Bromide	B			+						
	Phosphate	B									
	Sulfate	N								+	
	Uranium	B									
	Aluminum	B		+							
	Magnesium	N				+					
	Potassium	N			+						
	Silica	N									
	Sodium	N					+				
	Total dissolved solids	N	+	+						-	
	pH	N			+	+					
	Dissolved oxygen	N				-					
	Temperature	N			+						
	Well depth	N									
Iron	Nitrate	B	-	-		-					-
	Uranium	B	-		-	-					-
	Arsenic	B					+		+		
	Molybdenum	B					-		+		
	Chromium	B			-						
	Sulfate	N						+			
	Copper	B			-			-	-		
	Manganese	B	+					+			+
	Nitrogen as ammonia	B					+				
	Sodium	N					-				
	Dissolved oxygen	N	-	-	-	-	-			-	-
	pH	N	-	-	-		-			-	
	Well depth	N	+		+				-		-
	Radon	B			-						
	Total dissolved solids	N			+						
Manganese	Chromium	B				-		-			
	Nitrate	B			-		-				
	Arsenic	B			+						
	Sulfate	N							+		
	Uranium	B			+						
	Phosphate	B				+					
	Iron	B			+		+	+	+		+
	Copper	B		-			-				
	Zinc	B				+					-
	Aluminum	B									-
	Barium	B							+		

Table 11. Summary of logistic regression models for selected trace elements in groundwater sampled for the NAWQA Program across the United States by element and major aquifer group, 1992–2003.—Continued

[USG, unconsolidated sand and gravel; GLA, glacial unconsolidated sand and gravel; SCS, semiconsolidated sand; SAN, sandstone; SCR, sandstone and carbonate rock; CAR, carbonate rock; BAV, basaltic and volcanic rock; CRL, crystalline rock; B, binary; N, continuous; +, positive covariate; -, negative covariate; yellow shading indicates anions and ion complexes; blue shading indicates cations; green shading indicates other correlates]

Dependent variable	Explanatory variable	Type of variable	Major aquifer group								
			USG dry	USG humid	GLA	SCS	SAN	SCR	CAR	BAV	CRL
Manganese-Cont.	Cobalt	B			+						
	Lead	B							-		
	Nickel	B	+								
	Dissolved oxygen	N	-	-	-	-			-	-	-
	pH	N		+	-		-				-
	Well depth	N	-	-	-	-					
	Radon	B						-			
	Total dissolved solids	N					+				
	Temperature	N						-			
Molybdenum	Arsenic	B	+		+	+	+		+		
	Fluoride	B	+	+	+						+
	Uranium	B	+	+			+				+
	Bromide	B			-		+				
	Chromium	B		-							
	Nitrate	B							-		
	Selenium	B	+								
	Sulfate	N							+		
	Manganese	B	+	+	+						
	Silica	N		-	-						
	Aluminum	B		+							
	Iron	B									-
	Nickel	B			+						
	Zinc	B							+		
	pH	N	+		+	+	+				+
	Dissolved oxygen	N	-		-						
	Total dissolved solids	N		+		+					
	Well depth	N		+			+				
	Specific conductance	N			+						
	Radon	B				+			+		
Nickel	Bromide	B							-		+
	Chromium	B		+		+					
	Molybdenum	B			+						
	Nitrate	B							+		
	Selenium	B		-							
	Uranium	B	+								
	Aluminum	B	+	+	+		+				
	Cobalt	B		+	+	+					
	Copper	B	+				+				+
	Silica	N					+		-		-
	Zinc	B			+		+	+			
	Manganese	B				+	+				

Table 11. Summary of logistic regression models for selected trace elements in groundwater sampled for the NAWQA Program across the United States by element and major aquifer group, 1992–2003.—Continued

[USG, unconsolidated sand and gravel; GLA, glacial unconsolidated sand and gravel; SCS, semiconsolidated sand; SAN, sandstone; SCR, sandstone and carbonate rock; CAR, carbonate rock; BAV, basaltic and volcanic rock; CRL, crystalline rock; B, binary; N, continuous; +, positive covariate; -, negative covariate; yellow shading indicates anions and ion complexes; blue shading indicates cations; green shading indicates other correlates]

Dependent variable	Explanatory variable	Type of variable	Major aquifer group								
			USG dry	USG humid	GLA	SCS	SAN	SCR	CAR	BAV	CRL
Nickel-Cont.	Nitrogen as ammonia	B		-					-		
	Sodium	N		+				-			
	Calcium	N					+				
	Iron	B				-					
	Magnesium	N									-
	Potassium	N									+
	pH	N	-	-				-			-
	Specific conductance	N					-	+	+		
	Total dissolved solids	N	+			+					
	Temperature	N		+							
	Well depth	N					+				
Radon	Molybdenum	B			-	+	+		+		
	Nitrate	B	-		+	+	+				
	Sulfate	N			-				-		-
	Arsenic	B			-						-
	Chromium	B		-	-						
	Uranium	B		+							+
	Bromide	B	+								
	Fluoride	B			+						
	Phosphate	B					-				
	Selenium	B						+			
	Iron	B			-			+			
	Cobalt	B			+						
	Lead	B									+
	Silica	N						-			
	Manganese	B		-							
	pH	N	+		-				-		
	Temperature	N					-	-			-
	Dissolved oxygen	N		+						-	
	Specific conductance	N						-			
	Tritium	B	+								
	Well depth	N		-							
Selenium	Uranium	B	+	+	+		+	+			
	Nitrate	B	+		+	+					
	Arsenic	B				+		+			
	Sulfate	N								+	
	Bromide	B	+								
	Fluoride	B	+								
	Molybdenum	B	+								
	Iron	B	-			-	-				
	Manganese	B	-		-						

Table 11. Summary of logistic regression models for selected trace elements in groundwater sampled for the NAWQA Program across the United States by element and major aquifer group, 1992–2003.—Continued

[USG, unconsolidated sand and gravel; GLA, glacial unconsolidated sand and gravel; SCS, semiconsolidated sand; SAN, sandstone; SCR, sandstone and carbonate rock; CAR, carbonate rock; BAV, basaltic and volcanic rock; CRL, crystalline rock; B, binary; N, continuous; +, positive covariate; -, negative covariate; yellow shading indicates anions and ion complexes; blue shading indicates cations; green shading indicates other correlates]

Dependent variable	Explanatory variable	Type of variable	Major aquifer group								
			USG dry	USG humid	GLA	SCS	SAN	SCR	CAR	BAV	CRL
Selenium-Cont.	Aluminum	B	-								
	Sodium	N					+				
	pH	N								-	
	Total dissolved solids	N		+		+					
	Well depth	N	+	+							
	Specific conductance	N	+								
	Dissolved oxygen	N						+			
Strontium	Molybdenum	B									+
	Sulfate	N						+			
	Uranium	B			+						
	Calcium	N			+						+
	Manganese	B			-						
	Sodium	N			+						
	Specific conductance	N	+	+							
	Dissolved oxygen	N			-				-		
	Total dissolved solids	N				+	+				
	pH	N							-		
Uranium	Molybdenum	B	+	+		+	+	+			+
	Selenium	B	+		+			+			
	Arsenic	B		+					+		
	Bicarbonate	N				+		+			
	Fluoride	B			+						+
	Nitrate	B		+							-
	Phosphate	B	-						-		
	Chromium	B	+								
	Sulfate	N				+					
	Nitrogen as ammonia	B	-	-		-	-				
	Iron	B	-	-							-
	Calcium	N						+			+
	Copper	B	+	+							
	Nickel	B			+				+		
	Silica	N		-	-						
	Lead	B									+
	Magnesium	N			+		+				
	Manganese	B			+						
	Potassium	N							+		
	Total dissolved solids	N	+	+							
	Dissolved oxygen	N							-		
	pH	N		+							
	Well depth	N			-						

Cationic Elements

Low pH was a significant factor in the occurrences of many cationic metals such as Al, Fe, Mn, and Ni. In general, these metals, as well as Cu, Pb, and Zn, adsorb more strongly to aquifer materials as pH increases (McLean and Bledsoe, 1992; Salbu and Steinnes, 1994). Because of the similarity in behavior, many of these metals co-occurred in the samples used in this study. For example, Al covaried with Ni in groundwater from five of nine aquifer groups. Al covariation with Ni was generally found in aquifer groups with greater proportions of samples having anoxic conditions. Nitrogen as ammonia (an indicator of anoxic conditions) co-occurred with Al in the USGH, SCS, and SAN aquifer groups, whereas silica was inversely related to Al in the USGD, SCS, and CRL aquifer groups. In general, low pH was a strong geochemical predictor of groundwater Al occurrence, affecting the GLA, SCS, BAV, and CRL aquifer-group samples.

These findings are partly corroborated by analysis of the most significant covariates for Al across all aquifer groups. The percentage of samples with Al concentrations greater than or equal to 1 µg/L is less than 40 from samples collected from old water and without concentrations of Ni or Cr greater than or equal to 20 and 1 µg/L, respectively (fig. 15A). This percentage increases with the co-occurrence of Cr and Ni, but relations also are strengthened by the presence of young water (recharged after 1953) as compared to water that was recharged before 1953 (fig. 15A). Al concentrations in samples from wells in the SCR aquifer group varied with cations such as Cu, Mn, Na, and Zn (table 11). Al in groundwater samples from the GLA, SCS, and SAN aquifer groups covaried with elements or compounds common in anoxic conditions, such as Ni, nitrogen as ammonia, Fe, and Mn. Concentrations of Al in groundwater samples from the USGD and USGH aquifer groups, however, correlated directly with low-DO conditions.

Models for Fe occurrence from eight of the nine aquifer groups indicate that it was controlled primarily by low DO in the water samples (table 11) and by low pH (five of the nine groups). Only samples from the CAR aquifer group did not have DO, pH, or both as variables correlated with Fe. Fe and Mn, although often thought of as co-occurring, exhibit complex behavior that does not necessarily lead to co-occurrence. Models for Fe (at concentrations greater than or equal to 300 µg/L) showed co-occurrence with Mn (at concentrations greater than or equal to 50 µg/L) only in samples collected from the USGD and SCR aquifer groups, and Fe was inversely related to Mn in the CRL group. By contrast, Mn varied with Fe in models for five of the nine aquifer groups (table 11). Overall, Fe occurrence was controlled by both redox (DO) and pH, but redox appeared to control Mn occurrence more than pH. The models for Fe and Mn indicate that high Fe predicted the presence of high Mn, but the converse was not as often true. Thus, Mn occurred with Fe, but Fe generally occurred without reduced Mn. This result is consistent with the thermodynamic sequence of redox progression, whereby Mn is reduced first, followed by Fe (Froelich and others, 1979; McMahon and Chapelle, 2008), and also can be seen in the graph of Mn occurrence (greater than or equal to 50 µg/L) by categories of DO, pH, and Fe (fig. 15B).

The percentage of groundwater samples with Fe greater than or equal to 300 µg/L decreased if DO was greater than or equal to 1 mg/L, and pH was greater than or equal to 7, conditions under which Fe is relatively insoluble (fig. 15C). In addition, samples characterized as young water had less Fe than samples characterized as old water. Similarly, the percentage of samples with Mn decreased from about 90 to less than 30 as pH and DO increased (fig. 15B); however, Mn occurrence at concentrations of greater than or equal to 50 µg/L was consistently high (more than 90 percent of samples) and appeared independent of pH and DO in samples with 300 µg/L or more of Fe (fig. 15B). Low pH and low DO, as with Fe, are strong indicators of high Mn. Fe also inversely covaried with nitrate, U, or both in the USGD, USGH, GLA, SCS, and CRL aquifer groups. For water samples in the SAN and CAR aquifer groups, Fe covaried with As. Mn covaried with As and U (GLA) and with Ba (CAR), Co (GLA), Ni (USGD), and Zn (SCS) (table 11).

Ni occurrence covaried with several trace elements, and most often was related to low pH (USGD, USGH, and SCR, and CRL aquifer groups) or with factors associated with low pH, such as the presence of Al, Co, Cu, and Zn (table 11). The percentage of samples with Ni was consistently high (greater than 90 percent) when Co was present (fig. 15D).

Oxyanion- and Ion-Complex-Forming Elements

Models for oxyanion- and ion-complex-forming elements also were influenced by pH and redox variables. Unlike the cationic metals, however, increases in pH generally result in increased desorption of oxyanion-forming elements from aquifer materials, thus increasing the solubility of those metals. In particular, As and Mo occurred most often in high-pH conditions (five of nine aquifer groups in table 11).

Arsenic occurrence covaried with silica (USGD, USGH, GLA, SAN, and SCS aquifer groups), Mo (GLA, SCS, SAN, SCR, and CAR aquifer groups), and high pH (USGD, USGH, GLA, BAV, and CRL aquifer groups) (table 11). The percentage of samples with As concentrations greater than or equal to 1 µg/L and with low Mo and silica concentrations was about 12. This percentage increased to 40 to 45 percent if either Mo or silica were present and increased to about 85 percent if both Mo and silica were present (fig. 16A). The effect of pH on these relations is likely related to increased solubility through desorption, whereby the occurrence of As, associated with Mo or silica, was greater for high-pH samples than for low-pH samples. Arsenic co-occurred with U and phosphate in the USGH and GLA aquifer groups. Thus, competitive sorption also may play a role in the occurrence of As. Low DO correlated with As in the GLA, SCS, and CRL aquifer groups, indicating that in addition to the process of pH-driven desorption, redox may be an important control in some aquifer groups and (or) climates.

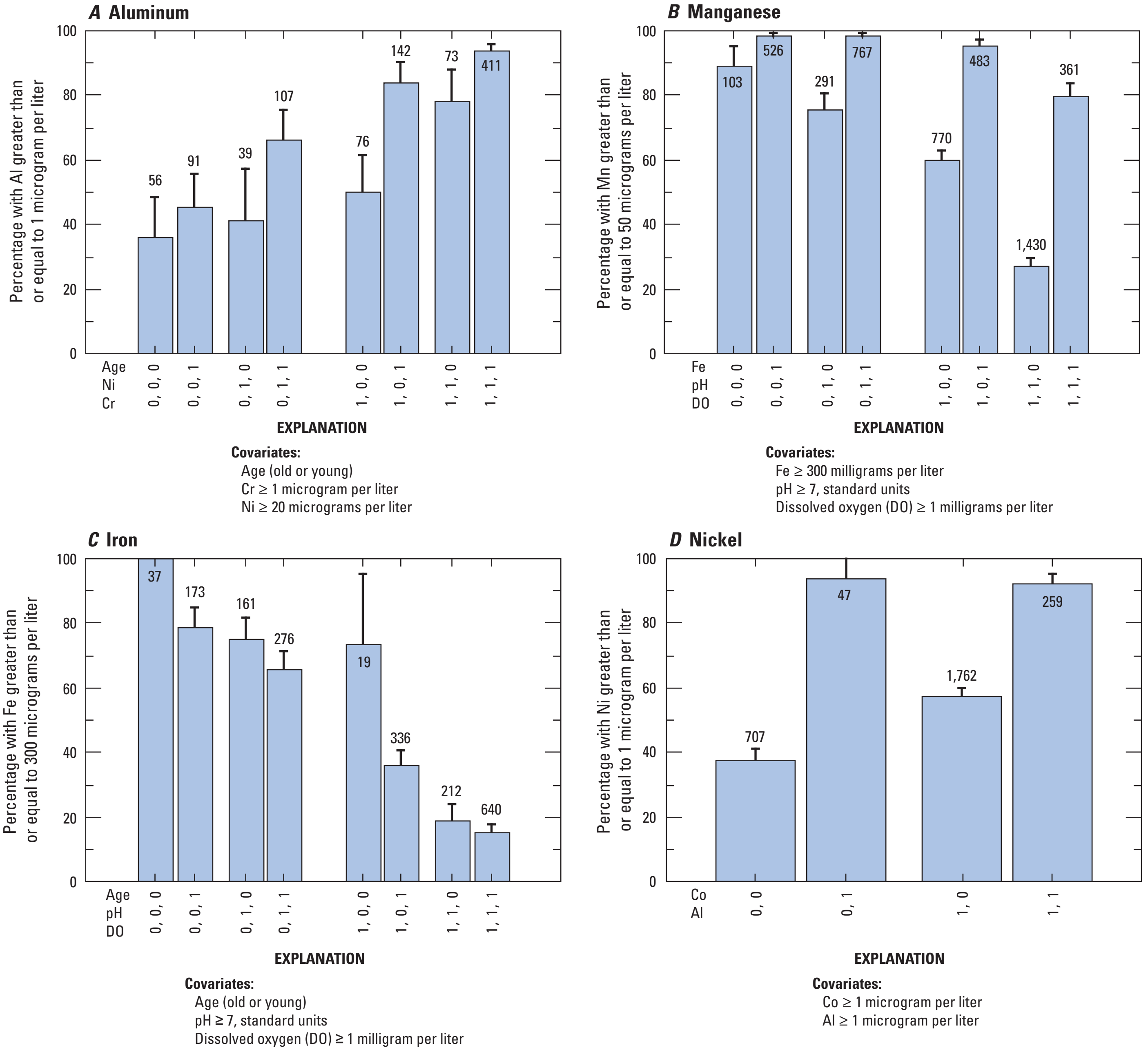

Figure 15. The percentages of groundwater samples with concentrations greater than reporting level for *(A)* aluminum (Al), *(B)* manganese (Mn), *(C)* iron (Fe), and *(D)* nickel (Ni), by major covariates from logistic regression models. Zero (0) indicates nonoccurrence of a covariate, and one (1) indicates occurrence except for age, for which zero is old (pre-1953), and one is young (post-1953) water. Number above bar is number of samples. Reporting level is 1 microgram per liter (µg/L) for aluminum and nickel; 300 µg/L for iron; and 50 µg/L for manganese. Error bars represent 95-percent confidence interval of the mean (binomial distribution). ≥, greater than or equal to; Cr, chromium; Co, cobalt.

