Occurrence of Uranium and ^{222}Radon in Glacial and Bedrock Aquifers in the Northern United States, 1993–2003

By Joseph D. Ayotte, Sarah M. Flanagan, and William S. Morrow

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Foreword

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

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

In the second decade of the Program (2001–2012), a major focus is on regional assessments of water-quality conditions and trends. These regional assessments are based on major river basins and principal aquifers, which encompass larger regions of the country than the Study Units. Regional assessments extend the findings in the Study Units by filling critical gaps in characterizing the quality of surface water and ground water, and by determining status and trends at sites that have been consistently monitored for more than a decade. In addition, the regional assessments continue to build an understanding of how natural features and human activities affect water quality. Many of the regional assessments employ modeling and other scientific tools, developed on the basis of data collected at individual sites, to help extend knowledge of water quality to unmonitored, yet comparable areas within the regions. The models thereby enhance the value of our existing data and our understanding of the hydrologic system. In addition, the models are useful in evaluating various resource-management scenarios and in predicting how our actions, such as reducing or managing nonpoint and point sources of contamination, land conversion, and altering flow and (or) pumping regimes, are likely to affect water conditions within a region.

Other activities planned during the second decade include continuing national syntheses of information on pesticides, volatile organic compounds (VOCs), nutrients, selected trace elements, and aquatic ecology; and continuing national topical studies on the fate of agricultural chemicals, effects of urbanization on stream ecosystems, bioaccumulation of mercury in stream ecosystems, effects of nutrient enrichment on stream ecosystems, and transport of contaminants to public-supply wells.

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.

Robert M. Hirsch
Associate Director for Water

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Conversion Factors, Water-Quality Units, and Abbreviations

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Radioactivity	
picocurie per liter (pCi/L)	0.037	becquerel per liter (Bq/L)

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

$$°F=(1.8×°C)+32$$

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

ABBREVIATED WATER-QUALITY UNITS

µg/L	micrograms per liter
mg/L	milligrams per liter
pCi/L	picocuries per liter
mg/g	milligram per gram; equivalent to 1 part per million
ppm	parts per million; equivalent to 1 mg/g

MISCELLANEOUS ABBREVIATIONS

redox	oxidation-reduction potential
MCL	Maximum Contaminant Level
AMCL	Alternative Maximum Contaminant Level
NAWQA	National Water-Quality Assessment
NURE	National Uranium Resource Evaluation program
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
TDS	total dissolved solids

AQUIFER GROUP CODES

CPG	Columbia Plateau glacial aquifer group
COS	Cambrian-Ordovician aquifer group
ECG	East-Central glacial aquifer group
NEC	New York and New England crystalline aquifer group
NEG	Northeastern glacial aquifer group
NCG	North-Central glacial aquifer group
WCG	West-Central glacial aquifer group
NPG	Northern Pacific glacial aquifer group
PWG	Pre-Wisconsinan glacial aquifer group

Occurrence of Uranium and ^{222}Radon in Glacial and Bedrock Aquifers in the Northern United States, 1993–2003

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Abstract

Water-quality data collected from 1,426 wells during 1993–2003 as part of the U.S. Geological Survey National Water-Quality Assessment (NAWQA) program were evaluated to characterize the water quality in glacial and bedrock aquifers of the northern United States. One of the goals of the NAWQA program is to synthesize data from individual studies across the United States to gain regional- and national-scale information about the behavior of contaminants. This study focused on the regional occurrence and distribution of uranium and ^{222}radon in ground water in the glacial aquifer system of the United States as well as in the Cambrian-Ordovician and the New York and New England crystalline aquifer systems that underlie the glacial aquifer system. The occurrence of uranium and ^{222}radon in ground water has long been a concern throughout the United States. In the glacial aquifers, as well as the Cambrian-Ordovician and the New York and New England crystalline aquifer systems of the United States, concentrations of uranium and ^{222}radon were highly variable. High concentrations of uranium and ^{222}radon affect ground water used for drinking water and for agriculture.

A combination of information or data on (1) national-scale ground-water regions, (2) regional-scale glacial depositional models, (3) regional-scale geology, and (4) national-scale terrestrial gamma-ray emissions were used to confirm and(or) refine the regions used in the analysis of the water-chemistry data. Significant differences in the occurrence of uranium and ^{222}radon, based primarily on geologic information were observed and used in this report. In general, uranium was highest in the Columbia Plateau glacial, West-Central glacial, and the New York and New England crystalline aquifer groups (75th percentile concentrations of 22.3, 7.7, and 2.9 micrograms per liter (µg/L), respectively). In the Columbia Plateau glacial and the West-Central glacial aquifer groups, about 10 percent of wells sampled had concentrations of uranium that exceeded the U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level of 30 µg/L; in the New York and New England crystalline aquifer group, 4 percent exceeded 30 µg/L.

Ground-water samples with high concentrations of uranium were commonly linked to geologic sources rich in uranium. In seven of nine aquifer groups defined for this study, concentrations of uranium correlated significantly with concentrations of sulfate in ground water (Spearman's rho = 0.20 to 0.56; $p < 0.05$). In the Columbia Plateau, glacial aquifers were derived in part from basaltic lava flows, some felsic volcanic rocks, and some paleo-lake bed materials that may be rich in uranium. In the Columbia Plateau and West-Central glacial aquifer groups, uranium correlated with total dissolved solids, bicarbonate, boron, lithium, selenium, and strontium. In the West-Central glacial aquifer group, rocks such as Cretaceous marine shales, which are abundant in uranium, probably contribute to the high concentrations in ground water; in the southern part of this group, which extends into Nebraska, the glacial or glacial-related sediment may be interbedded with uranium-rich materials that originated to the north and west and in the Rocky Mountains. In New England, crystalline bedrock that is granitic, such as two-mica granites, as well as other high-grade metamorphic rocks, has abundant uranium that is soluble in the predominantly oxic to sub-oxic geochemical conditions. This appears to contribute to high uranium concentrations in ground water.

The highest ^{222}radon concentrations were present in samples from wells completed in the New York and New England crystalline aquifer group; the median value (2,122 picocuries per liter (pCi/L)) was about 10 times the median value of the glacial and Cambrian-Ordovician aquifer groups. More than 25 percent of the samples from the New York and New England crystalline aquifer group wells had ^{222}radon concentrations that exceeded the proposed USEPA Alternative Maximum Contaminant Level (AMCL) of 4,000 pCi/L. ^{222}Radon concentrations in samples from the New York and New England crystalline aquifer group were similar to those found in other countries with similar geologic histories and(or) similar bedrock geology. In the New York and New England crystalline aquifer group, concentrations of ^{222}radon were correlated with uranium (Spearman's rho = 0.60; $p < 0.0001$) and with gross alpha particle activity (Spearman's rho = 0.72; $p < 0.0001$). Also, in some parts of the New York and New England crystalline aquifer group, ^{222}radon correlated with lead (Spearman's rho = 0.52; $p = 0.004$) and some of the lead concentrations (greater than 2 µg/L) were associated with high ^{222}radon concentrations (greater than 10,000 pCi/L).

Introduction

The U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program conducts regional assessments of ground-water quality conditions (Lapham and others, 2005). These assessments target principal aquifers, many of which underlie multiple States, (fig. 1) that are major sources for drinking water, irrigation, and other uses. Regional assessments complement and extend the findings of the NAWQA Study Units (fig. 2) and expand our understanding of ground-water quality over broad regions. These assessments are designed to increase our understanding of how natural features and human activities affect ground-water quality and will help with extrapolating results to unmonitored, comparable areas in other parts of the regions (Lapham and others, 2005). This study focused on uranium and ^{222}radon occurrence in three principal aquifers in the glaciated northern United States (the glacial, Cambrian-Ordovician, and the New York and New England crystalline aquifer systems).

Uranium occurs naturally in the Earth's crust, in plants and animals, and in surface and ground waters. Uranium is among the heaviest and largest elements forming the Earth's crust, and ranks about 48th in abundance. Uranium has 16 isotopes, all of which are radioactive. Natural uranium has three primary isotopes: ^{238}uranium (99.2 percent by weight), ^{235}uranium (0.7 percent), and ^{234}uranium (0.1 percent).