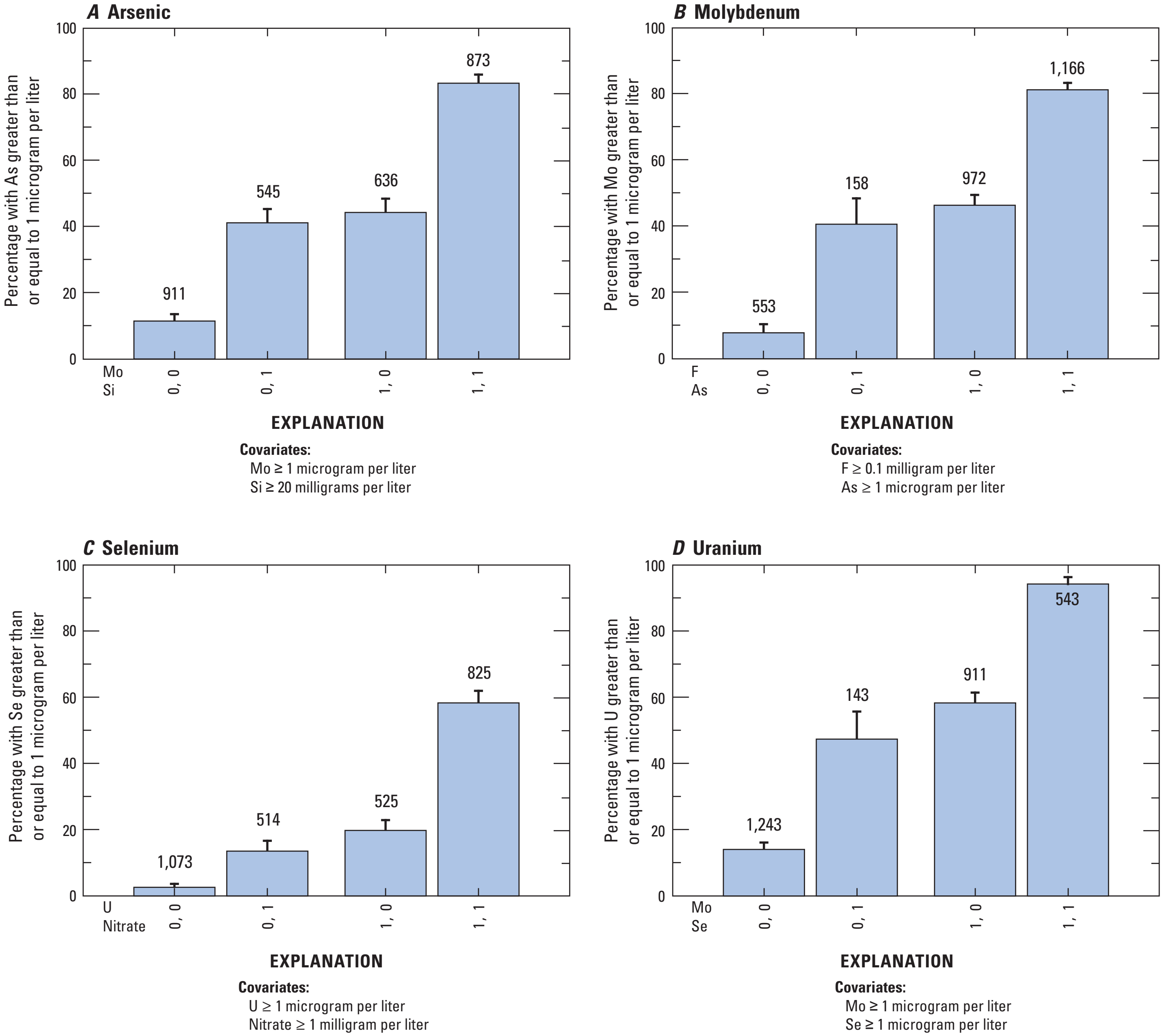

Figure 16. The percentages of groundwater samples with concentrations greater than or equal to 1 microgram per liter for *(A)* arsenic (As), *(B)* molybdenum (Mo), *(C)* selenium (Se), and *(D)* uranium (U), by major covariates from logistic regression models. Zero (0) indicates nonoccurrence of a covariate, and one (1) indicates occurrence. Number above bar is number of samples. Error bars represent the 95-percent confidence interval of the mean (binomial distribution); ≥, greater than or equal to; Si, silicon; F, flouride.

Mo in groundwater co-occurred with several trace elements, such as As, fluoride, Mn, and U. In groundwater from the CRL aquifer group, Mo co-occurred with fluoride, U, and high pH (table 11). These relations may be indicative of granitic lithologies, which are often enriched in these elements and can produce high pH in groundwater (Edmunds and Smedley, 2005). Mo was inversely related to Fe in the CRL aquifer group (table 11). In general, high pH and in some cases low DO or increasing well depth, appeared to provide a strong control for Mo. In samples with less than 0.1 mg/L of fluoride and less than 1 µg/L of As, the percentage with Mo greater than or equal to 1 µg/L was less than 10 (fig. 16B). This percentage increased to 40 to 50 percent if either fluoride or As was present and increased to more than 80 percent if both were present (fig. 16B). The effect of pH on these relations was similar to the effect on As in that the percentage of samples associated with As or silica was greater for high-pH samples than for low pH samples.

Se covaried with combinations of U, As, and nitrate (in the GLA, SAN, SCR, SCS, USGH, and USGD aquifer groups) (table 11). The percentages of samples with concentrations of Se greater than or equal to 1 µg/L increased with the occurrence of either nitrate or U (to about 13 and 20 percent, respectively) and to nearly 60 percent when both were present (fig. 16C). In the USGD aquifer group, Se covaried with bromide, fluoride, and sulfate in addition to U and nitrate. In four of nine aquifer groups, Se covaried inversely with Fe and (or) Mn. Se in groundwater from some aquifer groups also appears to be related to TDS and conductance (table 11).

U was present in about half of all groundwater samples in which it was measured and covaried with more than one ion in most aquifer groups. U covaried with Mo in the USGD, USGH, SCS, SAN, SCR, and CRL aquifer groups (table 11). Se (in the USGD, GLA, SCR, aquifer groups) and As (in the USGH and CAR aquifer groups) also covaried with U, as did complexing ions such as bicarbonate (in the SCS and SCR aquifer groups) and sulfate (in the SCS aquifer group). Fluoride in groundwater samples from the GLA and CRL aquifer groups covaried with U, possibly indicating sources in granitic rocks. The presence of nitrogen as ammonia and Fe in samples, however, was always inversely related to U, possibly indicating sufficiently anoxic conditions to immobilize U. Mo and Se were the most common covarying trace elements in samples from this study and were strongly related to the overall presence of U in the samples. The percentages of samples with U at concentrations greater than or equal to 1 µg/L increased with the co-occurrence of Se (to nearly 60 percent) or Mo (to nearly 50 percent); however, the percentages of samples with U increased to about 95 if both Se and Mo were present (fig. 16D).

The occurrence of trace elements such as As, Mo, Se, and U have been examined in detail in studies of unconsolidated aquifers (Deverel and Millard, 1988; Dubrovsky and others, 1991; Fujii and Swain, 1995; Welch and Lico, 1998; Seiler and others, 2003). In general, these studies found that lithologic sources, redox chemistry, and evaporative concentration were significant processes affecting occurrence. In particular, some Upper Cretaceous marine sedimentary rocks in the western United States appeared to be enriched in Se, U, and other elements (Seiler and others, 2003).

Other Elements

Rn covaried with some elements that are generally mobile under oxic conditions, including U (in the USGH and CRL aquifer groups), bromide (in the USGD aquifer group), fluoride (in the GLA aquifer group), and Se (in the SCR aquifer group). It also co-occurred with Mo in three aquifer groups. However, in the GLA group, Rn was inversely related to most covariates. Rn was generally related to factors indicative of recently recharged groundwater or groundwater from highly transmissive aquifers. These factors include low pH (as in the GLA and CAR aquifer groups), low water temperature (shallow water table), low specific conductance (short residence time), and shallow well depths.

Boron exists predominantly as an uncharged ion in groundwater (Hem, 1985). In this study, B frequently occurred in samples from the major aquifer groups, but exceedences of HHBs were less common (table 11). B covaried with relatively few other elements, and the covariates differed according to aquifer group.

Co-occurrence of Trace Elements at Concentrations Greater than Human-Health Benchmarks

Logistic regression analysis showed that several trace elements commonly occur together, and that some combinations of some trace elements are good predictors of the occurrence of other trace elements exceeding HHBs. Further analysis of the co-occurrence of trace elements that exceeded HHBs was done to identify samples with more than one trace-element exceedence of HHBs. In this way, it was possible to relate high concentrations of trace elements in water samples to potentially controlling factors and to identify which elements commonly co-occur. For example, in a study of domestic wells and multiple HHB exceedences, high TDS was shown to be related to the number of contaminants present in any given sample (DeSimone, 2009).

Recently, interest has increased in assessing contaminant mixtures as they relate to human health, partly to infer mechanisms of contamination and processes that control mobility. Characterizing all possible mixtures in a water sample is a difficult task; assessing the toxicity of any of these possible mixtures is even more challenging (Ryker and Small, 2008). Thus, for this analysis, which focused on trace elements, data on only selected trace elements were used in characterizing sample mixtures.

For this analysis, 2,714 groundwater samples with data on a specific set of trace elements—Sb, As, Ba, Be, Cd, Cr, Cu, Pb, Mn, Mo, Ni, Se, Ag, U, and Zn—were used. Radon was not included in the analysis because it occurs at concentrations exceeding the USEPA-proposed MCL of 300 pCi/L in 65 percent of samples (table 4) and would therefore co-occur with other contaminants in the majority of samples. B, Co, Sr, and Tl were not included because concentrations were measurable in too few samples or because of the absence of regulation by the USEPA. In this subset of data, the rate of HHB exceedence by at least one or more trace elements was 21.1 percent (572 of the 2,714 samples with at least one HHB exceedence). Of those, 62 samples (2.3 percent overall) had two or more trace elements that exceeded HHBs (table 12).

Most of the multiple exceedences of HHBs occurred in the USG aquifer group. Of the 62 samples with multiple HHB exceedences, 50 were from the USG. The overall percentage of multiple HHB exceedences in the USG-aquifer samples was 4.2 percent (50 of 1,187). Of the remaining 12 samples with multiple HHB exceedences, 6 were from the GLA, and 3 were from the CRL (table 12).

The multiple HHB exceedences in samples from the USG aquifer group were dominated by co-occurrences of two of the following three elements: As, Mn, and U (table 13). Forty-two percent of the HHB exceedences consisted of the co-occurrence of As and Mn, 18 percent consisted of U and Mn, and 8 percent consisted of As and U. Mo was included in 22 percent of the mixtures overall.

Multiple HHB exceedences in groundwater from the USG (42 of the 50) occurred in four areas: the northern High Plains, the Nevada Basin and Range, the California Central Valley, and the Santa Ana Basin. The sampled wells in these areas were predominantly in urban (17), agricultural (14), and mixed (11) land-use areas. Water samples from 21 of the same wells were classified as being mixed with respect to redox conditions: 13 were anoxic, and 6 were oxic, and 2 were not classified. Most of the elements that co-occur at concentrations greater than HHBs are redox sensitive and are more mobile under anoxic or mixed conditions; these conditions were more common in drinking-water wells and in shallow monitoring wells in urban areas than in wells in agricultural settings.

Sr and B were measured along with the broader suite described above in a subset of 819 samples, primarily in water samples from the USG aquifer group. Concentrations of B and Sr at concentrations greater than HHBs in the High Plains aquifer commonly occur in various combinations with As, Mn, Mo, and U (table 14). In the USG aquifer-group samples from the Santa Ana Basin and the Coastal Range Province of southern California, As, B, Mn, Mo, and U frequently co-occur. Sr concentrations that exceed HHBs also are found with high concentrations of As and Mo in the GLA aquifer group (table 14), primarily in western Ohio and eastern Indiana.

Table 12. Number of groundwater samples collected for the NAWQA Program across the United States and number of multiple human-health benchmark exceedences by aquifer group, 1992–2003.

[HHB, human-health benchmark; BAV, basaltic and volcanic rock; CAR, carbonate rock; GLA, glacial unconsolidated sand and gravel; CRL, crystalline rock; SAN, sandstone; SCR, sandstone and carbonate rock; SCS, semiconsolidated sand; USG, unconsolidated sand and gravel]

Aquifer group	Total number of samples	Samples with one or more HHB exceedences		Samples with two or more HHB exceedences	
		Number	Percentage	Number	Percentage
BAV	30	0	0.0	0	0.0
CAR	161	4	2.5	0	0.0
GLA	464	101	21.8	6	1.3
CRL	188	26	13.8	3	1.6
SAN	214	49	22.9	2	0.9
SCR	173	3	1.7	0	0.0
SCS	297	45	15.2	1	0.3
USG	1,187	344	29.0	50	4.2
Total	2,714	572	21.1	62	2.3

Table 13. Co-occurrence of trace elements at concentrations greater than human-health benchmarks in samples collected for the NAWQA Program across the United States from the unconsolidated sand and gravel aquifer group, 1992–2003.

[Total number of samples was 1,187; USG, unconsolidated sand and gravel; Mn, manganese; As, arsenic; U, uranium; Mo, molybdenum; Cd, cadmium; Se, selenium]

Number of trace elements exceeding human-health benchmarks	Number of samples with multiple exceedences (N = 50)	Percentage of multiple exceedences	Co-occurrence of trace elements in groundwater at concentrations above a human-health benchmark in the USG aquifer group					
4	2	4	Mn	As	U	Mo		
3	2	4	Mn	As	U			
	1	2		As	U	Mo		
	1	2	Mn		U	Mo		
2	21	42	Mn	As				
	9	18	Mn		U			
	4	8		As	U			
	4	8		As		Mo		
	3	6			U	Mo		
	1	2	Mn					Cd
	1	2		As			Se	
	1	2			U		Se	
Total exceedences by element			36	35	23	11	2	1

Table 14. Co-occurrence of trace elements with boron and strontium at concentrations greater than human-health benchmarks in groundwater samples collected for the NAWQA Program across the United States, 1992–2003.

[Total number of samples = 819; USG, unconsolidated sand and gravel; GLA, glacial unconsolidated sand and gravel; As, arsenic; B, boron; Mo, molybdenum; U, uranium; Mn, manganese; Sr, strontium]

Number of trace elements exceeding human-health benchmarks	Aquifer group	Number of samples with multiple exceedences (N = 14)	Co-occurrence of trace elements at concentrations above a human-health benchmarks in the USG and GLA aquifer groups					
4	USG	1	As	B		Mo		U
3	USG	1	As		Mn		Sr	
	USG	1		B		Mo		U
	USG	1				Mo	Sr	U
2	USG	1			Mn		Sr	
	USG	1	As	B				
	GLA/USG	5	As				Sr	
	GLA	1				Mo	Sr	
	USG	1		B	Mn			
	USG	1					Sr	U
Total exceedences by element			8	4	3	4	10	4

Summary

Trace-element and Rn concentrations in groundwater were assessed for samples collected between 1992 and 2003 in principal and other aquifers across the United States as part of the U.S. Geological Survey National Water-Quality Assessment Program (NAWQA). Water samples used for this study were collected primarily from shallow wells installed near the water table in particular land-use settings and from deeper public and domestic drinking-water wells. This study, the first comprehensive national assessment of NAWQA trace elements in groundwater, compares concentrations of trace elements at analytical reporting levels to assess occurrence and to identify geographic areas where trace elements exceed human-health benchmarks (HHBs) and may pose a human-health concern. The dataset contains trace element data from 5,183 wells and represents more than 40 principal and other aquifers. Trace elements measured include aluminum (Al), antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), boron (B), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), lithium (Li), manganese (Mn), molybdenum (Mo), nickel (Ni), selenium (Se), silver (Ag), strontium (Sr), thallium (Tl), uranium (U), vanadium (V), and zinc (Zn). Radon (Rn) gas also was measured and is included in the data analysis.

Climate had an important influence on the occurrence and distribution of trace elements in groundwater. Concentrations of trace elements were commonly greater in the dry regions of the United States than in humid regions. In particular, trace elements that form oxyanions or ion complexes, such as As, Ba, B, Cr, Mo, Se, Sr, U, and V, were greater in groundwater in dry regions than in more humid regions. Cu, Ni, and Zn also were greater in dry regions. By contrast, concentrations of elements that are mobile in anoxic and (or) low-pH groundwater, such as Al, Co, Fe, Pb, and Mn, were greater in humid regions.

Samples from drinking-water wells in dry regions had greater concentrations of As, Ba, Pb, Li, Sr, V, and Zn, than samples from monitoring wells. In humid regions, however, concentrations of most trace elements were greater in monitoring wells than in drinking-water wells; the exceptions were Cu, Pb, Zn, and Rn. Cu, Pb, and Zn are common trace elements in pumps and pipes used in the construction of drinking-water wells, and contamination from these sources may have contributed to their concentrations. Al, Sb, Ba, B, Cr, Co, Fe, Mn, Mo, Ni, Se, Sr, and U concentrations were all greater in monitoring wells than in drinking-water wells in the humid regions.

Groundwater from wells in agricultural settings had greater concentrations of some trace elements, such as As, Mo, and U, than from wells in urban settings. Concentrations of DO and pH also were greater in groundwater from agricultural wells than from urban wells. Significantly greater concentrations of B, Cr, Se, Ag, Sr, and V were found in agricultural wells in the dry regions. Groundwater from urban wells had greater concentrations of Co, Fe, Mn, and specific conductance than groundwater from agricultural wells.

Overall, groundwater in 19 percent of all wells (962 of 5,097) exceeded an HHB for at least one trace element, including Sb, As, Ba, Be, B, Cd, Cr, Cu, Pb, Mn, Mo, Ni, Se, Ag, Sr, Tl, U, and Zn. HHB or nonhealth-guideline exceedences were common in samples collected from wells in all aquifer groups across the United States. Water from wells in urban settings had greater rates of HHB exceedence than from wells in agricultural settings or wells in varied land-use areas (major aquifer studies). As a group, monitoring wells generally had greater benchmark or guideline-exceedence rates than domestic or public wells.

Mn occurred most often at concentrations greater than its HHB (12 percent), followed by As (7.0 percent), Sr (4.3 percent), U (4.0 percent), B (1.9 percent) and Mo (1.5 percent). Rn occurred at concentrations greater than the USEPA-proposed MCL of 300 pCi/L in 65 percent of samples, and 2.7 percent of Rn concentrations were greater than the USEPA-proposed AMCL of 4,000 pCi/L. In general, there were more exceedences of HHBs in groundwater in dry climates than in humid climates.

Trace-element contamination in groundwater far outpaces the concentrations of most other commonly assessed contaminants, such as VOCs, pesticides, and nitrate. One or more trace elements exceeded HHBs in samples from 13 percent of public-supply wells and 13 percent of domestic-supply wells; for pesticides and VOCs, for example, these rates were 2.2 percent or less. Nitrate exceeded its MCL in samples from 3 percent of public-supply wells and 7 percent of domestic-supply wells.

The geology of aquifers also is a major factor affecting trace-element occurrence in the United States. Eight major aquifer groups were characterized based on the type of geologic material and included (1) unconsolidated sand and gravel; (2) glacial unconsolidated sand and gravel; (3) sandstone; (4) crystalline rock; (5) sandstone and carbonate rock; (6) carbonate rock; (7) semiconsolidated sand; and (8) basaltic and other volcanic rock. The majority of the water samples and the largest percentages of HHB exceedences occurred in groundwater from unconsolidated sand and gravel (USG) and the glacial unconsolidated sand and gravel (GLA) aquifers. As, Fe, Mn, and U were the most commonly occurring trace elements exceeding HHBs or nonhealth guidelines in both of these aquifer groups.

Field measurements of pH and redox were related to trace-element occurrence and concentrations. Generally, anoxic and mixed redox conditions with low pH were more common in wells in the humid parts of the United States, whereas oxic, higher pH conditions prevailed in wells in the dry regions. Redox and pH effects were evident for As, Cr, Mo, and Se in all samples combined and from individual aquifer groups. Arsenic occurrence, for example, generally increased from oxic to anoxic groundwater when pH was less than 7; however, As occurrence was consistently high when pH was greater than 7, which may be related to pH-driven desorption. A similar pattern was seen for Mo and, to a lesser extent, Cr. In groundwater samples from the GLA aquifers, As concentrations increased as samples became increasingly anoxic and as pH increased. Also, the GLA aquifer group had the largest percentage of samples in the anoxic and mixed redox categories; thus redox-sensitive trace elements that are more mobile in anoxic conditions may occur more frequently. Arsenic, for example, exceeded 10 µg/L in 23 percent of samples of anoxic, high-pH groundwater and in 17 percent of samples of low-pH groundwater.

In general, older waters (mostly pre-1953) had more occurrences of trace elements, greater pHs, were from deeper wells, and had lower concentrations of dissolved oxygen than younger waters (defined as waters containing a fraction younger than 1953). Most oxyanion-forming trace elements occurred more frequently in old groundwater. However, although U occurrence was greater in older water collected from dry-region aquifers, in humid-region aquifers, U occurred more often in young water. This difference may be related to old, humid-region groundwater having lower concentrations of dissolved oxygen, a condition which can inhibit U mobility.

Logistic regression models were used to examine the relations of several trace elements to other chemical and ancillary data within selected major aquifer groups. The models showed that the pH and redox of groundwater were major controlling factors for many trace elements. In particular, low pH was found to be a significant factor in the occurrences of many cationic metals, such as Al, Fe, Mn, and Ni. In general, these metals, as well as Cu, Pb, and Zn, adsorb more strongly to aquifer materials as pH increases. The models for As occurrence were dominated by co-occurrence with silica, Mo, and high pH. About 12 percent of the samples with low silica or Mo had As concentrations greater than or equal to 1 µg/L. This proportion increased to about 45 percent if either Mo or silica was present and further to about 85 percent if both Mo and silica were present. The effect of increased pH on As concentrations is likely to increase solubility through desorption.

Co-occurrence of trace elements also was addressed by focusing on those that exceeded HHBs in any given sample. For this analysis, 2,714 samples that had data for Sb, As, Ba, Be, Cd, Cr, Cu, Pb, Mn, Mo, Ni, Se, Ag, U, and Zn were used. Because concentrations of Rn exceeded the USEPA-proposed MCL of 300 pCi/L in nearly 70 percent of samples, it would co-occur with most trace elements. For all selected samples from all aquifer groups, 21 percent (572 of 2,714 wells) had HHB exceedences of one or more trace elements. This was similar to the 19-percent (962 of 5,097 wells) rate of HHB exceedence for the complete dataset. Of the 2,714 wells, 62 (2.3 percent) had two or more trace elements that exceeded HHBs.

Multiple exceedences of HHBs occurred most often in the USG aquifer group. Of all of the samples with multiple exceedences, 50 of the 62 were from samples from the USG. The overall rate of multiple HHB exceedences in samples from the USG aquifer group was 4.2 percent and was dominated by combinations of As, Mn, and U. Eighty percent involved at least As and Mn, Mn and U, or As and U. Forty-two percent were only As and Mn, 18 percent were U and Mn, and 8 percent were As and U. Mo was involved in 22 percent of the mixtures overall, and mostly in conjunction with As and U.

B and Sr were measured in a subset of 819 samples (fewer samples than most trace elements) and sometimes co-occurred with other trace elements at concentrations greater than HHBs. These mixtures were primarily in samples from the USG aquifer group.

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Appendixes 1–5

Appendix 1. Selected national-scale studies of trace elements in groundwater.

[As, arsenic; Cd, cadmium; F, fluoride; Hg, mercury; Pb, lead; Po, polonium; Ra, radium; U, uranium]

Trace element	Geographic extent and design of study	Hydrogeologic setting	Number of wells	Reference
As	United States, various	Interior plains, Appalachian highlands, Intermontane plateaus, Rocky Mountains, Pacific Mountains	20,000	(Welch and others, 2000)
As	United States, various	Various	Many thousands	(Focazio and others, 1999)
Various	United States and Europe	Various	Various	(Alley, 1993)
As	United States	Various	Summary	(Ryker, 2003)
Various	United States, domestic wells	Various	2,171	(DeSimone, 2009)
^{226}Ra, ^{228}Ra, ^{210}Po, ^{210}Pb	United States, various	Various	99	(Focazio and others, 2001)
As, Cd, F, Pb, Hg, U, Rn	United States, random and nonrandom	Various	3,397–15,495	(Focazio and others, 2006)
Ra, Rn, U, gross alpha	United States, nonrandom	Public wells	Variable	(Hess and others, 1985)
Ra, Rn	United States	Public wells	Summary	(Michel, 1990)
Rn	United States	Indoor air radon data	Variable	(Gundersen and others, 1992)
U	United States, nonrandom	Public wells	59,812	(Cothern and Lappenbusch, 1982)

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Appendix 2. Wells sampled by the NAWQA Program, 1992–2003, by study type, land use, major aquifer group, and aquifer name.

[Aquifer number shown on figure 3. Number of wells = 5,147 of 5,183 (36 are missing well-depth data); usg, unconsolidated sand and gravel; gla, glacial unconsolidated sand and gravel; scs, semiconsolidated sand; san, sandstone; scr, sandstone and carbonate rock; car, carbonate rock; bav, basaltic and volcanic rock; igm, igneous and metamorphic rock]

Aquifer number	Lithology	Aquifer name	Study network code	Number of wells	Median well depth
1	usg	Basin and Range basin-fill aquifers	cazbluscr1	9	43
1	usg	Basin and Range basin-fill aquifers	cazbsus1a	34	465
1	usg	Basin and Range basin-fill aquifers	cazbsus2	29	330
1	usg	Basin and Range basin-fill aquifers	cazbsus3	19	264
1	usg	Basin and Range basin-fill aquifers	grsllusrc1	30	69
1	usg	Basin and Range basin-fill aquifers	grslsus1a	26	239
1	usg	Basin and Range basin-fill aquifers	grslsus1b	29	240
1	usg	Basin and Range basin-fill aquifers	nvbrlusag1	20	19.5
1	usg	Basin and Range basin-fill aquifers	nvbrlusag2	10	18
1	usg	Basin and Range basin-fill aquifers	nvbrlusur1	28	30
1	usg	Basin and Range basin-fill aquifers	nvbrlusur2	27	29
1	usg	Basin and Range basin-fill aquifers	nvbrsus1	22	775
1	usg	Basin and Range basin-fill aquifers	nvbrsus2	18	394.5
1	usg	Basin and Range basin-fill aquifers	nvbrsus3	17	155
2	usg	California Coastal Basin aquifers	sanalusrc1	25	24
2	usg	California Coastal Basin aquifers	sanasus1	29	585
2	usg	California Coastal Basin aquifers	sanasus2	20	966
2	usg	California Coastal Basin aquifers	sanasus3	22	699.5
3	usg	Central Valley aquifer system	sacrluscr1	28	35
3	usg	Central Valley aquifer system	sacrlusrc1	19	63
3	usg	Central Valley aquifer system	sacrsus1	31	150
3	usg	Central Valley aquifer system	sanjluscr1	18	145
3	usg	Central Valley aquifer system	sanjlusor1	20	170
3	usg	Central Valley aquifer system	sanjlusor2	20	147.5
3	usg	Central Valley aquifer system	sanjsus1	30	182
4	usg	Columbia Plateau basin-fill aquifers	ccptlusag1	8	31
4	usg	Columbia Plateau basin-fill aquifers	ccptlusag2	32	69.5
4	usg	Columbia Plateau basin-fill aquifers	ccptlusor1	31	48
4	usg	Columbia Plateau basin-fill aquifers	ccptsus1b	13	90
5	usg	High Plains aquifer	cnbrsus2	27	47
5	usg	High Plains aquifer	hpgwlusag1	30	160
5	usg	High Plains aquifer	hpgwlusag2	29	170
5	usg	High Plains aquifer	hpgwlusur1	30	27.5
5	usg	High Plains aquifer	hpgwsus1a	74	262.5
5	usg	High Plains aquifer	hpgwsus1b	48	201
5	usg	High Plains aquifer	hpgwsus1c	104	207.5
5	usg	High Plains aquifer	hpgwsus2	20	73.5
5	usg	High Plains aquifer	hpgwsus4	27	190
6	usg	Mississippi River Valley alluvial aquifer	misesus1	29	110
6	usg	Mississippi River Valley alluvial aquifer	misesus3	24	102.5

Appendix 2. Wells sampled by the NAWQA Program, 1992–2003, by study type, land use, major aquifer group, and aquifer name. —Continued

[Aquifer number shown on figure 3. Number of wells = 5,147 of 5,183 (36 are missing well-depth data); usg, unconsolidated sand and gravel; gla, glacial unconsolidated sand and gravel; scs, semiconsolidated sand; san, sandstone; scr, sandstone and carbonate rock; car, carbonate rock; bav, basaltic and volcanic rock; igm, igneous and metamorphic rock]

Aquifer number	Lithology	Aquifer name	Study network code	Number of wells	Median well depth
7	usg	Northern Rocky Mountains Intermontane Basins aquifer	nroksus1	31	137
7	usg	Northern Rocky Mountains Intermontane Basins aquifer	nroksus2	30	60
8	usg	Rio Grande aquifer system	rioglusag1	30	20
8	usg	Rio Grande aquifer system	riogluscr1	35	20
8	usg	Rio Grande aquifer system	rioglusur1	24	27
8	usg	Rio Grande aquifer system	riogsus1	30	169
9	usg	Snake River Plain basin-fill aquifers	usnkluscr1	27	34
9	usg	Snake River Plain basin-fill aquifers	usnkluscr3	1	180
9	usg	Snake River Plain basin-fill aquifers	usnksus1	9	67
9	usg	Snake River Plain basin-fill aquifers	usnksus2	23	150
9	usg	Snake River Plain basin-fill aquifers	usnksus3	10	119
10	usg	Surficial aquifer system	acfblusag1	16	41.5
10	usg	Surficial aquifer system	acfblusfo1	4	57.5
10	usg	Surficial aquifer system	gaflluscr1	23	27
10	usg	Surficial aquifer system	gafllusur3	16	23.5
10	usg	Surficial aquifer system	gaflsus1	32	27.5
10	usg	Surficial aquifer system	miselusrc1	24	48.5
10	usg	Surficial aquifer system	santluscr1	30	18
10	usg	Surficial aquifer system	sofllusfo1	5	10
10	usg	Surficial aquifer system	sofllusor1	31	13
11	usg	Willamette Lowland basin-fill aquifers	willsus1	70	60
12	gla	Glacial aquifer system	almnsus2	30	73
12	gla	Glacial aquifer system	connlusag1	40	21
12	gla	Glacial aquifer system	connlusfo1	40	17
12	gla	Glacial aquifer system	connlusur1	40	22
12	gla	Glacial aquifer system	delrsus3	16	114
12	gla	Glacial aquifer system	eiwaluscr1	31	18
12	gla	Glacial aquifer system	eiwalusrc1	30	23
12	gla	Glacial aquifer system	eiwasus2	32	52
12	gla	Glacial aquifer system	hdsnlusag1	14	19.5
12	gla	Glacial aquifer system	hdsnlusur1	27	29
12	gla	Glacial aquifer system	hdsnsus1	2	108
12	gla	Glacial aquifer system	leriluscr1	30	18
12	gla	Glacial aquifer system	lerilusrc1	30	25.5
12	gla	Glacial aquifer system	lerisus1	27	90
12	gla	Glacial aquifer system	linjsus1	1	152
12	gla	Glacial aquifer system	lirbluscr1	28	27.5
12	gla	Glacial aquifer system	lirbluscr2	29	20
12	gla	Glacial aquifer system	lirbsus1	30	245
12	gla	Glacial aquifer system	lirbsus2	30	50
12	gla	Glacial aquifer system	miamluscr1	26	25.5

Appendix 2. Wells sampled by the NAWQA Program, 1992–2003, by study type, land use, major aquifer group, and aquifer name. —Continued

[Aquifer number shown on figure 3. Number of wells = 5,147 of 5,183 (36 are missing well-depth data); usg, unconsolidated sand and gravel; gla, glacial unconsolidated sand and gravel; scs, semiconsolidated sand; san, sandstone; scr, sandstone and carbonate rock; car, carbonate rock; bav, basaltic and volcanic rock; igm, igneous and metamorphic rock]

Aquifer number	Lithology	Aquifer name	Study network code	Number of wells	Median well depth
12	gla	Glacial aquifer system	miamlusrc1	25	39
12	gla	Glacial aquifer system	miamsus1	30	60
12	gla	Glacial aquifer system	necblusrc1	29	23
12	gla	Glacial aquifer system	necbsus3	30	56
12	gla	Glacial aquifer system	pugtluscr1	22	28.5
12	gla	Glacial aquifer system	pugtlusrs1	27	47
12	gla	Glacial aquifer system	pugtsus1	30	66.5
12	gla	Glacial aquifer system	rednlusag1	26	25.5
12	gla	Glacial aquifer system	rednlusag2	20	15
12	gla	Glacial aquifer system	rednsus1	27	40
12	gla	Glacial aquifer system	rednsus2	25	58
12	gla	Glacial aquifer system	rednsus3	15	37
12	gla	Glacial aquifer system	uirbluscr1	29	14
12	gla	Glacial aquifer system	uirblusrc1	26	29
12	gla	Glacial aquifer system	uirbsus1	27	72
12	gla	Glacial aquifer system	uirbsus2	23	45
12	gla	Glacial aquifer system	umisluscr1	29	25
12	gla	Glacial aquifer system	umislusfo1	15	19
12	gla	Glacial aquifer system	umislusrc1	30	19
12	gla	Glacial aquifer system	whitluscr1	23	28
12	gla	Glacial aquifer system	whitluscr2	20	22.5
12	gla	Glacial aquifer system	whitluscr3	24	20.5
12	gla	Glacial aquifer system	whitlusur1	25	29
12	gla	Glacial aquifer system	wmiclusag1	26	30
12	gla	Glacial aquifer system	wmiclusag2	30	42
13	gla	Unconsolidated-deposit aquifers (Alaska)	cooksus1a	29	90
14	scs	Coastal Lowlands aquifer system	acadluscr1	27	26
14	scs	Coastal Lowlands aquifer system	acadlusrc1	28	58.5
14	scs	Coastal Lowlands aquifer system	acadsus1	30	140
14	scs	Coastal Lowlands aquifer system	acadsus2	30	115
14	scs	Coastal Lowlands aquifer system	trinsus3	23	138
15	scs	Mississippi Embayment aquifer system	miselusrc2	8	98
15	scs	Mississippi Embayment aquifer system	misesus2	30	675
16	scs	North Atlantic Coastal Plain aquifer system	albelusag1	17	12
16	scs	North Atlantic Coastal Plain aquifer system	albelusur1	14	62.5
16	scs	North Atlantic Coastal Plain aquifer system	albesus1	11	20
16	scs	North Atlantic Coastal Plain aquifer system	albesus2	16	21.5
16	scs	North Atlantic Coastal Plain aquifer system	dlmvluscr1	28	21.5
16	scs	North Atlantic Coastal Plain aquifer system	dlmvsus1	27	45
16	scs	North Atlantic Coastal Plain aquifer system	linjluscr1	15	31
16	scs	North Atlantic Coastal Plain aquifer system	linjlusfo1	13	19
16	scs	North Atlantic Coastal Plain aquifer system	linjlusrc1	30	24
16	scs	North Atlantic Coastal Plain aquifer system	linjlusur1	20	24
16	scs	North Atlantic Coastal Plain aquifer system	linjsus2	30	100

Appendix 2. Wells sampled by the NAWQA Program, 1992–2003, by study type, land use, major aquifer group, and aquifer name.—Continued

[Aquifer number shown on figure 3. Number of wells = 5,147 of 5,183 (36 are missing well-depth data); usg, unconsolidated sand and gravel; gla, glacial unconsolidated sand and gravel; scs, semiconsolidated sand; san, sandstone; scr, sandstone and carbonate rock; car, carbonate rock; bav, basaltic and volcanic rock; igm, igneous and metamorphic rock]

Aquifer number	Lithology	Aquifer name	Study network code	Number of wells	Median well depth
17	scs	Southeastern Coastal Plain aquifer system	mobllusc r1	29	35
17	scs	Southeastern Coastal Plain aquifer system	mobllusrc1	30	41.5
17	scs	Southeastern Coastal Plain aquifer system	moblsus1	31	165
17	scs	Southeastern Coastal Plain aquifer system	santlusrc1	30	19.5
17	scs	Southeastern Coastal Plain aquifer system	santsus1	30	245
18	scs	Texas coastal uplands aquifer system	trinsus2	23	160
19	san	Cambrian-Ordovician aquifer system	umissus3	25	180
19	san	Cambrian-Ordovician aquifer system	umissus4	25	200
19	san	Cambrian-Ordovician aquifer system	wmicsus1	29	170
20	san	Early Mesozoic basin aquifers	delrsus1	30	160
20	san	Early Mesozoic basin aquifers	linjsus3	17	200
20	san	Early Mesozoic basin aquifers	potosus2	20	148.5
21	san	Lower Tertiary aquifers	yellsus2	29	160
22	san	Pennsylvanian aquifers	almnlusmi1	30	83.5
22	san	Pennsylvanian aquifers	almnsus1	30	105
22	san	Pennsylvanian aquifers	kanalusmi1	28	76.5
22	san	Pennsylvanian aquifers	kanasus1	20	77.5
22	san	Pennsylvanian aquifers	whitluscr2	2	23
23	san	Valley and Ridge aquifers (sandstone)	delrsus2	30	192.5
23	san	Valley and Ridge aquifers (sandstone)	lsussus1	29	155
23	san	Valley and Ridge aquifers (sandstone)	potolusag2	23	122
23	san	Valley and Ridge aquifers (sandstone)	potolusfo1	3	160
23	san	Valley and Ridge aquifers (sandstone)	utenluscr1	11	18
24	scr	Edwards-Trinity aquifer system	sctxlusrc1	30	261
24	scr	Edwards-Trinity aquifer system	sctxsus1	19	335
24	scr	Edwards-Trinity aquifer system	sctxsus2	25	420
24	scr	Edwards-Trinity aquifer system	sctxsus3	30	1,268
24	scr	Edwards-Trinity aquifer system	trinsus1	24	155
25	scr	Mississippian aquifers	kanasus1	10	191
25	scr	Mississippian aquifers	lerisus1	1	120
25	scr	Mississippian aquifers	ltenlusag1	32	37.5
25	scr	Mississippian aquifers	ltensus1	32	87
25	scr	Mississippian aquifers	ltensus2	4	99
26	car	Biscayne aquifer	sofllusrc1	30	15
26	car	Biscayne aquifer	soflsus1	30	99