Uranium can be highly concentrated in intrusive igneous rocks, primarily granitic rocks (table 1). In felsic igneous rocks, uranium is concentrated in the micas and amphiboles. The large ionic radius and high valence state of uranium make it incompatible with the minerals created during the early stages of crystallization; therefore, uranium remains in the liquid phase of magma until the final stages of crystallization (Adams and others, 1959). Minerals formed during later stages of crystallization (such as biotite, muscovite, potassium feldspar, sodium feldspar, and quartz) can incorporate up to several percent of uranium in their crystal structure (Churchill, 1991). Uranium also is found in flat-lying bedded deposits in sedimentary rocks. Black shales, coals, asphalt, clays, silts, soils above limestone, and phosphate rocks also can contain large amounts of natural uranium (table 1).

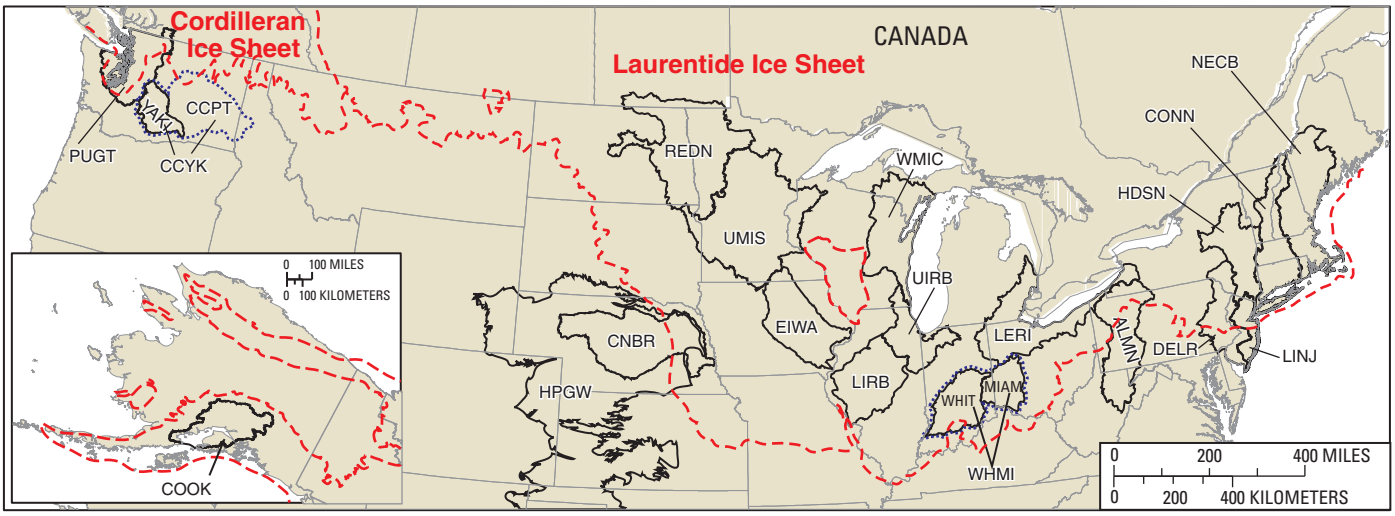
^{222}Radon is an inert gas and is not directly affected by geochemical conditions, yet is highly soluble in ground water. Although radon is formed by the radioactive decay process of uranium, radon and uranium do not necessarily co-occur in ground water. Concentrations of radon in ground water can be many orders of magnitude larger than the concentrations of its parent source. The decay of ^{238}uranium through ^{226}radium is the primary source of ^{222}radon (fig. 3). Geologic sources that might lead to high concentrations of ^{222}radon in soils and ground water are mainly (1) uranium-bearing metamorphosed rocks; (2) silica-rich volcanic rocks; (3) granite-intrusive (igneous) rocks that are highly deformed or sheared; and (4) sedimentary rocks including marine black shales, high-iron soils derived from carbonate, uranium-bearing fluvial sediments, glacial deposits (such as deltaic, marine, and lacustrine deposits), and phosphate rocks (Gundersen, 1991; National Academy of Sciences, 1999; Schumann, 1993a). Because it is the immediate daughter product of ^{226}radium and has a short half life (3.82 days), the presence of ^{222}radon in ground water depends on a readily available source of ^{226}radium and the hydraulic properties of the aquifer materials (Hall and others, 1987).

Concentrations of uranium in ground water also can differ as a result of the natural variability in the geology and in the depositional environment of the materials that compose these aquifers. Local factors, such as the availability of uranium minerals, ground-water flow characteristics, and geochemistry can affect uranium concentrations. Thus, the variation of uranium and ^{222}radon concentrations in ground water in the glacial aquifer system depends, in part, on the source of the aquifer materials. The source of glacial materials depends on (1) the direction of glacial ice lobe movement, (2) the previous glacial deposits, and (3) the underlying bedrock geology. Ice that flowed into the central United States from Canada came from various directions and carried materials from along its path. Glacial-aquifer material is a mix of existing glacial deposits (which may have originated elsewhere) and materials from the underlying bedrock, creating a composite mixture that can affect concentrations of natural contaminants, such as uranium and ^{222}radon.

Uranium and ^{222}radon can have adverse health effects on humans. In 2003, uranium became a regulated contaminant when the U.S. Environmental Protection Agency (USEPA) set a Maximum Contaminant Level (MCL) of 30 micrograms per liter (µg/L) for uranium in drinking water (U.S. Environmental Protection Agency, 2005). Regulating ^{222}radon is complicated because ^{222}radon is an inert gas that is widely detected in ground water, but its primary hazard is through inhalation from indoor air in living spaces (U.S. Environmental Protection Agency, 1999). Currently (2007), the USEPA has not established an MCL for radon in drinking water, but has proposed an MCL of 300 pCi/L and an Alternative Maximum Contaminant Level (AMCL) of 4,000 pCi/L for public-water supplies (U.S. Environmental Protection Agency, 1999). The AMCL would be in effect in states that have established remediation guidelines for radon in indoor air.

In Canada, the drinking-water standard for uranium is 20 µg/L (Health Canada, 2001). The World Health Organization (WHO) has established the lowest drinking-water standard for uranium, at 15 µg/L (World Health Organization, 2004). Two New England states have standards or recommendations for uranium that are lower than the USEPA MCL. The Vermont Department of Environmental Conservation, Water Supply Division, established an MCL for uranium in public water-supply system wells of 20 µg/L, which is based on health risk information from the State of Vermont Department of Health (Vermont Department of Health, 2006). The Maine Bureau of Health established a uranium MCL of 30 µg/L, but advises homeowners to "use less tap water for drinking" if uranium concentrations are between 20 and 30 µg/L (Maine

Figure 1. Locations of National Water-Quality Assessment (NAWQA) regional assessments in principal aquifers.



EXPLANATION

NAWQA STUDY UNIT boundary

COMBINED STUDY UNIT boundaries

GLACIAL EXTENT (approximate)

NAWQA STUDY UNIT

ALMN	Allegheny & Monongahela River Basins	LIRB	Lower Illinois River Basin
CNBR	Central Nebraska Basins	LERI	Lake Erie-Lake St. Clair Drainage
CONN	Connecticut, Housatonic and Thames River Basins	LINJ	Long Island & New Jersey Coastal Drainages
COOK	Cook Inlet Basin	NECB	New England Coastal Basins
DELR	Delaware River Basin	PUGT	Puget Sound Basin
EIWA	Eastern Iowa Basins	REDN	Red River of the North Basin
HDSN	Hudson River Basin	UIRB	Upper Illinois River Basin
HPGW	High Plains Regional Ground-Water Study	UMIS	Upper Mississippi River Basin
		WMIC	Western Lake Michigan Drainage

COMBINED STUDY UNITS

CCYK	Central Columbia Plateau (CCPT) and Yakima River Basin (YAKI)
WHMI	White River Basin (WHIT) and Great and Little Miami River Basins (MIAM)

Figure 2. Locations of National Water-Quality Assessment (NAWQA) program study units in the northern United States.

Bureau of Health, 2005). Other states in the glaciated areas of the U.S. have not adopted guidelines for uranium.