Appendix 2. Wells sampled by the NAWQA Program, 1992–2003, by study type, land use, major aquifer group, and aquifer name. —Continued

[Aquifer number shown on figure 3. Number of wells = 5,147 of 5,183 (36 are missing well-depth data); usg, unconsolidated sand and gravel; gla, glacial unconsolidated sand and gravel; scs, semiconsolidated sand; san, sandstone; scr, sandstone and carbonate rock; car, carbonate rock; bav, basaltic and volcanic rock; igm, igneous and metamorphic rock]

Aquifer number	Lithology	Aquifer name	Study network code	Number of wells	Median well depth
27	car	Floridan aquifer system	acfblusag1	3	44
27	car	Floridan aquifer system	acfbsus1	26	150
27	car	Floridan aquifer system	gaflsus1	4	69
27	car	Floridan aquifer system	santsus2	30	175
28	car	Ordovician aquifers	ltensus2	27	140
29	car	Ozark Plateaus aquifer system	ozrklusag1	20	167.5
29	car	Ozark Plateaus aquifer system	ozrklusag2	20	180
29	car	Ozark Plateaus aquifer system	ozrksus1	20	1,308.5
29	car	Ozark Plateaus aquifer system	ozrksus2a	30	196
29	car	Ozark Plateaus aquifer system	ozrksus3a	13	140
30	car	Piedmont and Blue Ridge carbonate-rock aquifers	lsuslusag1	30	160
31	car	Silurian-Devonian aquifers	eiwasus1	33	225
32	car	Valley and Ridge aquifers (carbonate)	kanasus2	1	325
32	car	Valley and Ridge aquifers (carbonate)	lsuslusag2	30	172.5
32	car	Valley and Ridge aquifers (carbonate)	lsuslusag3	30	159
32	car	Valley and Ridge aquifers (carbonate)	lsuslusur1	20	108
32	car	Valley and Ridge aquifers (carbonate)	potolusag1	29	144
32	car	Valley and Ridge aquifers (carbonate)	potolusag2	1	280
32	car	Valley and Ridge aquifers (carbonate)	utenluscr1	19	16
32	car	Valley and Ridge aquifers (carbonate)	utensus1	30	227.5
33	bav	Columbia Plateau basaltic-rock aquifers	ccptlusag1	18	101.5
33	bav	Columbia Plateau basaltic-rock aquifers	ccptlusag2	17	157
33	bav	Columbia Plateau basaltic-rock aquifers	ccptlusor1	9	170
33	bav	Columbia Plateau basaltic-rock aquifers	ccptsus1b	30	339
34	bav	Hawaiian volcanic-rock aquifers	oahusus1	30	512
35	bav	Snake River Plain basaltic-rock aquifers	usnkluscr2	29	225
35	bav	Snake River Plain basaltic-rock aquifers	usnkluscr3	28	202.5
35	bav	Snake River Plain basaltic-rock aquifers	usnkluscr4	15	360
35	bav	Snake River Plain basaltic-rock aquifers	usnksus1	34	315
35	bav	Snake River Plain basaltic-rock aquifers	usnksus2	13	232
36	bav	Early Mesozoic basin aquifers (basalt and volcanic)	linjsus3	4	167.5
36	bav	Early Mesozoic basin aquifers (basalt and volcanic)	potosus2	3	160
37	igm	New England crystalline-rock aquifers (unofficial name)	connsus1	30	235
37	igm	New England crystalline-rock aquifers (unofficial name)	linjsus1	29	202
37	igm	New England crystalline-rock aquifers (unofficial name)	necbsus1	28	187.5
37	igm	New England crystalline-rock aquifers (unofficial name)	necbsus2	30	303

Appendix 2. Wells sampled by the NAWQA Program, 1992–2003, by study type, land use, major aquifer group, and aquifer name. —Continued

[Aquifer number shown on figure 3. Number of wells = 5,147 of 5,183 (36 are missing well-depth data); usg, unconsolidated sand and gravel; gla, glacial unconsolidated sand and gravel; scs, semiconsolidated sand; san, sandstone; scr, sandstone and carbonate rock; car, carbonate rock; bav, basaltic and volcanic rock; igm, igneous and metamorphic rock]

Aquifer number	Lithology	Aquifer name	Study network code	Number of wells	Median well depth
38	igm	Piedmont and Blue Ridge crystalline-rock aquifers	acfblusur1	21	31
38	igm	Piedmont and Blue Ridge crystalline-rock aquifers	kanasus2	29	205
38	igm	Piedmont and Blue Ridge crystalline-rock aquifers	lsussus2	30	146.5
38	igm	Piedmont and Blue Ridge crystalline-rock aquifers	potosus1	25	142
38	igm	Piedmont and Blue Ridge crystalline-rock aquifers	santsus3	30	200
99	igm	Rocky Mountain Front Range (unofficial name)	spltsus1	27	225
99	san	Woodbine aquifer (not a principal aquifer)	trinlusur1	20	25.5
99	usg	Stream-valley aquifers–Bighorn, Wind, Powder River basins (unofficial name)	yelllusot1	29	15
99	usg	Stream-valley aquifers–Bighorn, Wind, Powder River basins (unofficial name)	yellsus1	25	19
99	usg	Stream-valley aquifers–South Platte River (unofficial name)	spltluscr1	30	23
99	usg	Stream-valley aquifers–South Platte River (unofficial name)	spltlusrc1	30	27.5
99	usg	Stream-valley aquifers–Valley and Ridge (unofficial name)	potolusag2	1	71
99	usg	Stream-valley aquifers–Upper Colorado River (unofficial name)	ucollusrc1	25	24
99	usg	Stream-valley aquifers–Upper Colorado River (unofficial name)	ucolsus1	29	60
99	usg	Stream-valley aquifers–Upper Colorado River (unofficial name)	ucolsus2	13	49

Appendix 3. Summary statistics and percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA Program, 1992–2003, by major aquifer group.

[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 by using USEPA toxicity data and methods (Toccalino and Norman, 2006); Action levels (ALs) are concentrations which, if exceeded, trigger treatment or other requirements in USEPA regulations for public water supplies; --, not applicable; <, value is less than value shown. All benchmarks and guidelines are in micrograms per liter except radon, for which the proposed benchmark is in picocuries per liter; reporting level is 1 microgram per liter except for boron (12 micrograms per liter), iron (10 micrograms per liter), radon, (80 picocuries per liter), and strontium (0.9 micrograms per liter). Percentiles below multiple censoring levels were estimated by regression on order statistics; percentiles not estimated if percentage of censored values was greater than 80; if percentiles were not estimated, actual values are shown for percentiles greater than or equal to the assessment level; USEPA Secondary Maximum Contaminant Level (SMCL) is a nonenforceable federal guideline to address the cosmetic or aesthetic considerations of drinking water]

Element	Number of samples	Percentage of samples with censored values	Concentration percentile, in µg/L (pCi/L for radon)								Human-health benchmark			Nonhealth guideline	
			Max	99th	95th	90th	75th	50th	25th	10th	Benchmark	Type	Percentage exceeding benchmark	Guideline value (SMCL)	Percentage exceeding SMCL
Unconsolidated sand and gravel aquifers															
Aluminum	1,226	28.4	1,100	180	13	7.4	4.2	3.0	0.90	0.43	--	--	--	50 or 200	2.2, 1.0
Antimony	1,318	85.5	5.0	1.0	< 1	< 1	< 1	< 1	< 1	< 1	6	MCL	0	--	--
Arsenic	1,507	25.2	550	64	19	11	5.5	2.0	0.80	0.31	10	MCL	12	--	--
Barium	1,376	0.20	5,100	620	350	220	130	71	36	20	2,000	MCL	0.1	--	--
Beryllium	1,318	99.4	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	4	MCL	0	--	--
Boron	552	5.3	3,400	2,000	750	400	150	63	29	14	1,000	HBSL	3.4	--	--
Cadmium	1,351	90.9	16	1.0	< 1	< 1	< 1	< 1	< 1	< 1	5	MCL	0.4	--	--
Chromium	1,367	32.1	150	18	8.0	6.0	3.4	1.5	0.74	0.44	100	MCL	0.1	--	--
Cobalt	1,326	71.1	18	4.4	1.5	0.77	0.33	0.14	0.065	0.033	--	--	--	--	--
Copper	1,372	34.6	2,000	33	8.0	5.0	2.3	1.0	0.51	0.27	1,300	AL	0.1	1,000	0.1
Iron	1,769	50.4	50,000	11,000	2,500	490	22	5.0	0.31	0.036	--	--	--	300	12
Lead	1,355	79.1	9.0	3.0	2.0	< 1	< 1	< 1	< 1	< 1	15	AL	0	--	--
Lithium	375	0.05	580	280	150	110	42	17	7.1	1.7	--	--	--	--	--
Manganese	1,700	39.6	9,800	1,900	740	380	43	1.9	0.17	0.025	300	HBSL	12	50	24
Molybdenum	1,368	22.0	1,500	59	20	12	5.8	2.4	0.92	0.38	40	HBSL	2.4	--	--
Nickel	1,369	37.9	58	18	7.0	4.9	2.7	1.0	0.34	0.16	100	HBSL	0	--	--
Radon	1,481	0.07	40,000	4,000	1,800	1,300	830	510	310	230	300 or 4,000	MCL[1]/AMCL[2]	77, 1.1	--	--
Selenium	1,395	56.3	94	35	11	6.2	2.3	0.72	0.23	0.086	50	MCL	0.30	--	--
Silver	1,297	99.0	8.0	< 1	< 1	< 1	< 1	< 1	< 1	< 1	100	HBSL	0.00	100	0
Strontium	483	0	26,000	9,200	4,100	2,400	1,000	530	290	130	4,000	HBSL	5.2	--	--
Thallium	366	86.9	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	2	MCL	0	--	--
Uranium	1,409	22.0	550	140	47	26	9.4	3.4	0.78	0.21	30	MCL	8.7	--	--
Vanadium	370	4.3	190	120	50	39	22	10	2.1	0.55	--	--	--	--	--
Zinc	1,335	16.3	3,300	290	100	60	17	4.4	1.7	0.49	2,000	HBSL	0.1	5,000	0

Appendix 3. Summary statistics and percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA program, 1992–2003, by major aquifer group.—Continued

[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 by using USEPA toxicity data and methods (Toccalino and Norman, 2006); Action levels (ALs) are concentrations which, if exceeded, trigger treatment or other requirements in USEPA regulations for public water supplies; --, not applicable; <, value is less than value shown. All benchmarks and guidelines are in micrograms per liter except radon, for which the proposed benchmark is in picocuries per liter; reporting level is 1 microgram per liter except for boron (12 micrograms per liter), iron (10 micrograms per liter), radon, (80 picocuries per liter), and strontium (0.9 micrograms per liter). Percentiles below multiple censoring levels were estimated by regression on order statistics; percentiles not estimated if percentage of censored values was greater than 80; if percentiles were not estimated, actual values are shown for percentiles greater than or equal to the assessment level; USEPA Secondary Maximum Contaminant Level (SMCL) is a nonenforceable federal guideline to address the cosmetic or aesthetic considerations of drinking water]

Element	Number of samples	Percentage of samples with censored values	Concentration percentile, in µg/L (pCi/L for radon)								Human-health benchmark			Nonhealth guideline	
			Max	99th	95th	90th	75th	50th	25th	10th	Benchmark	Type	Percentage exceeding benchmark	Guideline value (SMCL)	Percentage exceeding SMCL
Glacial unconsolidated sand and gravel aquifers															
Aluminum	485	27.8	820	200	31	14	5.0	3.0	0.99	0.41	--	--	--	50 or 200	3.1, 1.0
Antimony	498	89.2	3.30	1.36	< 1	< 1	< 1	< 1	< 1	< 1	6	MCL	0	--	--
Arsenic	512	55.3	340	42	17	6.52	1.47	0.41	0.12	0.030	10	MCL	6.8	--	--
Barium	513	0	1,100	660	290	210	110	65	29	11	2,000	MCL	0	--	--
Beryllium	511	97.7	1.24	< 1	< 1	< 1	< 1	< 1	< 1	< 1	4	MCL	0	--	--
Boron	274	5.47	2,600	1,100	160	78	42	27	16	9.5	1,000	HBSL	1.1	--	--
Cadmium	511	93.9	1.00	< 1	< 1	< 1	< 1	< 1	< 1	< 1	5	MCL	0	--	--
Chromium	491	48.9	17	11	7.0	5.5	3.3	1.1	0.59	0.37	100	MCL	0	--	--
Cobalt	501	64.7	95	7.2	3.0	1.8	0.58	0.20	0.076	0.031	--	--	--	--	--
Copper	501	46.3	130	53	14	8.7	2.4	0.94	0.38	0.15	1,300	AL	0	1,000	0
Iron	1,190	28.1	38,000	12,000	3,800	2,100	620	17	4.0	0.47	--	--	--	300	29.3
Lead	498	84.5	9.0	4.0	< 1	< 1	< 1	< 1	< 1	< 1	15	AL	0	--	--
Lithium	258	17.4	37	25	14	8.2	4.4	2.9	1.4	0.57	--	--	--	--	--
Manganese	1,148	11.8	28,000	2,200	1,000	550	230	49	5.2	1.2	300	HBSL	19.8	50	49.7
Molybdenum	499	34.1	110	60	15	7.7	3.0	1.4	0.38	0.15	40	HBSL	2	--	--
Nickel	502	24.9	52	17	9.0	5.5	3.0	1.6	0.59	0.26	100	HBSL	0	--	--
Radon	763	0.79	3,700	2,200	1,200	840	520	320	200	150	300 or 4,000	MCL[1]/AMCL[2]	53.7, 0	--	--
Selenium	511	83.5	56	4.0	1.5	< 1	< 1	< 1	< 1	< 1	50	MCL	0.2	--	--
Silver	507	99.8	1.0	< 1	< 1	< 1	< 1	< 1	< 1	< 1	100	HBSL	0	100	0
Strontium	259	0.39	9,100	6,700	1,200	580	270	130	84	43	4,000	HBSL	1.2	--	--
Thallium	202	98.1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	2	MCL	0	--	--
Uranium	640	53.8	140	16	5.8	3.3	1.2	0.36	0.088	0.025	30	MCL	0.5	--	--
Vanadium	174	53.5	16	13	3.2	2.1	0.94	0.29	0.14	0.069	--	--	--	--	--
Zinc	494	20.0	380	270	62	30	9.0	3.0	1.2	0.35	2,000	HBSL	0	5,000	0

Appendix 3. Summary statistics and percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA program, 1992–2003, by major aquifer group.—Continued

[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 by using USEPA toxicity data and methods (Toccalino and Norman, 2006); Action levels (ALs) are concentrations which, if exceeded, trigger treatment or other requirements in USEPA regulations for public water supplies; --, not applicable; <, value is less than value shown. All benchmarks and guidelines are in micrograms per liter except radon, for which the proposed benchmark is in picocuries per liter; reporting level is 1 microgram per liter except for boron (12 micrograms per liter), iron (10 micrograms per liter), radon, (80 picocuries per liter), and strontium (0.9 micrograms per liter). Percentiles below multiple censoring levels were estimated by regression on order statistics; percentiles not estimated if percentage of censored values was greater than 80; if percentiles were not estimated, actual values are shown for percentiles greater than or equal to the assessment level; USEPA Secondary Maximum Contaminant Level (SMCL) is a nonenforceable federal guideline to address the cosmetic or aesthetic considerations of drinking water]

Element	Number of samples	Percentage of samples with censored values	Concentration percentile, in µg/L (pCi/L for radon)								Human-health benchmark			Nonhealth guideline	
			Max	99th	95th	90th	75th	50th	25th	10th	Benchmark	Type	Percentage exceeding benchmark	Guideline value (SMCL)	Percentage exceeding SMCL
							Semiconsolidated sand aquifers								
Aluminum	301	29.9	710	440	103	49	12	3.0	0.64	0.17	--	--	--	50 or 200	10.2, 3.0
Antimony	338	83.1	2.0	< 1	< 1	< 1	< 1	< 1	< 1	< 1	6	MCL	0	--	--
Arsenic	373	69.4	55	8.0	3.0	1.9	0.68	0.20	0.069	0.026	10	MCL	0.8	--	--
Barium	343	0	2,000	820	390	280	140	68	25	9.7	2,000	MCL	0.3	--	--
Beryllium	338	82.8	16	1.8	< 1	< 1	< 1	< 1	< 1	< 1	4	MCL	0.3	--	--
Boron	181	13.3	250	230	67	54	33	18	11	7.6	1,000	HBSL	0	--	--
Cadmium	338	78.4	1.3	< 1	< 1	< 1	< 1	< 1	< 1	< 1	5	MCL	0	--	--
Chromium	338	50	17	13	8.0	6.0	2.0	0.94	0.51	0.30	100	MCL	0	--	--
Cobalt	339	48.1	210	31	6.9	4.1	1.1	0.28	0.079	0.028	--	--	--	--	
Copper	339	33.3	280	170	34	19	6.8	1.2	0.38	0.15	1,300	AL	0	1,000	0
Iron	570	23.5	81,000	23,000	12,000	4,900	570	22	7.0	1.7	--	--	--	300	29.2
Lead	339	62.2	480	28	5.1	3.0	< 1	< 1	< 1	< 1	15	AL	1.2	--	--
Lithium	155	2.6	62	56	29	20	13	4.0	1.0	0.35	--	--	--	--	--
Manganese	564	5.3	7,200	1,100	450	300	120	37	8.6	1.6	300	HBSL	9.8	50	44
Molybdenum	338	73	8.9	7.3	3.4	2.0	< 1	< 1	< 1	< 1	40	HBSL	0	--	--
Nickel	341	36.7	160	39	11	5.3	2.6	1.0	0.27	0.091	100	HBSL	0.3	--	--
Radon	243	0.8	2,200	1,500	1,000	780	430	260	150	87	300 or 4,000	MCL[1]/AMCL[2]	39.1, 0	--	--
Selenium	342	75.4	35	9.7	2.1	1.3	< 1	< 1	< 1	< 1	50	MCL	--	--	--
Silver	338	100	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	100	HBSL	0	100	0
Strontium	155	0	890	610	400	290	190	120	44	13	4,000	HBSL	0	--	--
Thallium	154	87.7	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	2	MCL	0	--	--
Uranium	339	69.3	16	9.6	3.2	1.0	< 1	< 1	< 1	< 1	30	MCL	0	--	--
Vanadium	154	41.6	8.1	7.3	4.8	3.9	2.0	0.33	0.15	0.062	--	--	--	--	--
Zinc	308	15.6	1,200	750	270	110	23	5.1	1.5	0.37	2,000	HBSL	0	5,000	0

Appendix 3. Summary statistics and percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA program, 1992–2003, by major aquifer group.—Continued

[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 by using USEPA toxicity data and methods (Toccalino and Norman, 2006); Action levels (ALs) are concentrations which, if exceeded, trigger treatment or other requirements in USEPA regulations for public water supplies; --, not applicable; <, value is less than value shown. All benchmarks and guidelines are in micrograms per liter except radon, for which the proposed benchmark is in picocuries per liter; reporting level is 1 microgram per liter except for boron (12 micrograms per liter), iron (10 micrograms per liter), radon, (80 picocuries per liter), and strontium (0.9 micrograms per liter). Percentiles below multiple censoring levels were estimated by regression on order statistics; percentiles not estimated if percentage of censored values was greater than 80; if percentiles were not estimated, actual values are shown for percentiles greater than or equal to the assessment level; USEPA Secondary Maximum Contaminant Level (SMCL) is a nonenforceable federal guideline to address the cosmetic or aesthetic considerations of drinking water]

Element	Number of samples	Percentage of samples with censored values	Concentration percentile, in µg/L (pCi/L for radon)								Human-health benchmark			Nonhealth guideline	
			Max	99th	95th	90th	75th	50th	25th	10th	Benchmark	Type	Percentage exceeding benchmark	Guideline value (SMCL)	Percentage exceeding SMCL
Sandstone aquifers															
Aluminum	229	22.7	970	630	25	7.0	4.0	3.0	1.3	0.59	--	--	--	50 or 200	3.5, 1.7
Antimony	256	98.1	6.3	2.0	< 1	< 1	< 1	< 1	< 1	< 1	6	MCL	0.4	--	--
Arsenic	282	67.7	57	17	5.4	3.9	1.1	0.58	0.23	0.10	10	MCL	1.4	--	--
Barium	283	1.4	2,700	1,800	530	350	190	63	21	6.8	2,000	MCL	0.4	--	--
Beryllium	258	96.9	18	4.0	< 1	< 1	< 1	< 1	< 1	< 1	4	MCL	0.8	--	--
Boron	86	25.6	630	630	300	270	140	30	12	5.1	1,000	HBSL	0	--	--
Cadmium	274	97.1	9.4	6.0	< 1	< 1	< 1	< 1	< 1	< 1	5	MCL	1.1	--	--
Chromium	275	43.6	13	7.0	6.0	5.0	3.0	1.1	0.66	0.41	100	MCL	0	--	--
Cobalt	261	78.5	680	270	14	4.0	< 1	< 1	< 1	< 1	--	--	--	--	--
Copper	280	42.5	140	85	26	18	5.7	1.4	0.39	0.13	1,300	AL	0	1,000	0
Iron	389	30.6	38,000	24,000	7,700	3,700	740	30	4.0	0.53	--	--	--	300	31.9
Lead	277	85.6	19	5.6	2.0	1.2	< 1	< 1	< 1	< 1	15	AL	0.4	--	--
Lithium	59	1.7	260	260	110	66	32	11	3.7	2.0	--	--	--	--	--
Manganese	376	23.4	5,400	2,400	990	620	190	33	2.0	0.73	300	HBSL	17	50	44.7
Molybdenum	257	67.7	4,700	40	7.7	4.0	1.0	0.42	0.12	0.039	40	HBSL	0.8	--	--
Nickel	262	37	670	340	33	8.0	3.0	1.3	0.25	0.072	100	HBSL	2.3	--	--
Radon	358	3.6	6,000	5,000	3,300	2,400	1,300	530	200	82	300 or 4,000	MCL[1]/AMCL[2]	64.5, 2.8	--	--
Selenium	282	88.3	92	47	2.4	< 1	< 1	< 1	< 1	< 1	50	MCL	0.4	--	--
Silver	264	100	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	100	HBSL	0	100	0
Strontium	59	0	6,400	6,400	3,800	1,900	690	190	66	27	4,000	HBSL	3.4	--	--
Thallium	57	94.7	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	2	MCL	0	--	--
Uranium	336	70.5	35	17	5.3	3.9	1.2	0.51	0.19	0.074	30	MCL	0.3	--	--
Vanadium	57	75.4	12	12	7.4	3.4	< 1	< 1	< 1	< 1	--	--	--	--	--
Zinc	238	9.2	870	580	260	140	42	8.1	2.0	1.0	2,000	HBSL	0	5,000	0

Appendix 3. Summary statistics and percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA program, 1992–2003, by major aquifer group.—Continued

[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 by using USEPA toxicity data and methods (Toccalino and Norman, 2006); Action levels (ALs) are concentrations which, if exceeded, trigger treatment or other requirements in USEPA regulations for public water supplies; --, not applicable; <, value is less than value shown. All benchmarks and guidelines are in micrograms per liter except radon, for which the proposed benchmark is in picocuries per liter; reporting level is 1 microgram per liter except for boron (12 micrograms per liter), iron (10 micrograms per liter), radon, (80 picocuries per liter), and strontium (0.9 micrograms per liter). Percentiles below multiple censoring levels were estimated by regression on order statistics; percentiles not estimated if percentage of censored values was greater than 80; if percentiles were not estimated, actual values are shown for percentiles greater than or equal to the assessment level; USEPA Secondary Maximum Contaminant Level (SMCL) is a nonenforceable federal guideline to address the cosmetic or aesthetic considerations of drinking water]

Element	Number of samples	Percentage of samples with censored values	Concentration percentile, in µg/L (pCi/L for radon)								Human-health benchmark			Nonhealth guideline	
			Max	99th	95th	90th	75th	50th	25th	10th	Benchmark	Type	Percentage exceeding benchmark	Guideline value (SMCL)	Percentage exceeding SMCL
Sandstone and carbonate-rock aquifers															
Aluminum	166	24.7	240	46	5.0	4.6	3.8	3.0	1.6	1.1	--	--	--	50 or 200	0.6, 0.6
Antimony	186	100	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	6	MCL	0	--	--
Arsenic	189	88.9	16	13	1.3	1.0	< 1	< 1	< 1	< 1	10	MCL	1.1	--	--
Barium	189	0	990	600	200	120	56	37	29	14	2,000	MCL	0	--	--
Beryllium	186	100	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	4	MCL	0	--	--
Boron	0	--	--	--	--	--	--	--	--	--	1,000	HBSL	--	--	--
Cadmium	186	100	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	5	MCL	0	--	--
Chromium	188	23.9	8.0	7.0	5.3	4.8	3.6	2.2	1.2	0.86	100	MCL	0	--	--
Cobalt	186	96.8	11	2.6	< 1	< 1	< 1	< 1	< 1	< 1	--	--	0	--	--
Copper	189	26.5	57	41	11	8.0	4.9	2.0	0.98	0.49	1,300	AL	0	1,000	0
Iron	222	59	5,800	2,300	410	120	11	2.4	0.25	0.038	--	--	--	300	7.7
Lead	187	72.7	9.0	6.8	4.0	2.7	1.0	0.44	0.18	0.082	15	AL	0	--	--
Lithium	0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Manganese	219	54.8	5,100	1,400	180	83	6.6	0.73	0.071	0.009	300	HBSL	3.2	50	13.2
Molybdenum	188	72.3	55	31	6.0	3.1	1.0	0.26	0.070	0.021	40	HBSL	0.5	--	--
Nickel	189	29.1	42	20	7.4	4.0	2.5	1.4	0.69	0.37	100	HBSL	0	--	--
Radon	136	13.8	2,600	2,000	1,300	870	510	260	120	63	300 or 4,000	MCL[1]/AMCL[2]	44.1, 0.0	--	--
Selenium	189	84.7	14	11	2.0	1.2	< 1	< 1	< 1	< 1	50	MCL	0	--	--
Silver	184	100	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	100	HBSL	--	100	0
Strontium	98	1	44,000	44,000	15,000	12,000	4,500	450	170	94	4,000	HBSL	25.5	--	--
Thallium	0	--	--	--	--	--	--	--	--	--	2	MCL	--	--	--
Uranium	187	84	93	13	3.2	1.4	< 1	< 1	< 1	< 1	30	MCL	0.5	--	--
Vanadium	0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Zinc	178	12.4	1,400	1,000	380	270	48	13	2.0	0.65	2,000	HBSL	0	5,000	0

Appendix 3. Summary statistics and percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA program, 1992–2003, by major aquifer group.—Continued

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Element	Number of samples	Percentage of samples with censored values	Concentration percentile, in µg/L (pCi/L for radon)								Human-health benchmark			Nonhealth guideline	
			Max	99th	95th	90th	75th	50th	25th	10th	Benchmark	Type	Percentage exceeding benchmark	Guideline value (SMCL)	Percentage exceeding SMCL
							Carbonate-rock aquifers								
Aluminum	195	9.2	130	54	15	12	6.0	4.2	2.6	1.0	--	--	--	50 or 200	1, 0
Antimony	189	0.5	5.0	< 1	< 1	< 1	< 1	< 1	< 1	< 1	6	MCL	0	--	--
Arsenic	229	81.7	19	12	3.0	2.0	< 1	< 1	< 1	< 1	10	MCL	1.3	--	--
Barium	189	7.9	540	260	120	69	33	19	10	2.9	2,000	MCL	0	--	--
Beryllium	189	100	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	4	MCL	--	--	--
Boron	0	--	--	--	--	--	--	--	--	--	1,000	HBSL	--	--	--
Cadmium	189	98.9	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	5	MCL	0	--	--
Chromium	190	31.6	9.0	7.7	6.0	5.0	4.0	2.0	0.84	0.54	100	MCL	0	--	--
Cobalt	189	88.4	5.0	1.6	< 1	< 1	< 1	< 1	< 1	< 1	--	--	0	--	--
Copper	189	45.0	26	23	7.0	5.2	3.0	1.1	0.59	0.32	1,300	AL	0	1,000	0
Iron	480	44.2	13,000	4,900	1,800	1,000	63	5.0	0.48	0.055	--	--	--	300	19
Lead	189	90.0	11	5.0	2.0	< 1	< 1	< 1	< 1	< 1	15	AL	0	--	--
Lithium	0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Manganese	463	45.1	3600	810	130	52.00	11	1.1	0.25	0.048	300	HBSL	1.9	50	10
Molybdenum	189	68.8	8.0	5.5	3.0	2.0	1.0	0.32	0.14	0.064	40	HBSL	0	--	--
Nickel	189	38.1	9.7	8.0	4.0	3.0	2.0	1.0	0.65	0.37	100	HBSL	0	--	--
Radon	431	1.6	6,000	2,400	1,300	900	650	410	180	110	300 or 4,000	MCL[1]/AMCL[2]	61, 0.2	--	--
Selenium	183	98.9	2.8	1.3	< 1	< 1	< 1	< 1	< 1	< 1	50	MCL	0	--	--
Silver	169	100	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	100	HBSL	--	100	0
Strontium	140	0	15,000	2,700	1,500	1,200	900	540	200	65	4,000	HBSL	0.7	--	--
Thallium	0	--	--	--	--	--	--	--	--	--	2	MCL	--	--	--
Uranium	318	70.4	39	13	5.8	2.0	< 1	< 1	< 1	< 1	30	MCL	0.3	--	--
Vanadium	0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Zinc	190	16.3	830	780	220	65	15	4.2	1.6	0.36	2,000	HBSL	0	5,000	0

Appendix 3. Summary statistics and percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA program, 1992–2003, by major aquifer group.—Continued

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Element	Number of samples	Percentage of samples with censored values	Concentration percentile, in µg/L (pCi/L for radon)								Human-health benchmark			Nonhealth guideline	
			Max	99th	95th	90th	75th	50th	25th	10th	Benchmark	Type	Percentage exceeding benchmark	Guideline value (SMCL)	Percentage exceeding SMCL
Basaltic- and volcanic-rock aquifers															
Aluminum	31	58.1	20	20	8.7	2.7	1.4	0.48	0.16	0.074	--	--	--	50 or 200	0, 0
Antimony	30	100	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	6	MCL	--	--	--
Arsenic	81	42.0	38	38	11	8.0	3.0	1.0	0.40	0.17	10	MCL	6.2	--	--
Barium	35	11.4	18	18	15	9.3	4.5	2.2	1.6	0.78	2,000	MCL	0	--	--
Beryllium	31	100	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	4	MCL	0	--	--
Boron	30	0	190	190	180	120	59	42	30	23	1,000	HBSL	0	--	--
Cadmium	81	100	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	5	MCL	0	--	--
Chromium	80	35	13	13	3.0	2.5	1.9	1.3	0.78	0.53	100	MCL	0	--	--
Cobalt	81	100	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	--	--	--	--	--
Copper	80	45.5	10	10	7.4	6.6	2.9	1.3	0.64	0.34	1,300	AL	0	1,000	0
Iron	232	65.5	4,100	970	59	12	5.0	0.66	0.10	0.019	--	--	--	300	3.4
Lead	81	76.5	4.0	4.0	1.9	1.5	0.92	0.53	0.31	0.19	15	AL	0	--	--
Lithium	31	9.7	7.0	7.0	2.1	1.3	0.92	0.61	0.46	0.32	--	--	--	--	--
Manganese	228	83.8	1,700	1,100	91	5.0	< 1	< 1	< 1	< 1	300	HBSL	2.6	50	6.1
Molybdenum	30	100	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	40	HBSL	0	--	--
Nickel	30	83.3	1.6	1.6	1.5	1.2	< 1	< 1	< 1	< 1	100	HBSL	0	--	--
Radon	192	1.6	2,700	2,300	1,300	940	520	220	110	83	300 or 4,000	MCL[1]/AMCL[2]	42.7, 0	--	--
Selenium	74	70.3	5.0	5.0	2.4	1.7	0.87	0.44	0.24	0.13	50	MCL	0	--	--
Silver	35	97.1	1.0	< 1	< 1	< 1	< 1	< 1	< 1	< 1	100	HBSL	--	100	0
Strontium	31	0	350	350	290	200	110	68	48	43	4,000	HBSL	0	--	--
Thallium	0	--	--	--	--	--	--	--	--	--	2	MCL	0	--	--
Uranium	33	97.0	1.5	1.5	< 1	< 1	< 1	< 1	< 1	< 1	30	MCL	0	--	--
Vanadium	31	0	58	58	56	48	41	25	15	12	--	--	--	--	--
Zinc	70	4.3	700	700	210	110	47	15	6.0	3.5	2,000	HBSL	0	5,000	0

Appendix 3. Summary statistics and percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA program, 1992–2003, by major aquifer group.—Continued

[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 by using USEPA toxicity data and methods (Toccalino and Norman, 2006); Action levels (ALs) are concentrations which, if exceeded, trigger treatment or other requirements in USEPA regulations for public water supplies; --, not applicable; <, value is less than value shown. All benchmarks and guidelines are in micrograms per liter except radon, for which the proposed benchmark is in picocuries per liter; reporting level is 1 microgram per liter except for boron (12 micrograms per liter), iron (10 micrograms per liter), radon, (80 picocuries per liter), and strontium (0.9 micrograms per liter). Percentiles below multiple censoring levels were estimated by regression on order statistics; percentiles not estimated if percentage of censored values was greater than 80; if percentiles were not estimated, actual values are shown for percentiles greater than or equal to the assessment level; USEPA Secondary Maximum Contaminant Level (SMCL) is a nonenforceable federal guideline to address the cosmetic or aesthetic considerations of drinking water]

Element	Number of samples	Percentage of samples with censored values	Concentration percentile, in µg/L (pCi/L for radon)								Human-health benchmark			Nonhealth guideline	
			Max	99th	95th	90th	75th	50th	25th	10th	Benchmark	Type	Percentage exceeding benchmark	Guideline value (SMCL)	Percentage exceeding SMCL
Crystalline-rock aquifers															
Aluminum	193	19.17	360	260	28	11	5.1	3.7	2.0	0.77	--	--	--	50 or 200	3.6, 1.0
Antimony	194	94.85	4.8	3.2	< 1	< 1	< 1	< 1	< 1	< 1	6	MCL	0	--	--
Arsenic	223	78.48	51	29	11	4.0	1.00	0.26	0.064	0.018	10	MCL	5.4	--	--
Barium	194	6.7	320	200	99	82	43	12	3.8	1.3	2,000	MCL	0	--	--
Beryllium	194	96.91	7.5	1.7	< 1	< 1	< 1	< 1	< 1	< 1	4	MCL	0.5	--	--
Boron	51	56.86	130	130	52	27	16	12	7.5	5.2	1,000	HBSL	0	--	--
Cadmium	194	97.94	1.5	< 1	< 1	< 1	< 1	< 1	< 1	< 1	5	MCL	0	--	--
Chromium	194	43.3	8.0	6.9	4.0	3.0	1.8	1.0	0.62	0.395	100	MCL	0	--	--
Cobalt	194	90.21	12	3.0	< 1	< 1	< 1	< 1	< 1	< 1	--	--	--	--	--
Copper	194	23.71	420	330	51	22	10	3.1	0.92	0.31	1,300	AL	0	1,000	0
Iron	279	39.07	22,000	10,000	640	260	26	6.2	0.94	0.18	--	--	--	300	9.3
Lead	194	79.38	13	8.0	3.2	2.1	0.55	0.15	0.040	0.014	15	AL	0	--	--
Lithium	58	1.72	1,200	1,200	35	20	8.5	5.0	2.6	0.98	--	--	--	--	--
Manganese	278	24.82	720	620	190	100	22	4.6	1.0	0.25	300	HBSL	3.6	50	16.2
Molybdenum	194	62.89	34	19	6.0	4.0	1.8	0.57	0.21	0.081	40	HBSL	0	--	--
Nickel	194	56.7	12	7.0	5.0	3.0	1.7	0.52	0.202	0.086	100	HBSL	0	--	--
Radon	273	0.73	220,000	45,000	14,000	8,600	4,300	2,200	1,100	460	300 or 4,000	MCL[1]/AMCL[2]	91.9, 28.2	--	--
Selenium	190	92.63	3.9	3.0	1.0	< 1	< 1	< 1	< 1	< 1	50	MCL	0	--	--
Silver	194	98.45	1.0	< 1	< 1	< 1	< 1	< 1	< 1	< 1	100	HBSL	0	100	0
Strontium	84	0	1,700	1,700	500	410	210	110	56	30	4,000	HBSL	0	--	--
Thallium	58	94.8	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	2	MCL	0	--	--
Uranium	279	67.38	430	150	26	12	1.7	0.27	0.045	0.009	30	MCL	3.9	--	--
Vanadium	47	87.23	2.1	2.1	1.7	< 1	< 1	< 1	< 1	< 1	--	--	--	--	--
Zinc	193	24.87	1,000	870	200	48	11	3.0	1.0	0.21	2,000	HBSL	0	5,000	0

[1] USEPA proposed maximum contaminant level (MCL) for radon in water.

[2] USEPA proposed alternative maximum contaminant level (AMCL) for radon in water: a proposed higher allowable MCL if accompanied by a multimedia mitigation program to address radon risk in indoor air.

Appendix 4. Summary of the percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA Program, 1992–2003, by pH, redox state, and major aquifer group.