Some state health and regulatory agencies have established their own recommendations concerning acceptable levels of ^{222}radon in drinking water. For example, recommendations regarding treatment for the removal of ^{222}radon from domestic drinking-water supplies take effect at 2,000 pCi/L in New Hampshire (New Hampshire Department of Environmental Services, 2005), at 4,000 pCi/L in Vermont, at 10,000 pCi/L in Massachusetts, and at 5,000 pCi/L in Connecticut (Connecticut Department of Health, 2006). The Maine Department of Human Services recommends that remedial actions should be taken when ^{222}radon concentrations are greater than 20,000 pCi/L (University of Maine, 1996). Other states within the glaciated regions of the United States have not adopted guidelines for ^{222}radon.

The glacial aquifers of the northern United States are important sources of water supply. Estimates of water use in the glacial aquifer system indicated that about 3.56 billion gallons per day (Bgal/d) were withdrawn for all uses during 2000 with about 1.95 Bgal/d for public supply (Maupin and Barber, 2005). Irrigation accounted for 29 percent (1.02 Bgal/d) of all withdrawals (Maupin and Barber, 2005). Irrigation can affect contaminant concentrations found in glaciofluvial aquifers. Irrigation water can contain high concentrations of naturally occurring dissolved salts, major ions, and trace elements, as well as fertilizers and pesticides, that are undesirable for crop growth and(or) human consumption. These chemical inputs can leach past the crop root zone and contaminate the underlying aquifer or subsurface drainage systems in what is called irrigation return flow (National Academy of Sciences, 1989).

Withdrawals from the Cambrian-Ordovician and the New York and New England crystalline aquifer systems totaled 932 million gallons per day (Mgal/d) and 96.3 Mgal/d, respectively in 2000. Public supply accounted for about 63 percent of total withdrawals from the Cambrian-Ordovician aquifer system and 76 percent of total withdrawals from the New York and New England crystalline aquifer system (Maupin and Barber, 2005).

Purpose and Scope

This report presents uranium and ^{222}radon concentrations in three principal aquifers in the northern United States and describes possible sources. The three principal aquifers are (1) the glacial aquifer system in the northern United States, (2) the Cambrian-Ordovician aquifer system, primarily in Minnesota, Wisconsin, Iowa, and Michigan, and (3) the New York and New England crystalline aquifer system in New England and New York (fig. 1). The water-chemistry data used in the assessment were collected during 1993–2003 from 1,426 wells, which are part of the networks used in the NAWQA program. The distribution and concentrations of uranium and ^{222}radon in glacial and bedrock aquifers of the

Table 1. Typical range of uranium concentrations in various rock types.

[<, less than; >, greater than; ~, approximately. Table 1 is modified from Ivanovich and Harmon (1992), table 2.1, p. 36]

Rock type	Name	Uranium (parts per million)
Igneous	Two-mica granite Calc-alkaline granites Alkalic plutonic rocks	3–300
	Granites Granodiorites Rhyolites Dacites	2.2–6.1
	Gabbros	0.8
	Basalts	0.1–1
	Ultramafics	<0.015
Metamorphic	Eclogites	0.3–3
	Granulites	4.9
	Gneiss	2.0
	Schist	2.5
	Phyllite	1.9
	Slate	2.7
Sedimentary	Orthoquartzite	0.45–3.2
	Greywackes	0.5–2.0
	Shales: grey-green, red-yellow, black	2–4 2–4 3–1, 250
	Bauxite	11.4
	Limestones	~2
	Dolomites	0.03–2
	Phosphates	50–300
	Evaporites	<0.1
	Speleothem	<0.03–100
	Living molluscs	<0.01–0.5
	Fossil molluscs	0.l5–8
	Coral	2–4
	Manganese nodules	2–8
	Oceanic sands and clays	0.7–4
	Peat	1–12
	Lignite	<50–80
	Coal	<10–<6,000
	Asphalt	10–3,760
	Oil	4–77

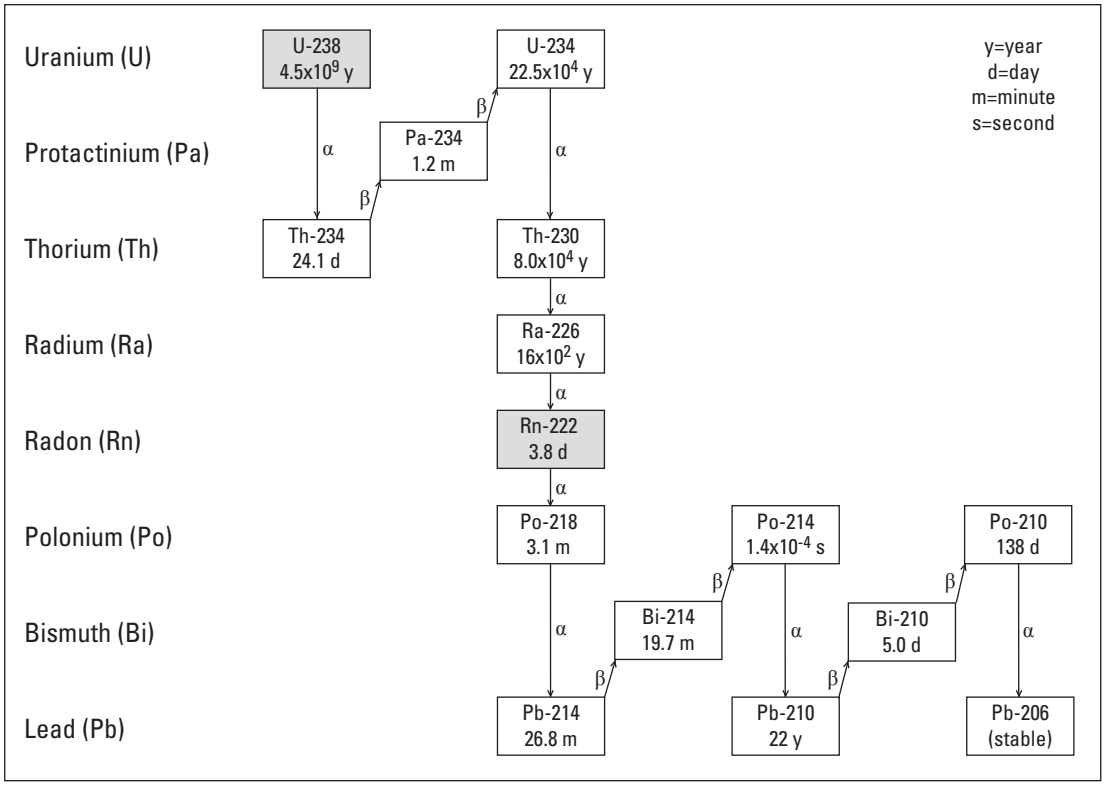


Figure 3. Uranium-238 radioactive decay series.

northern United States are shown on maps, and the relations of uranium and ^{222}radon to each other and to selected water-chemistry constituents, gross alpha particle radioactivity, and physical properties are illustrated in graphs. Statistical summaries of uranium and ^{222}radon concentrations and significant statistical correlations are listed in tables.

Health Effects of Uranium and ^{222}Radon

Uranium enters the human body primarily through ingestion of food and water or by inhalation of airborne uranium-bearing dust particles or aerosols. Little is known about the long-term health effects on humans of exposure to low-level environmental uranium. Studies of occupationally exposed persons, like uranium miners, have shown that the major health effect of uranium in the body is renal (kidney) toxicity (Leggett, 1989; Taylor and Taylor, 1997). Because uranium tends to concentrate in specific locations in the body, such as in the skeletal structure and the liver, risk of bone and liver cancer and blood diseases (such as leukemia) also are increased.

A recent study of uranium concentrations in drinking-water wells in Finland and in urine samples from individuals using these wells found an association between increased uranium exposure through drinking water and increased excretion levels of several solutes, including calcium, in urine (Kurttio and others, 2002). The Finnish study also suggests that a safe concentration for uranium in drinking water is less than 30 µg/L. In addition, recent epidemiology studies have shown that many heavy metals (cadmium, selenium, arsenic, cobalt, copper, nickel, chromium, lead, mercury, tin, uranium, and vanadium) possess estrogenic properties and may act as endocrine disrupters in mammals exposed to these metals in the environment (Choe and others, 2003; Martin and others, 2003).