[Elements for which at least 1 percent of samples exceeded guidelines are shown with blue shading; the total number of these elements is shown at the bottom of the table; low pH is less than 7, whereas high pH is greater than or equal to 7; N, number of samples; %, percentage; --, no data; ≥, greater than or equal to; benchmark or guidelines are in micrograms per liter for all elements except radon, for which the proposed benchmark is in picocuries per liter]

Element	Benchmark or guideline	Low pH						High pH					
		Oxic		Mixed		Anoxic		Oxic		Mixed		Anoxic	
		N	%	N	%	N	%	N	%	N	%	N	%
Unconsolidated sand and gravel aquifers (USG)													
Aluminum	200	116	0.86	45	6.7	57	11	710	0.28	125	0.0	143	0.0
Antimony	6	133	0.0	43	0.0	55	0.0	787	0.0	123	0.0	145	0.0
Arsenic	10	168	3.6	54	7.4	63	9.5	837	11	147	17	170	19
Barium	2,000	141	0.0	51	0.0	57	0.0	802	0.0	138	0.0	152	0.66
Beryllium	4	133	0.0	43	0.0	55	0.0	787	0.0	123	0.0	145	0.0
Boron	1,000	59	3.4	17	18	12	8.3	352	1.1	63	7.9	42	7.1
Cadmium	5	133	0.75	43	0.0	55	0.0	787	0.25	123	0.81	146	0.68
Chromium	100	137	0.0	49	2.0	55	0.0	777	0.0	133	0.0	150	0.0
Copper	1,300	134	0.0	51	0.0	57	0.0	777	0.0	137	0.73	149	0.0
Iron	300	225	0.0	77	39	70	86	988	0.0	155	14	172	53
Lead	15	133	0.0	44	0.0	56	0.0	789	0.0	124	0.0	145	0.0
Manganese	300	199	0.0	73	32	67	42	968	0.0	149	36	162	54
Molybdenum	40	140	1.4	50	4.0	56	0.0	799	1.3	138	8.0	151	2.0
Nickel	100	141	0.0	50	0.0	56	0.0	798	0.0	138	0.0	151	0.0
Radon	300	186	82	49	84	46	57	883	81	112	73	141	54
Selenium	50	140	0.0	49	0.0	57	0.0	800	0.38	137	0.73	152	0.0
Silver	100	129	0.0	39	0.0	53	0.0	780	0.0	122	0.0	142	0.0
Strontium	4,000	54	5.6	19	16	25	4.0	309	3.9	40	13	28	0.0
Thallium	2	41	0.0	7	0.0	5	0.0	252	0.0	34	0.0	25	0.0
Uranium	30	160	6.9	53	15	58	0.0	806	7.1	138	23	155	7.1
Zinc	2,000	124	0.81	47	0.0	57	0.0	762	0.0	133	0.0	148	0.0
Number of elements with ≥ 1% exceedence			6		10		7		6		8		7

Appendix 4. Summary of the percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA Program, 1992–2003, by pH, redox state, and major aquifer group. —Continued

[Elements for which at least 1 percent of samples exceeded guidelines are shown with blue shading; the total number of these elements is shown at the bottom of the table; low pH is less than 7, whereas high pH is greater than or equal to 7; N, number of samples; %, percentage; --, no data; ≥, greater than or equal to; benchmark or guidelines are in micrograms per liter for all elements except radon, for which the proposed benchmark is in picocuries per liter]

Element	Benchmark or guideline	Low pH						High pH					
		Oxic		Mixed		Anoxic		Oxic		Mixed		Anoxic	
		N	%	N	%	N	%	N	%	N	%	N	%
Glacial unconsolidated sand and gravel aquifers (GLA)													
Aluminum	200	99	0.0	78	5.1	42	2.4	85	0.0	73	0.0	94	0.0
Antimony	6	104	0.0	80	0.0	41	0.0	89	0.0	75	0.0	94	0.0
Arsenic	10	104	0.0	82	3.7	42	17	92	1.1	76	1.3	101	23
Barium	2,000	104	0.0	82	0.0	41	0.0	94	0.0	77	0.0	99	0.0
Beryllium	4	104	0.0	81	0.0	41	0.0	93	0.0	77	0.0	99	0.0
Boron	1,000	75	0.0	46	0.0	25	0.0	45	0.0	37	2.7	35	2.9
Cadmium	5	104	0.0	81	0.0	41	0.0	93	0.0	77	0.0	99	0.0
Chromium	100	100	0.0	81	0.0	40	0.0	88	0.0	75	0.0	92	0.0
Copper	1,300	104	0.0	80	0.0	42	0.0	91	0.0	75	0.0	94	0.0
Iron	300	220	0.0	167	29	90	77	264	0.0	188	29	220	75
Lead	15	104	0.0	80	0.0	41	0.0	89	0.0	75	0.0	94	0.0
Manganese	300	206	0.0	168	37	88	44	238	0.0	189	32	220	26
Molybdenum	40	104	0.0	80	0.0	41	0.0	90	3.3	75	5.3	94	1.1
Nickel	100	104	0.0	81	0.0	42	0.0	90	0.0	75	0.0	94	0.0
Radon	300	159	81	102	62	65	40	154	68	84	36	173	24
Selenium	50	103	0.0	81	0.0	42	0.0	95	1.1	76	0.0	99	0.0
Silver	100	103	0.0	81	0.0	39	0.0	92	0.0	77	0.0	99	0.0
Strontium	4,000	73	0.0	46	2.2	22	0.0	46	2.2	33	0.0	30	3.3
Thallium	2	58	0.0	42	0.0	10	0.0	36	0.0	26	0.0	22	0.0
Uranium	30	108	0.0	85	0.0	55	0.0	129	1.6	100	1.0	141	0.0
Zinc	2,000	98	0.0	78	0.0	42	0.0	89	0.0	74	0.0	99	0.0
Number of elements with ≥ 1% exceedence			1		6		5		6		7		7

Appendix 4. Summary of the percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA Program, 1992–2003, by pH, redox state, and major aquifer group. —Continued

[Elements for which at least 1 percent of samples exceeded guidelines are shown with blue shading; the total number of these elements is shown at the bottom of the table; low pH is less than 7, whereas high pH is greater than or equal to 7; N, number of samples; %, percentage; --, no data; ≥, greater than or equal to; benchmark or guidelines are in micrograms per liter for all elements except radon, for which the proposed benchmark is in picocuries per liter]

Element	Bench-mark or guideline	Low pH						High pH					
		Oxic		Mixed		Anoxic		Oxic		Mixed		Anoxic	
		N	%	N	%	N	%	N	%	N	%	N	%
Semiconsolidated sand aquifers (SCS)													
Aluminum	200	100	1.0	68	10	44	2.3	7	0.0	14	0.0	18	0.0
Antimony	6	104	0.0	70	0.0	46	0.0	18	0.0	14	0.0	25	0.0
Arsenic	10	125	0.0	74	1.4	50	4.0	18	0.0	16	0.0	27	0.0
Barium	2,000	104	1.0	70	0.0	46	0.0	18	0.0	16	0.0	26	0.0
Beryllium	4	104	0.0	70	1.4	46	0.0	18	0.0	14	0.0	25	0.0
Boron	1,000	67	0.0	41	0.0	25	0.0	2	0.0	9	0.0	7	0.0
Cadmium	5	104	0.0	70	0.0	46	0.0	18	0.0	14	0.0	25	0.0
Chromium	100	103	0.0	69	0.0	46	0.0	18	0.0	16	0.0	26	0.0
Copper	1,300	104	0.0	70	0.0	46	0.0	18	0.0	15	0.0	25	0.0
Iron	300	195	0.0	142	37	73	79	28	0.0	19	63	37	62
Lead	15	104	2.9	70	1.4	46	0.0	18	0.0	15	0.0	25	0.0
Manganese	300	189	0.0	142	13	73	25	28	0.0	19	26	37	11
Molybdenum	40	104	0.0	70	0.0	46	0.0	18	0.0	14	0.0	25	0.0
Nickel	100	104	0.0	70	1.4	46	0.0	18	0.0	15	0.0	26	0.0
Radon	300	80	36	38	47	37	32	15	6.7	10	40	15	27
Selenium	50	104	0.0	70	0.0	46	0.0	18	0.0	16	0.0	26	0.0
Silver	100	104	0.0	70	0.0	46	0.0	18	0.0	14	0.0	25	0.0
Strontium	4,000	53	0.0	33	0.0	22	0.0	2	0.0	9	0.0	6	0.0
Thallium	2	53	0.0	33	0.0	22	0.0	2	0.0	9	0.0	6	0.0
Uranium	30	104	0.0	70	0.0	46	0.0	18	0.0	15	0.0	25	0.0
Zinc	2,000	98	0.0	67	0.0	45	0.0	9	0.0	16	0.0	20	0.0
Number of elements with ≥ 1% exceedence			4		8		5		1		3		3

Appendix 4. Summary of the percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA Program, 1992–2003, by pH, redox state, and major aquifer group. —Continued

[Elements for which at least 1 percent of samples exceeded guidelines are shown with blue shading; the total number of these elements is shown at the bottom of the table; low pH is less than 7, whereas high pH is greater than or equal to 7; N, number of samples; %, percentage; --, no data; ≥, greater than or equal to; benchmark or guidelines are in micrograms per liter for all elements except radon, for which the proposed benchmark is in picocuries per liter]

Element	Benchmark or guideline	Low pH						High pH					
		Oxic		Mixed		Anoxic		Oxic		Mixed		Anoxic	
		N	%	N	%	N	%	N	%	N	%	N	%
Sandstone aquifers (SAN)													
Aluminum	200	20	0.0	27	11	31	0.0	78	0.0	14	0.0	50	0.0
Antimony	6	33	0.0	30	0.0	33	0.0	84	1.2	16	0.0	49	0.0
Arsenic	10	35	0.0	31	0.0	34	0.0	99	4.0	16	0.0	51	0.0
Barium	2,000	35	0.0	31	0.0	34	0.0	100	0.0	16	0.0	51	2.0
Beryllium	4	33	0.0	30	3.3	33	0.0	84	0.0	16	0.0	49	0.0
Boron	1,000	19	0.0	--	--	--	--	46	0.0	4	0.0	13	0.0
Cadmium	5	35	0.0	30	3.3	33	0.0	99	1.0	16	0.0	49	0.0
Chromium	100	33	0.0	30	0.0	33	0.0	99	0.0	16	0.0	51	0.0
Copper	1,300	35	0.0	31	0.0	34	0.0	100	0.0	16	0.0	49	0.0
Iron	300	40	0.0	40	60	50	90	143	0.0	26	42	72	50
Lead	15	35	0.0	31	0.0	34	2.9	99	0.0	16	0.0	49	0.0
Manganese	300	39	0.0	37	54	49	53	135	0.0	27	15	74	11
Molybdenum	40	33	0.0	30	0.0	33	0.0	85	1.2	16	0.0	49	2.0
Nickel	100	33	0.0	31	3.2	34	2.9	84	0.0	16	0.0	49	0.0
Radon	300	35	86	34	44	46	24	131	86	26	62	71	55
Selenium	50	35	0.0	31	0.0	34	0.0	100	1.0	16	0.0	51	0.0
Silver	100	35	0.0	29	0.0	32	0.0	97	0.0	15	0.0	45	0.0
Strontium	4,000	14	0.0	--	--	--	--	28	0.0	4	25	10	0.0
Thallium	2	14	0.0	--	--	--	--	27	0.0	4	0.0	10	0.0
Uranium	30	36	0.0	34	2.9	43	0.0	117	0.0	24	0.0	62	0.0
Zinc	2,000	22	0.0	27	0.0	32	0.0	79	0.0	15	0.0	50	0.0
Number of elements with ≥ 1% exceedence			1		8		5		6		4		5

Appendix 4. Summary of the percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA Program, 1992–2003, by pH, redox state, and major aquifer group. —Continued

[Elements for which at least 1 percent of samples exceeded guidelines are shown with blue shading; the total number of these elements is shown at the bottom of the table; low pH is less than 7, whereas high pH is greater than or equal to 7; N, number of samples; %, percentage; --, no data; ≥, greater than or equal to; benchmark or guidelines are in micrograms per liter for all elements except radon, for which the proposed benchmark is in picocuries per liter]

Element	Benchmark or guideline	Low pH						High pH					
		Oxic		Mixed		Anoxic		Oxic		Mixed		Anoxic	
		N	%	N	%	N	%	N	%	N	%	N	%
Sandstone and carbonate-rock aquifers (SCR)													
Aluminum	200	80	1.3	8	0.0	5	0.0	64	0.0	2	0.0	6	0.0
Antimony	6	80	0.0	8	0.0	4	0.0	73	0.0	3	0.0	7	0.0
Arsenic	10	81	0.0	8	0.0	6	0.0	73	2.7	3	0.0	7	0.0
Barium	2,000	81	0.0	8	0.0	6	0.0	73	0.0	3	0.0	7	0.0
Beryllium	4	80	0.0	8	0.0	4	0.0	73	0.0	3	0.0	7	0.0
Boron	1,000	--	--	--	--	--	--	--	--	--	--	--	--
Cadmium	5	80	0.0	8	0.0	4	0.0	73	0.0	3	0.0	7	0.0
Chromium	100	80	0.0	8	0.0	6	0.0	73	0.0	3	0.0	7	0.0
Copper	1,300	81	0.0	8	0.0	6	0.0	73	0.0	3	0.0	7	0.0
Iron	300	91	0.0	20	30	7	57	76	0.0	7	0.0	8	75
Lead	15	80	0.0	8	0.0	5	0.0	73	0.0	3	0.0	7	0.0
Manganese	300	89	0.0	20	25	7	0.0	75	0.0	7	29	8	0.0
Molybdenum	40	81	0.0	8	0.0	5	0.0	73	1.4	3	0.0	7	0.0
Nickel	100	81	0.0	8	0.0	6	0.0	73	0.0	3	0.0	7	0.0
Radon	300	53	57	7	57	6	33	62	34	2	0.0	5	60
Selenium	50	81	0.0	8	0.0	6	0.0	73	0.0	3	0.0	7	0.0
Silver	100	80	0.0	8	0.0	4	0.0	72	0.0	2	0.0	7	0.0
Strontium	4,000	46	8.7	1	0.0	4	100	40	30	1	0.0	5	80
Thallium	2	--	--	--	--	--	--	--	--	--	--	--	--
Uranium	30	80	0.0	8	0.0	5	0.0	73	0.0	3	0.0	7	0.0
Zinc	2,000	80	0.0	8	0.0	6	0.0	69	0.0	3	0.0	7	0.0
Number of elements with ≥ 1% exceedence			3		3		3		4		1		3

Appendix 4. Summary of the percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA Program, 1992–2003, by pH, redox state, and major aquifer group.—Continued

[Elements for which at least 1 percent of samples exceeded guidelines are shown with blue shading; the total number of these elements is shown at the bottom of the table; low pH is less than 7, whereas high pH is greater than or equal to 7; N, number of samples; %, percentage; --, no data; ≥, greater than or equal to; benchmark or guidelines are in micrograms per liter for all elements except radon, for which the proposed benchmark is in picocuries per liter]

Element	Bench-mark or guideline	Low pH						High pH					
		Oxic		Mixed		Anoxic		Oxic		Mixed		Anoxic	
		N	%	N	%	N	%	N	%	N	%	N	%
Carbonate-rock aquifers (CAR)													
Aluminum	200	21	0.0	12	0.0	37	0.0	103	0.0	1	0.0	18	0.0
Antimony	6	21	0.0	11	0.0	37	0.0	98	0.0	1	0.0	18	0.0
Arsenic	10	28	0.0	14	7.1	37	5.4	127	0.0	1	0.0	19	0.0
Barium	2,000	21	0.0	11	0.0	37	0.0	98	0.0	1	0.0	18	0.0
Beryllium	4	21	0.0	11	0.0	37	0.0	98	0.0	1	0.0	18	0.0
Boron	1,000	--	--	--	--	--	--	--	--	--	--	--	--
Cadmium	5	21	0.0	11	0.0	37	0.0	98	0.0	1	0.0	18	0.0
Chromium	100	21	0.0	11	0.0	37	0.0	99	0.0	1	0.0	18	0.0
Copper	1,300	21	0.0	11	0.0	37	0.0	98	0.0	1	0.0	18	0.0
Iron	300	58	0.0	22	41	49	90	286	0.0	9	22	49	73
Lead	15	21	0.0	11	0.0	37	0.0	98	0.0	1	0.0	18	0.0
Manganese	300	52	0.0	22	14	49	6.1	276	0.0	9	0.0	48	6.3
Molybdenum	40	21	0.0	11	0.0	37	0.0	98	0.0	1	0.0	18	0.0
Nickel	100	21	0.0	11	0.0	37	0.0	98	0.0	1	0.0	18	0.0
Radon	300	49	69	19	79	49	73	254	58	8	88	46	43
Selenium	50	20	0.0	11	0.0	37	0.0	93	0.0	1	0.0	18	0.0
Silver	100	20	0.0	11	0.0	30	0.0	90	0.0	1	0.0	14	0.0
Strontium	4,000	8	0.0	7	0.0	33	0.0	77	1.3	5	0.0	9	0.0
Thallium	2	--	--	--	--	--	--	--	--	--	--	--	--
Uranium	30	23	0.0	11	0.0	38	0.0	213	0.47	6	0.0	23	0.0
Zinc	2,000	21	0.0	11	0.0	37	0.0	99	0.0	1	0.0	18	0.0
Number of elements with ≥ 1% exceedence			1		4		4		2		2		3

Appendix 4. Summary of the percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA Program, 1992–2003, by pH, redox state, and major aquifer group. —Continued

[Elements for which at least 1 percent of samples exceeded guidelines are shown with blue shading; the total number of these elements is shown at the bottom of the table; low pH is less than 7, whereas high pH is greater than or equal to 7; N, number of samples; %, percentage; --, no data; ≥, greater than or equal to; benchmark or guidelines are in micrograms per liter for all elements except radon, for which the proposed benchmark is in picocuries per liter]