The Surgeon General of the United States has recognized exposure to ^{222}radon gas as being second only to cigarette smoking as a cause of lung cancer (U.S. Environmental Protection Agency, 1992). ^{222}Radon itself is a relatively inert gas and almost all of the gas that is inhaled is exhaled (Kendall and Smith, 2002). One study found a significant correlation between lung cancer rates and radon levels in Maine, a state known for high concentrations of ^{222}radon in ground water and soils (Hess and others, 1979). An analysis of several epidemiologic studies, however, found a relation between lung cancer and inhalation of radon decay products only in underground miners (Lubin and Boice, 1997).

Previous Investigations

Previous investigations of uranium and ^{222}radon in ground water range from national to local scale. Several national studies provided a comprehensive assessment of the general occurrence and distribution of uranium and ^{222}radon in ground water throughout the United States (Aieta and others, 1987; Cothern and Lappenbusch, 1982; Focazio and others, 2001; Hess and others, 1985; Longtin, 1988; Michael and Cothern, 1986; Michael and Jordana, 1987; National Academy of Sciences, 1999; Otton and others, 1992; U.S. Environmental Protection Agency, 2005; Wanty and Nordstrom, 1993; Zapecza and Szabo, 1988). One study in particular that examined radionuclide occurrence by geologic provinces of the United States (Hess and others, 1985) found that uranium concentrations in ground water were highest in the Colorado Plateau, West Central Platform, and Rocky Mountains, whereas ^{222}radon concentrations in ground water were highest in the New England and Appalachian Highlands/Piedmont. A study on the water-quality data for public-supply wells determined that high concentrations of ^{222}radon in ground water occurred primarily in the New England states, followed by the Appalachian states, the Rocky Mountain states, and small areas of the Southwest and the Great Plains (National Academy of Sciences, 1999). Most of these studies recognized the importance of geologic and geochemical controls on the occurrence of all radionuclides. Numerous regional and statewide studies pertinent to the northern United States also have been done and are described below by region.

Radionuclides in the Northeast

The occurrence of ^{222}radon in the northeast United States has been documented in many studies. These studies found that ^{222}radon concentrations were highest in granitic and high-grade metamorphic bedrock aquifers and were related to hydrologic and hydraulic factors including well pumping (Brutsaert and others, 1981; Hall and others, 1987; Hall and others, 1985; Hess and others, 1979; Maloney, 1988; Moore, 2004; Robinson and others, 2004; Thomas, 1987).

Studies on the occurrence of uranium in ground water in the northeast is limited except for several studies in New Jersey (Szabo and dePaul, 1998; Szabo and others, 2005; Szabo and Zapecza, 1991; Wanty and others, 1992a) and one in Connecticut (Brown and Zielinski, 2004). In these studies, concentrations of uranium and ^{222}radon were related to pH, redox, geology, and other factors (Brown and Zielinski, 2004; Szabo and dePaul, 1998; Szabo and others, 2005; Szabo and Zapecza, 1991; Wanty and others, 1992a).

Radionuclides in the Midwest

Concentrations of ^{222}radon in the glacial aquifer system in the Midwest and the Cambrian-Ordovician aquifer system generally were low but exceeded 100,000 pCi/L in north-central Wisconsin (Mudrey and Bradbury, 1993). ^{222}Radon was present in ground water from crystalline bedrock and glacial aquifers on some Indian reservations in Wisconsin, but radon concentrations were higher in water from bedrock wells than from glacial wells (DeWild and Krohelski, 1995). Results from a study of ^{222}radon in glacial till in southwestern Ohio and southeastern Indiana indicated that the original ^{226}radium source (parent) material was shale in the till but that phosphate fertilizers could be a source (Hair and Baldwin, 1995). In Illinois, uranium concentrations in ground water correlated strongly with sulfate in oxic environments, and in general, ^{222}radon concentrations were less than 1,000 pCi/L (Morrow, 2001). In the Cambrian-Ordovician aquifer system, uranium and ^{222}radon concentrations were relatively low but, ^{226}radium concentrations commonly exceeded the USEPA MCL of 5 pCi/L (Gilkeson and Cowart, 1987). Other studies in this region determined that ^{222}radon concentrations were less than 1,000 pCi/L in glacial and bedrock aquifers (Field and Kross, 1998; Kelley and Mehrhoff, 1993; Stark and others, 2000).

Radionuclides in the West

Parts of the alluvial aquifers in eastern Nebraska and parts of the eastern Platte River valley are derived from glacial outwash (Jennifer Stanton, U.S. Geological Survey, written commun., 2006). In the South Platte River Basin of Nebraska and Colorado, concentrations of uranium from shallow, unconsolidated aquifers commonly exceeded the drinking-water standard of 30 µg/L (Bruce and McMahon, 1998; Dennehy and others, 1998; Parnell, 2000). Uranium concentrations were higher in ground-water samples from alluvial aquifers along the South Platte River than in those from bedrock aquifers in the Rocky Mountains. Background concentrations of ^{222}radon in the glacial aquifer system were substantially higher than the national average; however, median radon concentrations were higher in water samples from the crystalline aquifer than in water samples from the alluvial aquifer (Dennehy and others, 1998). In Alaska, concentrations of uranium in ground water from glacial aquifers in the Cook Inlet area were all less than 1 µg/L (Glass, 2001).

Process Studies and Other Data Related to Radionuclides in Ground Water

Studies relating agricultural irrigation practices to concentrations of uranium in surface and ground waters in the western United States indicated that uranium concentrations were high (greater than 30 µg/L) in waters draining agricultural lands and where streamflow was predominantly from irrigation return flows (Naftz, 1996; Seiler, 2004; Zielinski and others, 1995). High uranium concentrations in surface waters from irrigated areas of the western United States were associated with high evaporation rates, as indicated by high total dissolved solids concentrations (greater than or equal to 500 mg/L), and with fine-grained marine sediments (Cretaceous shale) (Naftz, 1996). High concentrations of uranium in samples from aquifers in an

irrigated area in Nebraska, similar to deposits of the glacial aquifer system, likely resulted from dissolution of volcanic ash or other minerals in underlying bedrock (Verstraeten and others, 2000). Also, induced flow of pumped ground water to deeper parts of aquifers may be an important mechanism of moving uranium-enriched shallow, oxic ground water to public-supply wells (Craig Brown, U.S. Geological Survey, written commun., 2006).

Studies that use process-based models to explain ^{222}radon occurrence provide insight into factors that control ^{222}radon concentrations, although the conclusions derived from these studies sometimes differ. Researchers acknowledge that uranium concentrations in aquifer minerals, porosity, and density of bedrock are factors related to high ^{222}radon concentrations in ground water (Fleischer, 1983; Wanty and others, 1992b). The effect of the presence of ^{226}radium along fractures, flow velocity, and fracture size also have been examined (Folger and others, 1996). More recent research proposes a chemically based diffusion/exchange model to explain elevated ^{222}radon concentrations in fractured rock and the relation of ^{222}radon to ^{226}radium (Wood and others, 2004). A study of ^{222}radon and uranium concentrations in ground water from glacial and fractured-rock aquifers found that porosity and location of the uranium on the fracture were the controlling factors for ^{222}radon concentrations (Veeger and Ruderman, 1998). Other studies have identified areas of high ^{222}radon potential based on geologic characteristics for igneous, metamorphic, sedimentary, and unconsolidated deposits (Gundersen, 1989; Gundersen, 1991; Gundersen, 1993; Gundersen and others, 1992; Moreland and others, 1998).

Other regional data related to radionuclides in the environment were useful in explaining the occurrence of radionuclides in ground water. Data on uranium and other trace elements from the National Uranium Resource Evaluation (NURE) Hydrogeochemical and Stream Sediment Reconnaissance Program (HSSR), a program tasked with identifying uranium resources within the United States, are available for thousands of stream-sediment samples (Smith, 2001a; Smith, 2001b). These data were used as one indicator of areas where sources of uranium may be available to the ground-water system. These sources, however, may not affect concentrations in the ground water because other factors, such as geochemical controls may have greater effect on the solubility and mobility of uranium.

An aerial survey of terrestrial gamma-ray emissions of near-surface sediments, also part of the NURE program, resulted in maps that show estimated isotope concentrations of ^{40}potassium, equivalent ^{238}uranium, and ^{232}thorium in the United States (Duval, 1990). Most of the gamma-ray emissions were from the upper 25 centimeters (cm) of surficial materials (primarily rock or soil). Although ground water may not be in direct contact with the sediments that produce the gamma-ray response, these can be regional scale indicators of the potential for the presence of uranium and ^{222}radon in ground water.

Study Design and Methods

This study focused on three principal aquifers within the glaciated terrain of the northern United States (including the Cook Inlet Basin in Alaska)—(1) the glacial (and glaciofluvial) aquifer system, (2) the Cambrian-Ordovician aquifer system of the upper Midwest and (3) the New York and New England crystalline aquifer system (Lapham and others, 2005) (fig. 1). The largest of the principal aquifers is the glacial aquifer system. In a generalized scheme, the glacial aquifer system has been divided into four areas as a framework to describe general variation in ground-water quality (Warner and Arnold, 2005). This generalized framework was based on hydraulic properties (susceptibility) and features related to contaminant sources (vulnerability), but because mineralogical and(or) geochemical differences among the areas have not been documented, these divisions are subject to revision (Warner and Arnold, 2005). Revisions to the NAWQA glacial aquifer system framework, based in part on information related to mineralogy and geochemistry, were made for the purposes of this report and are described below.

For this study, the glacial aquifer system framework has been modified to account for the geologic source material of the glacial aquifers as a proxy for uranium or other radionuclides in the aquifer matrix. The modified framework is generalized and differentiates the glacial aquifer system on the basis of information on surficial geology, bedrock geology, and late Wisconsinan glacial lobe positions (fig. 4) and flow directions (Duval, 1990; Heath, 1984; King and Beikman, 1974; Meinzer, 1923; Mickelson and others, 1983; Mickelson and Colgan, 2003; Schumann, 1993b). Data representing late Wisconsinan glacial lobe positions were grouped by considering (1) the direction of the glacial lobe movement, which accounts for geologic source materials in the up-ice direction and, (2) the underlying bedrock geology, which accounts for local geologic materials. In addition, national data on equivalent ^{238}uranium (eU) and ^{232}thorium (eTh) content from terrestrial gamma-ray surveys of near-surface sediments (Duval, 1990) were used to refine areas of potentially high radionuclide concentrations in ground water (fig. 5).

Based on the above criteria and for the purposes of this report, the study design for comparing uranium and ^{222}radon concentrations in the glacial, Cambrian-Ordovician, and New York and New England crystalline aquifer systems includes nine aquifer groups: (1) Northern Pacific glacial aquifers, (2) Columbia Plateau glacial aquifers, (3) West-Central glacial aquifers from the James, Des Moines, and Red River (western part) glacial lobes, (4) North-Central glacial aquifers from the Late Wisconsinan Red River (eastern part), Wadena, Rainy, Lake Superior, and Green Bay glacial lobes, (5) East-Central glacial aquifers from the Late Wisconsinan Lake Michigan, Huron, and Huron-Erie glacial lobes, (6) Pre-Wisconsinan glacial aquifers, (7) Northeastern glacial aquifers, (8) Cambrian-Ordovician aquifers, and (9) New York and New England crystalline aquifers (fig. 6, table 2).

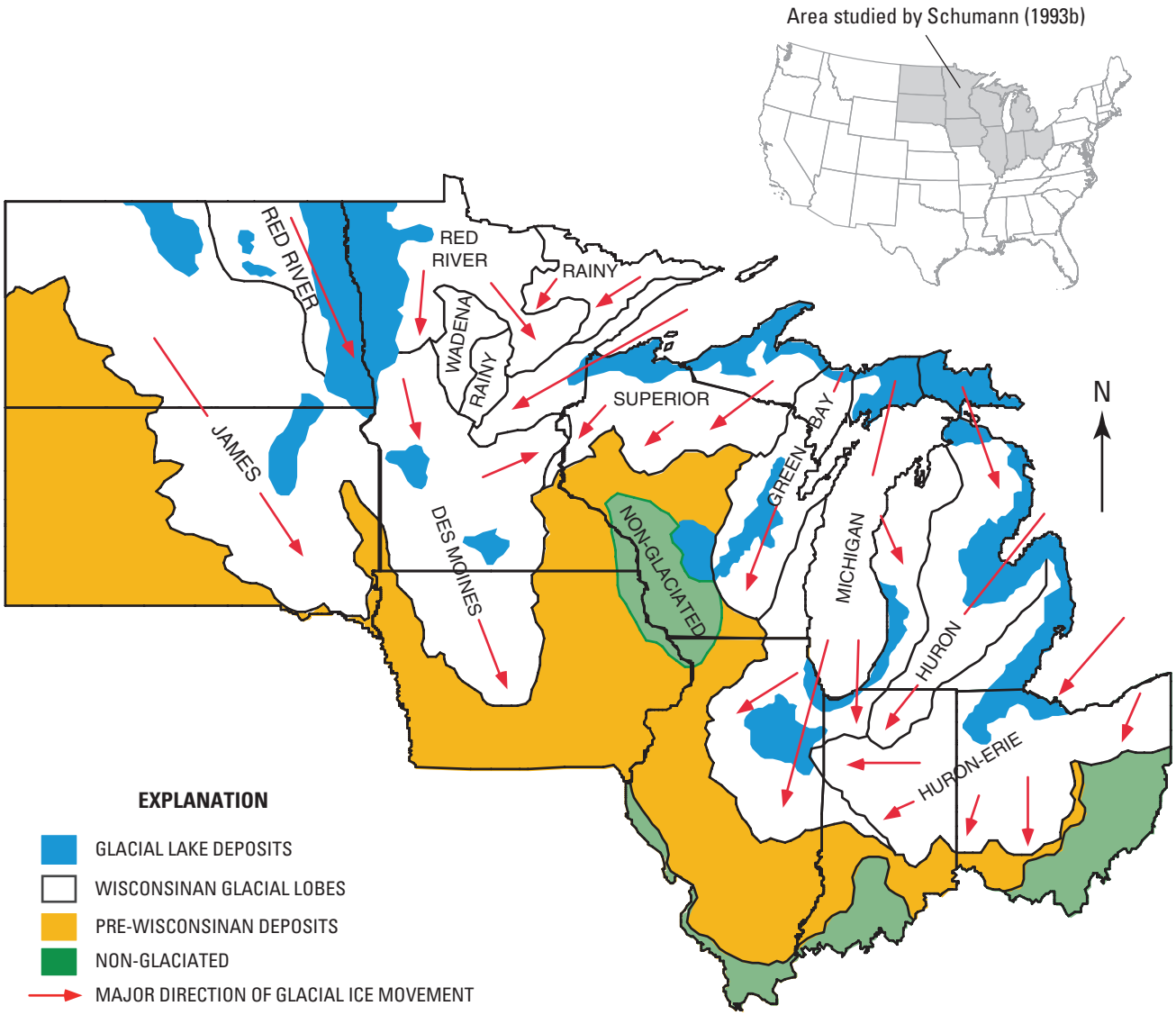


Figure 4. Generalized glacial geologic map of the upper Midwestern United States and names of major glacial lobes that were used to modify the glacial aquifer framework.