Element	Benchmark or guideline	Low pH						High pH					
		Oxic		Mixed		Anoxic		Oxic		Mixed		Anoxic	
		N	%	N	%	N	%	N	%	N	%	N	%
Basaltic- and other volcanic-rock aquifers (BAV)													
Aluminum	200	16	0.0	--	--	--	--	14	0.0	--	--	--	--
Antimony	6	16	0.0	--	--	--	--	14	0.0	--	--	--	--
Arsenic	10	17	0.0	--	--	1	0.0	16	0.0	--	--	--	--
Barium	2,000	17	0.0	--	--	1	0.0	16	0.0	--	--	--	--
Beryllium	4	16	0.0	--	--	--	--	14	0.0	--	--	--	--
Boron	1,000	16	0.0	--	--	--	--	14	0.0	--	--	--	--
Cadmium	5	17	0.0	--	--	1	0.0	16	0.0	--	--	--	--
Chromium	100	17	0.0	--	--	1	0.0	16	0.0	--	--	--	--
Copper	1,300	17	0.0	--	--	1	0.0	16	0.0	--	--	--	--
Iron	300	20	0.0	1	100	1	100	148	0.0	9	33	4	50
Lead	15	17	0.0	--	--	1	0.0	16	0.0	--	--	--	--
Manganese	300	19	0.0	1	0.0	1	100	146	0.0	9	33	4	0.0
Molybdenum	40	16	0.0	--	--	--	--	14	0.0	--	--	--	--
Nickel	100	16	0.0	--	--	--	--	14	0.0	--	--	--	--
Radon	300	19	11	1	0.0	--	--	127	43	9	89	3	33
Selenium	50	17	0.0	--	--	1	0.0	16	0.0	--	--	--	--
Silver	100	17	0.0	--	--	1	0.0	16	0.0	--	--	--	--
Strontium	4,000	16	0.0	--	--	--	--	14	0.0	--	--	--	--
Thallium	2	16	0.0	--	--	--	--	14	0.0	--	--	--	--
Uranium	30	17	0.0	1	0.0	--	--	15	0.0	--	--	--	--
Zinc	2,000	16	0.0	--	--	--	--	15	0.0	--	--	--	--
Number of elements with ≥ 1% exceedence			1		1		2		1		3		2

Appendix 4. Summary of the percent exceedences of human-health benchmarks and nonhealth guidelines for trace elements in groundwater across the United States sampled by the NAWQA Program, 1992–2003, by pH, redox state, and major aquifer group.—Continued

[Elements for which at least 1 percent of samples exceeded guidelines are shown with blue shading; the total number of these elements is shown at the bottom of the table; low pH is less than 7, whereas high pH is greater than or equal to 7; N, number of samples; %, percentage; --, no data; ≥, greater than or equal to; benchmark or guidelines are in micrograms per liter for all elements except radon, for which the proposed benchmark is in picocuries per liter]

Element	Bench-mark or guideline	Low pH						High pH					
		Oxic		Mixed		Anoxic		Oxic		Mixed		Anoxic	
		N	%	N	%	N	%	N	%	N	%	N	%
Crystalline-rock aquifers (CRL)													
Aluminum	200	91	0.0	15	13	4	0.0	62	0.0	2	0.0	16	0.0
Antimony	6	91	0.0	15	0.0	4	0.0	63	0.0	2	0.0	16	0.0
Arsenic	10	102	0.0	16	0.0	4	0.0	76	11	3	0.0	19	16
Barium	2,000	91	0.0	15	0.0	4	0.0	63	0.0	2	0.0	16	0.0
Beryllium	4	91	0.0	15	6.7	4	0.0	63	0.0	2	0.0	16	0.0
Boron	1,000	12	0.0	2	0.0	--	--	26	0.0	--	--	11	0.0
Cadmium	5	91	0.0	15	0.0	4	0.0	63	0.0	2	0.0	16	0.0
Chromium	100	91	0.0	15	0.0	4	0.0	63	0.0	2	0.0	16	0.0
Copper	1,300	91	0.0	15	0.0	4	0.0	63	0.0	2	0.0	16	0.0
Iron	300	141	0.0	25	28	5	100	76	0.0	3	67	23	52
Lead	15	91	0.0	15	0.0	4	0.0	63	0.0	2	0.0	16	0.0
Manganese	300	141	0.0	24	17	5	40	76	0.0	3	0.0	23	17
Molybdenum	40	91	0.0	15	0.0	4	0.0	63	0.0	2	0.0	16	0.0
Nickel	100	91	0.0	15	0.0	4	0.0	63	0.0	2	0.0	16	0.0
Radon	300	138	90	25	92	5	100	73	99	3	100	23	83
Selenium	50	90	0.0	15	0.0	4	0.0	60	0.0	2	0.0	16	0.0
Silver	100	91	0.0	15	0.0	4	0.0	63	0.0	2	0.0	16	0.0
Strontium	4,000	30	0.0	9	0.0	--	--	31	0.0	1	0.0	12	0.0
Thallium	2	12	0.0	2	0.0	--	--	31	0.0	1	0.0	12	0.0
Uranium	30	141	2.8	25	0.0	5	0.0	76	7.9	3	0.0	23	0.0
Zinc	2,000	91	0.0	15	0.0	4	0.0	62	0.0	2	0.0	16	0.0
Number of elements with ≥ 1% exceedence			2		5		3		3		2		4

Appendix 5. Summaries of logistic regression analyses of selected trace elements by major aquifer group.

[Dependent variable, binary (0 for non-occurrence, 1 for occurrence, above reporting level); EXP(B), exponentiated model coefficient (equivalent to odds ratio, > 1 means direct relation and < 1 means inverse relation); *c* statistic is a measure of model discrimination (area under the receiver operating characteristics curve); Hosmer-Lemeshow[1] statistic is a measure of model fit; N, continuous; B, binary; <, less than; --, not analyzed]

Dependent variable	Explanatory variable	Type of variable	EXP(B)	*p*-value	*c* statistic (model discrimination)	Hosmer–Lemeshow statistic
			Unconsolidated sand and gravel aquifers–Dry climate			
Aluminum	Silica	N	0.957	< 0.0001	0.811	0.0709
	Dissolved oxygen	N	0.872	0.0002		
	Phosphate	B	1.830	0.0031		
	Nickel	B	2.340	<0.0001		
	Lead	B	6.280	0.0050		
	Selenium	B	0.420	<0.0001		
	Chromium	B	2.014	0.0007		
	Radon	B	2.092	0.0008		
Arsenic	Boron	B	2.765	0.0460	0.952	0.001
	pH	N	8.874	0.0073		
	Silica	N	1.170	< 0.0001		
Boron	Arsenic	B	5.112	0.0008	0.876	0.1068
	Total dissolved solids	N	1.010	< 0.0001		
Iron	pH	N	0.100	0.0002	0.959	0.8788
	Dissolved oxygen	N	0.170	0.0007		
	Nitrate	B	0.199	0.0081		
	Uranium	B	0.195	0.0006		
	Manganese	B	1.001	0.0016		
	Well depth	N	1.003	0.0392		
Manganese	Nickel	B	1.227	0.0002	0.915	0.0540
	Dissolved oxygen	N	0.507	< 0.0001		
	Well depth	N	0.996	< 0.0001		
Molybdenum	Fluoride	B	5.277	0.0017	0.825	0.3994
	Uranium	B	9.254	< 0.0001		
	Selenium	B	2.174	0.0038		
	Dissolved oxygen	N	0.782	< 0.0001		
	pH	N	4.918	< 0.0001		
	Arsenic	B	2.442	0.0014		
	Manganese	B	2.289	0.0043		
Nickel	Total dissolved solids	N	1.002	< 0.0001	0.807	0.1808
	Aluminum	N	2.749	< 0.0001		
	Copper	B	1.686	0.0074		
	Uranium	B	2.341	0.0007		
	pH	N	0.456	0.0025		
Radon	Tritium	B	3.147	0.0002	0.703	0.9576
	Bromide	B	3.839	< 0.0001		
	pH	N	3.691	0.0123		
	Nitrate	B	0.445	0.0147		

Appendix 5. Summaries of logistic regression analyses of selected trace elements by major aquifer group.—Continued

[Dependent variable, binary (0 for non-occurrence, 1 for occurrence, above reporting level); EXP(B), exponentiated model coefficient (equivalent to odds ratio, > 1 means direct relation and < 1 means inverse relation); *c* statistic is a measure of model discrimination (area under the receiver operating characteristics curve); Hosmer-Lemeshow[1] statistic is a measure of model fit; N, continuous; B, binary; <, less than; --, not analyzed]

Dependent variable	Explanatory variable	Type of variable	EXP(B)	*p*-value	*c* statistic (model discrimination)	Hosmer–Lemeshow statistic
		Unconsolidated sand and gravel aquifers–Dry climate—Continued				
Selenium	Specific conductance	N	1.001	0.0005	0.884	0.1986
	Bromide	B	2.316	0.0018		
	Well depth	N	1.003	< 0.0001		
	Nitrate	B	4.376	< 0.0001		
	Aluminum	B	0.377	< 0.0001		
	Fluoride	B	13.452	0.0003		
	Manganese	B	0.331	< 0.0001		
	Molybdenum	B	2.188	0.0204		
	Uranium	B	3.690	0.0010		
	Iron	B	0.417	0.0018		
Strontium	Specific conductance	N	1.005	< 0.0001	0.942	0.0828
Uranium	Total dissolved solids	N	1.002	0.0005	0.908	0.7753
	Nitrogen as ammonia	B	0.228	0.0001		
	Phosphate	B	0.329	<0.0001		
	Copper	B	2.441	0.0022		
	Iron	B	0.434	0.0087		
	Molybdenum	B	9.775	< 0.0001		
	Selenium	B	5.292	< 0.0001		
	Chromium	B	2.144	0.0046		
		Unconsolidated sand and gravel aquifers–Humid climate				
Aluminum	Calcium	N	0.994	0.0079	0.877	0.9472
	Nitrogen as ammonia	B	5.796	0.0095		
	Dissolved oxygen	N	0.834	0.0005		
	Arsenic	B	2.166	0.0359		
	Fluoride	B	0.251	0.0007		
	Nickel	B	2.650	0.0085		
	Chromium	B	6.924	< 0.0001		
Arsenic	pH	N	1.695	0.0077	0.807	0.0118
	Potassium	N	1.229	0.0002		
	Silica	N	1.042	< 0.0001		
	Phosphate	B	2.602	< 0.0001		
	Aluminum	B	2.826	0.0003		
	Copper	B	0.405	0.0005		
	Uranium	B	2.974	0.0001		
Boron	Total dissolved solids	N	1.006	< 0.0001	0.901	0.0445
	Aluminum	B	2.751	0.0197		
	Molybdenum	B	3.595	0.0024		

Appendix 5. Summaries of logistic regression analyses of selected trace elements by major aquifer group.—Continued

[Dependent variable, binary (0 for non-occurrence, 1 for occurrence, above reporting level); EXP(B), exponentiated model coefficient (equivalent to odds ratio, > 1 means direct relation and < 1 means inverse relation); *c* statistic is a measure of model discrimination (area under the receiver operating characteristics curve); Hosmer-Lemeshow[1] statistic is a measure of model fit; N, continuous; B, binary; <, less than; --, not analyzed]

Dependent variable	Explanatory variable	Type of variable	EXP(B)	*p*-value	*c* statistic (model discrimination)	Hosmer–Lemeshow statistic
		Unconsolidated sand and gravel aquifers–Humid climate—Continued				
Copper	pH	N	0.449	0.0003	0.832	0.4555
	Bromide	B	0.362	0.0002		
	Sulfate	N	1.015	< 0.0001		
	Lead	B	4.137	0.0004		
	Uranium	B	3.194	0.0002		
	Zinc	B	5.423	< 0.0001		
	Selenium	B	2.273	0.0537		
Iron	Dissolved oxygen	N	0.350	< 0.0001	0.939	< 0.0001
	pH	N	0.308	< 0.0001		
	Nitrate	B	0.096	< 0.0001		
Manganese	Dissolved oxygen	N	0.436	< 0.0001	0.884	0.8578
	pH	N	1.961	0.0014		
	Copper	B	0.465	0.0056		
	Well depth	N	0.998	0.00009		
Molybdenum	Total dissolved solids	N	1.003	< 0.0001	0.903	0.1047
	Silica	N	0.981	0.0039		
	Well depth	N	1.006	< 0.0001		
	Fluoride	B	2.264	0.0002		
	Aluminum	B	2.366	0.0305		
	Manganese	B	2.559	0.0010		
	Uranium	B	2.869	< 0.0001		
	Chromium	B	0.489	0.0222		
Nickel	Temperature	N	1.125	< 0.0001	0.842	0.0687
	pH	N	0.419	0.0001		
	Sodium	N	1.011	0.0009		
	Nitrogen as ammonia	B	0.420	0.0031		
	Aluminum	B	3.589	0.0012		
	Selenium	B	0.340	0.0074		
	Cobalt	B	17.385	0.0003		
	Chromium	B	3.465	< 0.0001		
Radon	Chromium	B	0.168	< 0.0001	0.867	< 0.0001
	Well depth	N	0.998	0.0004		
	Uranium	B	3.718	0.0002		
	Dissolved oxygen	N	1.299	0.0006		
	Manganese	B	0.284	0.0048		
Selenium	Total dissolved solids	N	1.003	< 0.0001	0.866	0.0187
	Uranium	B	2.655	0.0119		
	Well depth	N	1.002	< 0.0001		

Appendix 5. Summaries of logistic regression analyses of selected trace elements by major aquifer group.—Continued

[Dependent variable, binary (0 for non-occurrence, 1 for occurrence, above reporting level); EXP(B), exponentiated model coefficient (equivalent to odds ratio, > 1 means direct relation and < 1 means inverse relation); *c* statistic is a measure of model discrimination (area under the receiver operating characteristics curve); Hosmer-Lemeshow[1] statistic is a measure of model fit; N, continuous; B, binary; <, less than; --, not analyzed]

Dependent variable	Explanatory variable	Type of variable	EXP(B)	*p*-value	*c* statistic (model discrimination)	Hosmer–Lemeshow statistic
		Unconsolidated sand and gravel aquifers–Humid climate—Continued				
Strontium	Specific conductance	N	1.006	< 0.0001	0.972	0.6053
Uranium	pH	N	2.577	0.0008	0.912	0.5779
	Silica	N	0.964	0.0002		
	Total dissolved solids	N	1.004	< 0.0001		
	Nitrate	B	3.367	0.0002		
	Nitrogen as ammonia	B	0.102	< 0.0001		
	Copper	B	1.865	0.0386		
	Arsenic	B	3.571	0.0002		
	Iron	B	0.456	0.0233		
	Molybdenum	B	1.921	0.0336		
Zinc	Silica	N	1.023	0.0068	0.852	0.1797
	Phosphate	B	0.526	0.0283		
	Copper	B	9.011	< 0.0001		
	Chromium	B	0.115	< 0.0001		
	Dissolved oxygen	N	1.237	0.0002		
		Glacial unconsolidated sand and gravel aquifers				
Aluminum	pH	N	0.530	0.0006	0.851	0.0904
	Iron	B	0.433	0.0087		
	Chromium	B	16.366	< 0.0001		
	Manganese	B	5.327	< 0.0001		
	Nickel	B	3.096	< 0.0001		
Arsenic	pH	N	2.312	0.0001	0.801	0.7528
	Silica	N	1.066	0.0007		
	Dissolved oxygen	N	0.819	< 0.0001		
	Molybdenum	B	2.518	0.0005		
	Uranium	B	1.555	0.0966		
	Well depth	N	1.008	0.0002		
Boron	pH	N	2.695	0.0105	0.821	0.2896
	Bromide	B	4.036	0.0007		
	Molybdenum	B	2.396	0.0337		
	Temperature	N	1.144	0.0055		
	Potassium	N	1.088	0.0251		
Copper	Potassium	N	1.094	0.0337	0.799	0.6210
	Nitrate	B	3.068	< 0.0001		
	Sulfate	N	1.011	< 0.0001		
	Aluminum	B	0.380	< 0.0001		
	Iron	B	0.478	0.0026		
	Molybdenum	B	0.363	< 0.0001		
	Uranium	B	2.160	0.0078		
	Zinc	B	4.842	< 0.0001		

Appendix 5. Summaries of logistic regression analyses of selected trace elements by major aquifer group.—Continued

[Dependent variable, binary (0 for non-occurrence, 1 for occurrence, above reporting level); EXP(B), exponentiated model coefficient (equivalent to odds ratio, > 1 means direct relation and < 1 means inverse relation); *c* statistic is a measure of model discrimination (area under the receiver operating characteristics curve); Hosmer-Lemeshow[1] statistic is a measure of model fit; N, continuous; B, binary; <, less than; --, not analyzed]

Dependent variable	Explanatory variable	Type of variable	EXP(B)	*p*-value	*c* statistic (model discrimination)	Hosmer–Lemeshow statistic
			Glacial unconsolidated sand and gravel aquifers—Continued			
Iron	pH	N	0.326	< 0.0001	0.928	0.9070
	Total dissolved solids	N	1.002	0.0316		
	Well depth	N	1.011	0.0018		
	Dissolved oxygen	N	0.517	< 0.0001		
	Copper	B	0.326	0.0017		
	Uranium	B	0.311	0.0034		
	Chromium	B	0.420	0.0161		
	Radon	B	0.110	< 0.0001		
Manganese	pH	N	0.607	0.0095	0.857	0.8400
	Well depth	N	0.986	< 0.0001		
	Dissolved oxygen	N	0.812	< 0.0001		
	Arsenic	B	2.385	0.0033		
	Iron	B	2.252	0.0034		
	Uranium	B	3.112	0.0002		
	Cobalt	B	4.702	0.0001		
	Nitrate	B	0.426	0.0043		
Molybdenum	Specific conductance	N	1.002	< 0.0001	0.893	0.2575
	pH	N	3.651	< 0.0001		
	Silica	N	0.911	0.0002		
	Bromide	B	0.383	0.0040		
	Dissolved oxygen	N	0.899	0.0415		
	Arsenic	B	2.914	0.0016		
	Fluoride	B	10	< 0.0001		
	Manganese	B	4.157	0.0002		
	Nickel	B	2.957	0.0004		
Nickel	Aluminum	B	3.410	< 0.0001	0.768	0.0984
	Molybdenum	B	2.342	< 0.0001		
	Zinc	B	2.862	0.0002		
	Cobalt	B	6.181	< 0.0001		
Lead	Magnesium	N	0.957	0.0108	0.825	0.5371
	Chloride	N	1.012	0.0003		
	Potassium	N	0.582	0.0254		
	Copper	B	1.063	< 0.0001		
Radon	pH	N	0.416	0.0006	0.933	0.3919
	Nitrate	B	3.015	0.0004		
	Sulfate	N	0.989	0.0025		
	Arsenic	B	0.349	0.0012		

Appendix 5. Summaries of logistic regression analyses of selected trace elements by major aquifer group.—Continued

[Dependent variable, binary (0 for non-occurrence, 1 for occurrence, above reporting level); EXP(B), exponentiated model coefficient (equivalent to odds ratio, > 1 means direct relation and < 1 means inverse relation); *c* statistic is a measure of model discrimination (area under the receiver operating characteristics curve); Hosmer-Lemeshow[1] statistic is a measure of model fit; N, continuous; B, binary; <, less than; --, not analyzed]

Dependent variable	Explanatory variable	Type of variable	EXP(B)	*p*-value	*c* statistic (model discrimination)	Hosmer–Lemeshow statistic
			Glacial unconsolidated sand and gravel aquifers—Continued			
Radon—Continued	Fluoride	B	2.356	0.0107		
	Iron	B	0.325	0.0003		
	Molybdenum	B	0.466	0.0211		
	Cobalt	B	2.427	0.0213		
	Chromium	B	0.542	0.0271		
Selenium	Nitrate	B	4.384	0.0004	0.797	0.9472
	Uranium	B	5.161	< 0.0001		
	Manganese	B	0.250	0.0009		
Strontium	Calcium	N	1.020	< 0.0001	0.815	0.2493
	Sodium	N	1.010	0.0300		
	Dissolved oxygen	N	.0865	0.0105		
	Manganese	B	0.280	0.0060		
	Uranium	B	5.062	0.0001		
Uranium	Magnesium	N	1.057	< 0.0001	0.876	0.8847
	Silica	N	0.918	0.0015		
	Well depth	N	0.971	< 0.0001		
	Fluoride	B	3.321	0.0012		
	Nickel	B	3.173	0.0011		
	Manganese	B	5.226	0.0005		
	Selenium	B	4.092	0.0015		
Zinc	Temperature	N	0.920	0.0028	0.753	0.8044
	Specific conductance	N	0.999	0.0117		
	Silica	N	1.090	0.0063		
	Copper	B	4.161	< 0.0001		
	Nickel	B	2.247	0.0034		
	Radon	B	0.404	0.0016		
	Cobalt	B	3.764	0.0108		
			Semiconsolidated sand aquifers			
Aluminum	pH	N	0.363	< 0.0001	0.856	0.7376
	Silica	N	0.938	< 0.0001		
	Nitrogen as ammonia	B	2.974	0.0250		
	Nickel	B	3.211	0.0031		
	Iron	B	3.062	0.0063		
	Well depth	N	0.997	0.0340		
Arsenic	Dissolved oxygen	N	0.688	0.0003	0.824	0.2713
	Molybdenum	B	3.198	0.0013		
	Cobalt	B	1.908	0.0653		
	Silica	B	1.039	0.0019		

Appendix 5. Summaries of logistic regression analyses of selected trace elements by major aquifer group.—Continued

[Dependent variable, binary (0 for non-occurrence, 1 for occurrence, above reporting level); EXP(B), exponentiated model coefficient (equivalent to odds ratio, > 1 means direct relation and < 1 means inverse relation); *c* statistic is a measure of model discrimination (area under the receiver operating characteristics curve); Hosmer-Lemeshow[1] statistic is a measure of model fit; N, continuous; B, binary; <, less than; --, not analyzed]

Dependent variable	Explanatory variable	Type of variable	EXP(B)	*p*-value	*c* statistic (model discrimination)	Hosmer–Lemeshow statistic
			Semiconsolidated sand aquifers—Continued			
Boron	Magnesium	N	1.142	0.0006	0.784	0.2073
	Dissolved oxygen	N	0.888	0.0577		
	pH	N	1.646	0.0192		
Iron	Dissolved oxygen	N	0.692	< 0.0001	0.812	0.4138
	Nitrate	B	0.192	0.0011		
	Uranium	B	0.248	0.0077		
Manganese	Well depth	N	0.995	0.0010	0.817	0.4914
	Dissolved oxygen	N	0.702	< 0.0001		
	Phosphate	B	3.446	0.0005		
	Zinc	B	4.638	0.0006		
	Chromium	B	0.519	0.0472		
Molybdenum	pH	N	23.641	0.0007	0.971	0.9381
	Total dissolved solids	N	1.005	0.0728		
	Arsenic	B	24.806	0.0022		
	Radon	B	9.477	0.0079		
Nickel	Total dissolved solids	N	1.001	0.0510	0.818	0.1158
	Iron	B	0.482	0.0120		
	Manganese	B	4.4523	0.0039		
	Cobalt	B	15.759	< 0.0001		
	Chromium	B	2.803	0.0002		
Radon	Nitrate	B	2.839	0.00018	0.692	0.9451
	Molybdenum	B	10.720	< 0.0001		
Selenium	Nitrate	B	3.720	0.0016	0.785	0.0469
	Total dissolved solids	N	1.001	0.0096		
	Iron	B	0.296	0.0020		
	Arsenic	B	3.016	0.0133		
Strontium	Total dissolved solids	N	1.011	< 0.0001	0.849	< 0.0001
Uranium	Molybdenum	B	17.527	< 0.0001	0.926	0.0022
	Nitrogen as ammonia	B	0.074	0.0009		
	Sulfate	N	1.018	0.0109		
	Bicarbonate	N	1.005	0.0056		

Appendix 5. Summaries of logistic regression analyses of selected trace elements by major aquifer group.—Continued

[Dependent variable, binary (0 for non-occurrence, 1 for occurrence, above reporting level); EXP(B), exponentiated model coefficient (equivalent to odds ratio, > 1 means direct relation and < 1 means inverse relation); *c* statistic is a measure of model discrimination (area under the receiver operating characteristics curve); Hosmer-Lemeshow[1] statistic is a measure of model fit; N, continuous; B, binary; <, less than; --, not analyzed]

Dependent variable	Explanatory variable	Type of variable	EXP(B)	*p*-value	*c* statistic (model discrimination)	Hosmer–Lemeshow statistic
			Sandstone aquifers			
Aluminum	Bromide	B	0.142	0.0030	0.954	0.9446
	Nitrogen as ammonia	B	37.779	< 0.0001		
	Phosphate	B	0.194	0.0049		
	Nickel	B	8.611	0.0005		
	Chromium	B	54.073	< 0.0001		
Arsenic	Silica	N	1.040	0.0498	0.765	0.4879
	Molybdenum	B	5.719	< 0.0001		
	Uranium	B	0.0278	0.0278		
Boron	Sodium	N	2.0005	< 0.0001	0.972	0.7816
Iron	pH	N	0.231	0.0002	0.953	0.1861
	Sodium	N	0.991	0.0205		
	Nitrogen as ammonia	B	28.063	< 0.0001		
	Dissolved oxygen	N	0.525	< 0.0001		
	Arsenic	B	3.895	0.0416		
	Molybdenum	B	0.206	0.0398		
Manganese	pH	N	0.189	< 0.0001	0.922	0.9936
	Total dissolved solids	N	1.001	0.0095		
	Nitrate	B	0.129	0.0064		
	Iron	B	17.920	< 0.0001		
	Copper	B	0.128	< 0.0001		
Molybdenum	pH	N	6.523	< 0.0001	0.929	0.0003
	Bromide	B	6.187	< 0.0001		
	Well depth	N	1.007	0.0010		
	Arsenic	B	6.655	0.0004		
	Uranium	B	6.948	< 0.0001		
Nickel	Specific conductance	N	0.999	0.0051	0.880	0.532
	Calcium	N	1.025	0.0003		
	Silica	N	1.142	0.0013		
	Well depth	N	1.006	0.0133		
	Aluminum	B	10.755	< 0.0001		
	Copper	B	6.989	< 0.0001		
	Manganese	B	6.749	0.0015		
	Zinc	B	8.674	0.0119		
Radon	Temperature	N	0.798	0.0237	0.835	0.4521
	Nitrate	B	28.709	< 0.0001		
	Phosphate	B	0.482	0.0551		
	Molybdenum	B	9.670	< 0.0001		

Appendix 5. Summaries of logistic regression analyses of selected trace elements by major aquifer group.—Continued

[Dependent variable, binary (0 for non-occurrence, 1 for occurrence, above reporting level); EXP(B), exponentiated model coefficient (equivalent to odds ratio, > 1 means direct relation and < 1 means inverse relation); *c* statistic is a measure of model discrimination (area under the receiver operating characteristics curve); Hosmer-Lemeshow[1] statistic is a measure of model fit; N, continuous; B, binary; <, less than; --, not analyzed]

Dependent variable	Explanatory variable	Type of variable	EXP(B)	*p*-value	*c* statistic (model discrimination)	Hosmer–Lemeshow statistic
			Sandstone aquifers—Continued			
Selenium	Sodium	N	1.005	<0.0001	0.864	0.5721
	Uranium	B	6.970	< 0.0001		
	Iron	B	0.084	0.0009		
Strontium	Total dissolved solids	N	1.002	0.0118	0.814	0.0241
Uranium	Magnesium	N	1.087	< 0.0001	0.923	0.5177
	Nitrogen as ammonia	B	0.055	< 0.0001		
	Molybdenum	B	24.836	< 0.0001		
			Sandstone and carbonate-rock aquifers			
Aluminum	Calcium	N	0.986	0.0007	0.951	0.5763
	Sodium	N	1.094	0.0161		
	Copper	B	8.843	0.0011		
	Manganese	B	19.088	0.0019		
	Zinc	B	21.719	< 0.0001		
	Chromium	B	24.352	0.0003		
Arsenic	Temperature	N	0.803	0.0010	0.827	0.8154
	Molybdenum	B	11.318	0.0007		
	Zinc	B	0.103	0.0081		
Boron	--					
Iron	Copper	B	0.215	0.0066	0.907	0.1299
	Sulfate	N	1.001	0.0375		
	Manganese	B	46.877	0.0003		
Manganese	Temperature	N	0.696	0.0001	0.906	0.0947
	Iron	B	23.787	< 0.0001		
	Chromium	B	0.253	0.0472		
	Radon	B	0.143	0.0112		
Molybdenum	--					
Nickel	Specific conductance	N	1.006	< 0.0001	0.807	0.4762
	pH	N	0.219	0.0025		
	Sodium	N	0.938	0.0020		
	Zinc	B	19.108	0.0056		
Radon	Temperature	N	0.823	0.0015	0.813	0.4555
	Specific conductance	N	0.999	0.0789		
	Silica	N	0.825	0.0419		
	Iron	B	5.048	0.0116		
	Selenium	B	9.544	0.0051		

Appendix 5. Summaries of logistic regression analyses of selected trace elements by major aquifer group.—Continued

[Dependent variable, binary (0 for non-occurrence, 1 for occurrence, above reporting level); EXP(B), exponentiated model coefficient (equivalent to odds ratio, > 1 means direct relation and < 1 means inverse relation); *c* statistic is a measure of model discrimination (area under the receiver operating characteristics curve); Hosmer-Lemeshow[1] statistic is a measure of model fit; N, continuous; B, binary; <, less than; --, not analyzed]

Dependent variable	Explanatory variable	Type of variable	EXP(B)	*p*-value	*c* statistic (model discrimination)	Hosmer–Lemeshow statistic
			Sandstone and carbonate-rock aquifers—Continued			
Selenium	Dissolved oxygen	N	1.525	0.0012	0.837	0.3103
	Arsenic	B	4.285	0.0519		
	Uranium	B	65.706	< 0.0001		
Strontium	Sulfate	N	1.072	0.0008	0.982	0.9075
Uranium	Molybdenum	B	6.734	0.0002	0.862	0.5618
	Selenium	B	1.932	0.0007		
	Bicarbonate	N	1.007	0.0248		
	Calcium	N	1.007	0.0159		
			Carbonate-rock aquifers			
Aluminum	Calcium	N	1.024	< 0.0001	0.801	0.6415
	Magnesium	N	0.914	< 0.0001		
	Sulfate	N	0.982	0.0693		
	Copper	B	1.873	0.0818		
Arsenic	Temperature	N	1.425	< 0.0001	0.906	0.0615
	Molybdenum	B	10.625	< 0.0001		
Iron	Well depth	N	0.981	0.0003	0.941	0.4243
	Arsenic	B	5.437	0.0329		
	Copper	B	0.027	< 0.0001		
	Molybdenum	B	4.295	0.0371		
Manganese	Sulfate	N	1.039	0.0210	0.922	0.2292
	Dissolved oxygen	N	0.728	0.0004		
	Barium	B	12.365	0.0018		
	Iron	B	8.533	< 0.0001		
	Lead	B	0.080	0.0033		
Molybdenum	Nitrate	B	0.363	0.0720	0.877	0.0025
	Sulfate	N	1.008	0.0124		
	Arsenic	B	13.173	< 0.0001		
	Zinc	B	4.497	0.0209		
	Radon	B	8.615	0.0001		
Nickel	Specific conductance	N	1.009	< 0.0001	0.909	0.0012
	Silica	N	0.762	< 0.0001		
	Bromide	B	0.280	0.0141		
	Nitrate	B	5.878	0.0032		
	Nitrogen as ammonia	B	0.052	< 0.0001		

Appendix 5. Summaries of logistic regression analyses of selected trace elements by major aquifer group.—Continued

[Dependent variable, binary (0 for non-occurrence, 1 for occurrence, above reporting level); EXP(B), exponentiated model coefficient (equivalent to odds ratio, > 1 means direct relation and < 1 means inverse relation); *c* statistic is a measure of model discrimination (area under the receiver operating characteristics curve); Hosmer-Lemeshow[1] statistic is a measure of model fit; N, continuous; B, binary; <, less than; --, not analyzed]

Dependent variable	Explanatory variable	Type of variable	EXP(B)	*p*-value	*c* statistic (model discrimination)	Hosmer–Lemeshow statistic
			Carbonate-rock aquifers—Continued			
Radon	pH	N	0.168	0.0002	0.802	0.1311
	Sulfate	N	0.979	0.0445		
	Molybdenum	B	9.741	< 0.0001		
Strontium	pH	N	0.110	0.0145	0.884	0.0549
	Dissolved oxygen	N	0.718	< 0.0001		
Selenium	--					
Uranium	Potassium	N	1.208	0.0041	0.854	0.2260
	Dissolved oxygen	N	0.814	0.0530		
	Phosphate	B	0.141	0.0018		
	Arsenic	B	7.540	0.0002		
	Nickel	B	6.623	0.0007		
			Basaltic- and other volcanic-rock aquifers			
Aluminum	pH	N	0.015	0.0557	0.863	0.3956
	Dissolved oxygen	N	58.869	0.0072		
Arsenic	Radon	B	67.655	0.0112	0.986	0.6350
	Sulfate	N	1.218	0.0313		
	pH	N	168.835	0.0123		
Boron	Total dissolved solids	N	0.895	0.0288	0.957	0.9358
	Sulfate	N	6.917	0.0266		
Iron	pH	N	0.074	0.0116	0.930	0.9393
	Dissolved oxygen	N	0.479	0.0003		
Manganese	Dissolved oxygen	N	0.513	< 0.0001	0.906	0.4485
Molybdenum	--					
Nickel	--					
Radon	Dissolved oxygen	N	0.615	< 0.0001	0.823	0.0109
Selenium	Sulfate	N	1.076	0.0006	0.901	0.0198
	pH	N	0.044	0.0042		
Strontium	--					
Uranium	--					

Appendix 5. Summaries of logistic regression analyses of selected trace elements by major aquifer group.—Continued

[Dependent variable, binary (0 for non-occurrence, 1 for occurrence, above reporting level); EXP(B), exponentiated model coefficient (equivalent to odds ratio, > 1 means direct relation and < 1 means inverse relation); *c* statistic is a measure of model discrimination (area under the receiver operating characteristics curve); Hosmer-Lemeshow[1] statistic is a measure of model fit; N, continuous; B, binary; <, less than; --, not analyzed]

Dependent variable	Explanatory variable	Type of variable	EXP(B)	*p*-value	*c* statistic (model discrimination)	Hosmer–Lemeshow statistic
			Crystalline-rock aquifers			
Aluminum	pH	N	0.467	0.0009	0.792	0.6110
	Silica	N	0.888	< 0.0001		
	Chromium	B	3.495	0.0022		
	Temperature	N	1.161	0.0185		
Arsenic	Barium	N	0.117	0.0082	0.821	0.3963
	Nickel	B	2.961	0.0244		
	pH	N	1.962	0.0055		
	Dissolved oxygen	N	0.720	0.0031		
Copper	pH	N	0.342	0.0004	0.910	0.4821
	Dissolved oxygen	N	1.302	0.0035		
	Iron	B	0.210	0.0027		
	Nickel	B	6.361	0.0006		
	Zinc	B	3.188	0.0342		
Iron	Dissolved oxygen	N	0.650	0.0015	0.914	0.8912
	Nitrate	B	0.061	0.0210		
	Uranium	B	0.199	0.0178		
	Manganese	B	1.005	0.0035		
	Well depth	N	0.995	0.0121		
Manganese	Dissolved oxygen	N	0.608	0.0010	0.916	0.6589
	pH	N	0.209	0.0001		
	Iron	B	11.674	< 0.0001		
	Zinc	B	0.240	0.0414		
	Aluminum	B	0.181	0.0121		
Molybdenum	pH	N	4.058	< 0.0001	0.928	0.4879
	Fluoride	B	10.007	< 0.0001		
	Iron	B	0.354	0.0573		
	Uranium	B	3.447	0.0094		
Nickel	pH	N	0.901	0.0691	0.878	0.1475
	Magnesium	N	0.636	< 0.0001		
	Potassium	N	1.189	0.0039		
	Silica	N	0.911	0.0004		
	Bromide	B	5.575	0.0014		
	Copper	B	10.189	0.0005		
Lead	Temperature	N	1.163	0.0086	0.794	0.0345
	Molybdenum	B	0.142	0.0030		
	Uranium	B	6.350	0.0050		
	Radon	B	3.802	0.0077		
	Dissolved oxygen	N	1.230	0.0140		

Appendix 5. Summaries of logistic regression analyses of selected trace elements by major aquifer group.—Continued

[Dependent variable, binary (0 for non-occurrence, 1 for occurrence, above reporting level); EXP(B), exponentiated model coefficient (equivalent to odds ratio, > 1 means direct relation and < 1 means inverse relation); *c* statistic is a measure of model discrimination (area under the receiver operating characteristics curve); Hosmer-Lemeshow[1] statistic is a measure of model fit; N, continuous; B, binary; <, less than; --, not analyzed]

Dependent variable	Explanatory variable	Type of variable	EXP(B)	*p*-value	*c* statistic (model discrimination)	Hosmer–Lemeshow statistic
			Crystalline-rock aquifers—Continued			
Radon	Temperature	N	0.867	0.0292	0.832	0.6834
	Sulfate	N	0.917	0.0018		
	Arsenic	B	0.162	0.0045		
	Uranium	B	14.724	< 0.0001		
	Lead	B	2.724	0.0438		
Strontium	Calcium	N	1.099	0.0011	0.826	0.6674
	Molybdenum	B	8.883	0.0180		
Selenium	--					
Uranium	Calcium	N	1.080	< 0.0001	0.923	0.3881
	Nitrate	B	0.266	0.313		
	Fluoride	B	4.863	0.0073		
	Iron	B	0.153	0.0011		
	Molybdenum	B	14.865	< 0.0001		
	Lead	B	11.696	0.0010		
Zinc	Temperature	N	1.252	0.0251	0.863	0.0209
	pH	N	0.279	0.0001		
	Silica	B	0.921	0.0129		
	Copper	B	3.245	0.0126		
	Cobalt	B	0.047	0.0326		

[1] Hosmer, D.W., and Lemeshow, S., 2000, Applied logistic regression (2nd ed.): New York, John Wiley and Sons, 375 p.

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For more information concerning this report, contact:

Director
U.S. Geological Survey
New Hampshire-Vermont Water Science Center
331 Commerce Way, Suite 2
Pembroke, NH 03275
dc_nh@usgs.gov

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

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