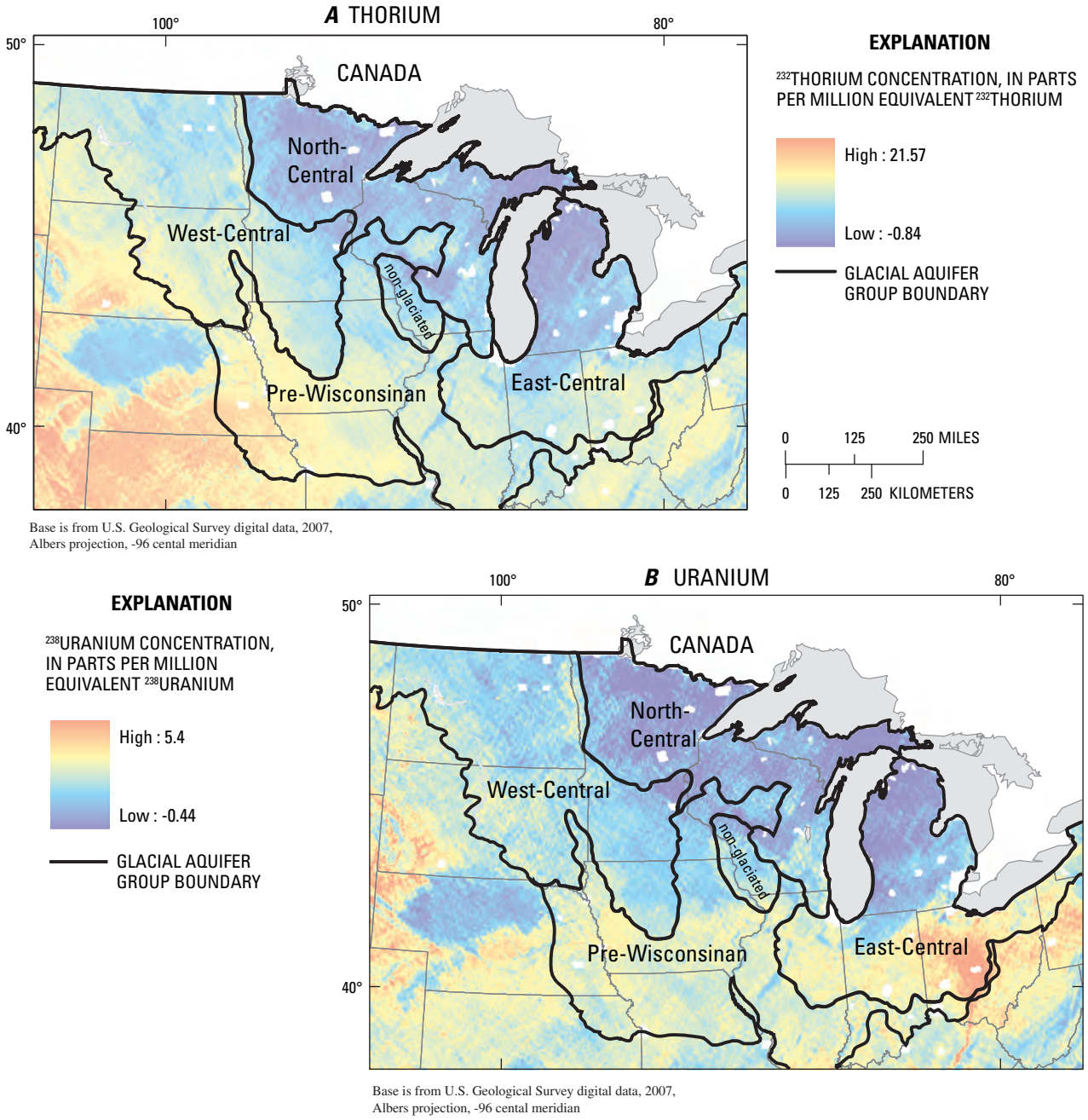
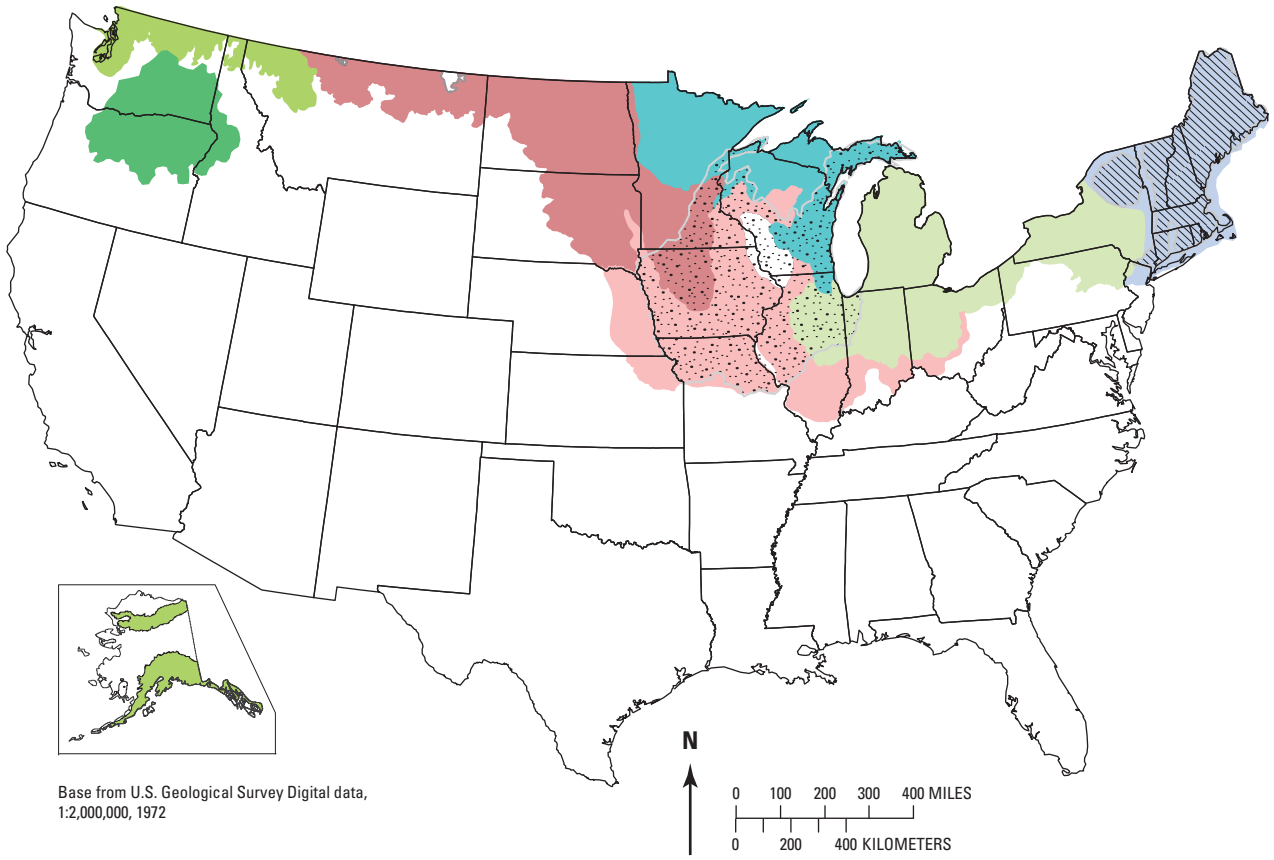


Figure 5. Distributions of (*A*) equivalent ^{232}thorium and (*B*) equivalent ^{238}uranium concentrations of near-surface sediments from aerometric gamma-ray surveys in the upper Midwestern United States used to modify the glacial aquifer framework.



EXPLANATION

AQUIFER GROUP CODE	AQUIFER GROUP
NPG	Northern Pacific glacial (includes Cook Inlet basin, Alaska, not shown)
CPG	Columbia Plateau glacial
WCG	West-Central glacial (James, Des Moines, and western part of the Red River glacial lobes)
NCG	North-Central glacial (eastern part of the Red River, Wadena, Rainy, Lake Superior, and Green Bay glacial lobes)
PWG	Pre-Wisconsinan glacial
ECG	East-Central glacial (Lake Michigan, Huron, and Huron-Erie glacial lobes)
COS	Cambrian-Ordovician (sandstones and dolomite)
NEG	Northeastern glacial
NEC	New York and New England crystalline (fractured bedrock)

Figure 6. Locations of generalized aquifer groups in the northern United States.

The boundaries of the Cambrian-Ordovician and the New York and New England crystalline aquifer systems were not modified but are referred to as groups, rather than systems, in this report, to be consistent with the terminology for the glacial aquifers. Additionally, the sediments in the Nebraska portion of the Pre-Wisconsinan glacial aquifers were derived in part from Cretaceous shale deposits transported within the Dakota lobe (which extended further south than the James lobe, into eastern Nebraska) (Colgan, 1999; Meinzer, 1923; Srhoba and others, 2001; Wayne, 1985) and associated loess (Muhs and Bettis, 2000) and may contain substantial amounts of uranium. This also was supported by the eTh and eU data (fig. 5) from aerometric surveys. Because these deposits are genetically similar to the deposits associated with the James lobe (Schumann, 1993b) and the Dakota lobe (Meinzer, 1923; Wayne, 1985), the wells in Nebraska were included in the West-Central glacial aquifers group. The eTh and eU data also were used to differentiate between the western part of the Red River lobe deposits (composed in part of Cretaceous shale) and the eastern part (composed of sediments derived more from granitic materials) (figs. 4 and 5).

Water-Quality Data Sources and Well Selection

NAWQA water-quality data are stored permanently in the USGS National Water Information System (NWIS). In 1999, the NAWQA program developed a data warehouse to better facilitate national and regional analysis of water-quality data from 51 study units started between 1991 and 1997 (Bell and Williamson, 2006). Water-quality data analyzed in this study were obtained from the NAWQA data warehouse in 2004.

The following criteria were used for selection of wells monitored as part of the NAWQA program: (1) wells were installed in glacial, Cambrian-Ordovician, or the New York and New England crystalline aquifers and were sampled as part of the NAWQA program (fig. 2) and (2) the wells had one uranium and(or) ^{222}radon water-quality data value. A total of 1,426 wells met the above criteria. Nearly 60 percent (817) of these wells had a water-quality value for both uranium and ^{222}radon. In the dataset, 1,106 wells have uranium data and 1,137 have ^{222}radon data. Within the NAWQA program, these wells also were assigned to a NAWQA well network. These well networks were designed to represent (1) the ground-water quality of major aquifer systems or (2) the immediate effects of a particular land-use setting on ground-water quality in an individual NAWQA study unit and are explained in appendix 1. The major aquifer networks were largely domestic and public-supply drinking-water wells and were selected without consideration of the surrounding land uses. Wells in the land-use networks were typically shallow, 2-in.-diameter monitoring wells, screened at or near the water table, and were selected to target predominantly agricultural or urban land uses within a 500-meter radius. In a few cases, the wells sampled for land-use networks were public-supply or domestic wells (appendixes 1 and 2). A total of 56 NAWQA well networks were used in this study. On average, each NAWQA well network had about 30 wells, and the water-quality data were collected over an 11-year period, from 1993 to 2003. Statistical summaries for concentrations of uranium and ^{222}radon for each NAWQA well network are presented in appendix 2.

Sampling and Analysis

Ground-water samples were collected and analyzed for major ions, nutrients, trace elements, chlorofluorocarbons (CFCs), and other constituents from multiple study units, in accordance with NAWQA protocols (Koterba and others, 1995; Lapham and others, 1995). Isotope data for radium species, ^{18}oxygen, deuterium, and tritium also were available for some of the study units. Prior to collection of the samples, wells were pumped until the water temperature, dissolved oxygen, specific conductance, and pH were stable (Koterba and others, 1995). Cleaned fluorinated ethylene polypropylene tubing with stainless steel fittings was connected to either a submersible pump or to a water line close to the wellhead. Samples were collected at a flow rate of 0.05 liters per minute (L/min) in a portable sampling chamber. Samples for trace elements (including uranium), nutrients, and major ions were processed through a 0.45-µm disposable polypropylene capsule filter; the trace-element and cation samples were then acidified with ultra pure nitric acid to a pH of less than 2. The analyses for uranium and other trace elements were made at the USGS National Water Quality Laboratory (NWQL) in Denver, Colo., using inductively-coupled plasma mass spectrometry (ICP/MS) methods; laboratory reporting levels (LRL) ranged from 0.2–1 µg/L (Faires, 1993; Ivahnenko and others, 1996). Analyses for ^{222}radon were done by liquid scintillation methods; LRLs ranged from 52 to 80 pCi/L (Mullin and Wanty, 1991; Prichard and Gessell, 1977).

Analysis of Ancillary Data and Explanatory Variables

A variety of other data were compiled to analyze the variation of radionuclides within all the aquifer groups. Many of these data were obtained from the USGS NAWQA data warehouse (U.S. Geological Survey, 2005). Ancillary data from geographic information systems (GIS) were also compiled for the analysis of uranium and ^{222}radon occurrence. The information compiled included (1) aquifer type—bedrock or glacial unconsolidated, aquifer texture, geographic location and source material; (2) well construction information such as well depth, and well type; (3) population statistics (U.S. Bureau of the Census, 2000); (4) the lithology and litho-chemical character of near surface bedrock in New England (Robinson and Kapo, 2003; Robinson, 1997); (5) National Uranium Resource Evaluation Stream Sediment Chemistry

Table 2. Description of aquifer groups within the glaciated northern United States investigated for the occurrence and distribution of radionuclides.

[Groups were compiled and modified from previous studies (Heath, 1984; Meinzer, 1923; Michael and Cothern, 1986; Michael and Jordana, 1987; Schumann, 1993; U.S. Geological Survey, 2000; U.S. Geological Survey, 2003; Wayne, 1985)]

Principal aquifer	Aquifer group	Aquifer group code	Geologic framework	Hydrologic system
Glacial aquifer system	Northern Pacific glacial aquifers (deposits of the Cordilleran ice sheet)	NPG	Variably mountainous terrain with narrow alluvial and glaciofluvial valleys	Ground-water withdrawals largely from alluvial and glaciofluvial sediments in the valleys; lesser amounts from underlying crystalline-bedrock aquifers.
Glacial aquifer system	Columbia Plateau glacial aquifers	CPG	Volcanic rocks, thick sequence of lava flows interbedded with unconsolidated deposits, covered in places by sediment of glaciofluvial origin	Semiarid with large irrigation withdrawals from streams and the lava interflow zones; irrigation water moves downward into the ground-water system and then discharges to rivers.
Glacial aquifer system	West-central glacial aquifers (deposits of the James, Des Moines, and the Red River (western part) glacial lobes)	WCG	Glacial sediments derived mostly from Cretaceous age sedimentary rocks consisting of shale, limestone, and sandstone	Largest ground-water withdrawals are from thick glacial deposits that include coarse-grained aquifers and from underlying sedimentary bedrock.
Glacial aquifer system	North-central glacial aquifers (deposits of the Red River (eastern part) and Wadena, Rainy, Lake Superior, and Green Bay glacial lobes)	NCG	Glacial sediments overlying predominantly Precambrian granite, metamorphic, and volcanic rocks. Also, some areas of limestone	Largest ground-water withdrawals are from coarse-grained glacial deposits and from underlying Precambrian igneous and metamorphic rocks in most of the area. Some sedimentary bedrock in the south and east.
Glacial aquifer system	East-central glacial aquifers (deposits of the Lake Michigan, Huron, and Huron-Erie glacial lobes)	ECG	Glacial sediments overlying predominantly dolomites, shale, and sandstone	Largest ground-water withdrawals are from coarse-grained glacial deposits.
Glacial aquifer system	Pre-Wisconsinan glacial aquifers	PWG	Glacial sediments overlying Paleozoic dolomite, carbonate, shale, and sandstone	Largest ground-water withdrawals are from coarse-grained glacial deposits.
Glacial aquifer system	Northeastern glacial aquifers	NEG	Glacial sediments derived mostly from fractured crystalline rocks	Largest ground-water withdrawals are from coarse-grained glacial deposits and from underlying crystalline bedrock.
Cambrian–Ordovician aquifer system	Cambrian–Ordovician aquifers	COS	Sandstone and dolomite interlayered with confining units	Ground-water withdrawals primarily from sandstone units but also derive water from vertical leakage through confining layers.
New York and New England crystalline aquifer system	New York and New England crystalline aquifers	NEC	Predominantly fractured igneous and metamorphic bedrock	Ground-water withdrawals for domestic and public supply from secondary brittle fractures in crystalline rock.

data (Smith, 2001a; Smith, 2001b); (6) terrestrial gamma mapping data (Duval, 1990); (7) index of recharge to ground water and hydrologic landscape models (Wolock, 2003a; Wolock, 2003b); (8) water-sample temperature, pH, specific conductance, and dissolved oxygen data, and a variety of related water-chemistry data from samples collected concurrently with the radionuclide samples.

Statistical Analyses

A large proportion of the samples had uranium and other water-chemistry data that were reported as "less than the LRL." For each constituent with concentrations below multiple LRLs, the data were examined in order to determine the highest LRL. Reported concentrations above the lowest LRL, but below the highest LRL, were censored to the highest LRL. This enables the use of all the data in nonparametric statistical analyses without making assumptions about the distribution of the data below the LRL (Helsel and Hirsch, 1992). The highest LRL for uranium was 1 µg/L and the highest LRL for ^{222}radon was 80 pCi/L. For this study, 62 percent of the uranium data and less than 1 percent of the ^{222}radon data were below their respective highest LRLs. Nonparametric statistics, which do not require distributional assumptions about data less than LRLs, were used to describe distributions or compare data among groups. Statistical analyses were performed using all data values, including censored data (data reported as below the LRL).

Contingency table analysis (Pearson's Chi Square test for independence) was used to measure the association of uranium and ^{222}radon (presence or absence) with a grouping variable of two or more categories (Helsel and Hirsch, 1992). Group-comparison tests such as the Wilcoxon and the Kruskal-Wallis tests were used to determine whether the distributions of the data from two or more groups were significantly different (Helsel, 2005; Helsel and Hirsch, 1992; SAS Institute, 1999). Where group-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, 2005; Helsel and Hirsch, 1992; SAS Institute, 1999). Although other methods exist for estimating the distribution of missing data and comparing groups, such as substitution and distributional methods (Helsel, 2005), nonparametric methods offer several benefits including (1) no assumption of normally distributed data; (2) good statistical power; and (3) data below the LRL are used without fabrication, resulting in an accurate portrayal of the "less than the LRL" information (Helsel, 1990; Helsel, 2005; Helsel and Cohn, 1988; Helsel and Hirsch, 1992).

Spearman correlation coefficients (rho) were computed to measure the strength of the relation between environmental factors and concentrations of uranium and ^{222}radon (Helsel and Hirsch, 1992). The significance level (α) for all statistical tests was equal to 0.05.

Evaluations of Quality-Assurance and Quality-Control Data

Water-quality data are subject to bias and variability during sample collection, processing, and analysis. The type and magnitude of bias and variability can be determined by analysis of quality-control samples (Mueller and others, 1997). Field-blank samples can verify that sample collection, processing, and analytical protocols were sufficient to prevent the introduction of contaminants into samples. Replicate environmental samples allow assessment of measurement variability due to sample collection, processing, and laboratory analysis protocols. Quality-control samples, including field blanks and replicates, were collected according to NAWQA protocols (Koterba and others, 1995).

For trace elements including uranium, 130 field blanks (12 percent) were collected for the 1,106 wells sampled. Five of 130 field-blank samples (4 percent) contained a measurable amount of uranium. The highest uranium concentration among those was 0.12 µg/L—well below the highest LRL of 1 µg/L used in this study.

Replicate samples for uranium analysis were collected at 65 wells (6 percent of the samples). Replicate samples for ^{222}radon analysis were collected at 88 of the 1,137 wells sampled (8 percent). The relative percent difference (RPD) between the environmental sample and corresponding replicate sample was calculated as the absolute value of the difference in replicate concentrations divided by the environmental concentration, multiplied by 100. The RPD of the concentrations between the environmental samples and the corresponding replicate samples was less than 7 percent for uranium and 15 percent for ^{222}radon. It was concluded that sample processing and analysis did not introduce enough variation in the environmental data to affect the interpretation of results.

Uranium and ^{222}Radon in Glacial and Bedrock Aquifers

Uranium concentrations differ significantly by principal aquifer. The median uranium concentrations for each of the three principal aquifers were less than 1 µg/L (table 3). Uranium concentrations were highest in the New York and New England crystalline aquifer systems and lowest in the Cambrian-Ordovician aquifer system (table 3). In the glacial aquifer system, uranium concentrations differed between specific geographic regions, and these differences are discussed by aquifer group in the following section. Concentrations of uranium in ground water exceeded 10 µg/L in about 10 percent of the samples from wells in this study; however, only 2.5 percent of samples exceeded the USEPA MCL of 30 µg/L for uranium. Thirty-eight percent of all samples had uranium concentrations greater than 1 µg/L.

Table 3. Summary statistics for concentrations of uranium and ^{222}radon, by principal aquifer in the glaciated northern United States, 1993–2003.

[Concentrations of uranium and ^{222}radon for principal aquifers with the same Tukey group letter do not differ significantly at the 95-percent confidence level (alpha = 0.05). Max, maximum; Min, minimum; P, percentile (90, 75, 25, 10); <, less than]

Principal aquifer	Number of samples	Max	P90	P75	Median	P25	P10	Min	Tukey group
Uranium concentration, in micrograms per liter									
New York and New England crystalline aquifer system	117	428.9	12.8	2.9	< 1	< 1	< 1	< 1	A
Glacial aquifer system	913	162.3	7.5	2.1	< 1	< 1	< 1	< 1	A
Cambrian-Ordovician aquifer system	76	5	3	1	< 1	< 1	< 1	< 1	B
^{222}Radon concentration, in picocuries per liter									
New York and New England crystalline aquifer system	110	215,210	10,950	4,738	2,122	1,200	565	< 80	A
Glacial aquifer system	950	8,056	899	557	340	219	156	< 80	B
Cambrian-Ordovician aquifer system	77	2,700	940	648	370	230	184	< 80	B

Similarly, ^{222}radon differed significantly by principal aquifer. The median ^{222}radon concentration was highest in the New York and New England crystalline aquifer system. This concentration was seven times the proposed MCL (2,122 pCi/L). The 75th percentile for ^{222}radon (4,738 pCi/L) exceeded the USEPA proposed AMCL of 4,000 pCi/L (table 3). The median ^{222}radon concentration was slightly greater than the USEPA proposed MCL of 300 pCi/L in samples from the glacial (340 pCi/L) and Cambrian-Ordovician (370 pCi/L) aquifer systems.

Uranium by Aquifer Group

Concentrations of uranium in ground water differed significantly among the nine aquifer groups analyzed in this study (table 4). The highest concentrations of uranium in ground water were present in samples from the Columbia Plateau glacial aquifer group (CPG) (fig. 7A), the West-Central glacial aquifer group (WCG) (fig. 7A), and the New York and New England crystalline aquifer group (NEC) (fig. 8A).

Table 4. Summary statistics for concentrations of uranium, by aquifer group, for the glaciated northern United States, 1993–2003.

[See table 2 for descriptions of aquifer groups. For aquifer groups with the same Tukey group letter, concentrations of uranium do not differ significantly at the 95-percent confidence level (alpha = 0.05). Max, maximum; Min, minimum; P, percentile (90, 75, 25, 10); <, less than]

Aquifer group (code)	Number of samples	Concentration of uranium, in micrograms per liter							
		Max	P90	P75	Median	P25	P10	Min	Tukey group
Columbia Plateau glacial (CPG)	46	67.9	29.9	22.3	11.9	6.0	3.8	< 1	A
West-Central glacial (WCG)	177	162.3	31.9	7.7	2.9	1	< 1	< 1	B
New York and New England crystalline (NEC)	117	428.9	12.8	2.9	< 1	< 1	< 1	< 1	C
East-Central glacial (ECG)	283	21.1	3.3	1.4	< 1	< 1	< 1	< 1	CD
Cambrian-Ordovician (COS)	76	5	3	1	< 1	< 1	< 1	< 1	CD
North-Central glacial (NCG)	171	11.9	2.2	< 1	< 1	< 1	< 1	< 1	D
Pre-Wisconsinan glacial (PWG)	71	17	2	< 1	< 1	< 1	< 1	< 1	D
Northeastern glacial (NEG)	126	15.8	1.3	< 1	< 1	< 1	< 1	< 1	D
Northern Pacific glacial (NPG)	39	< 1	< 1	< 1	< 1	< 1	< 1	< 1	D

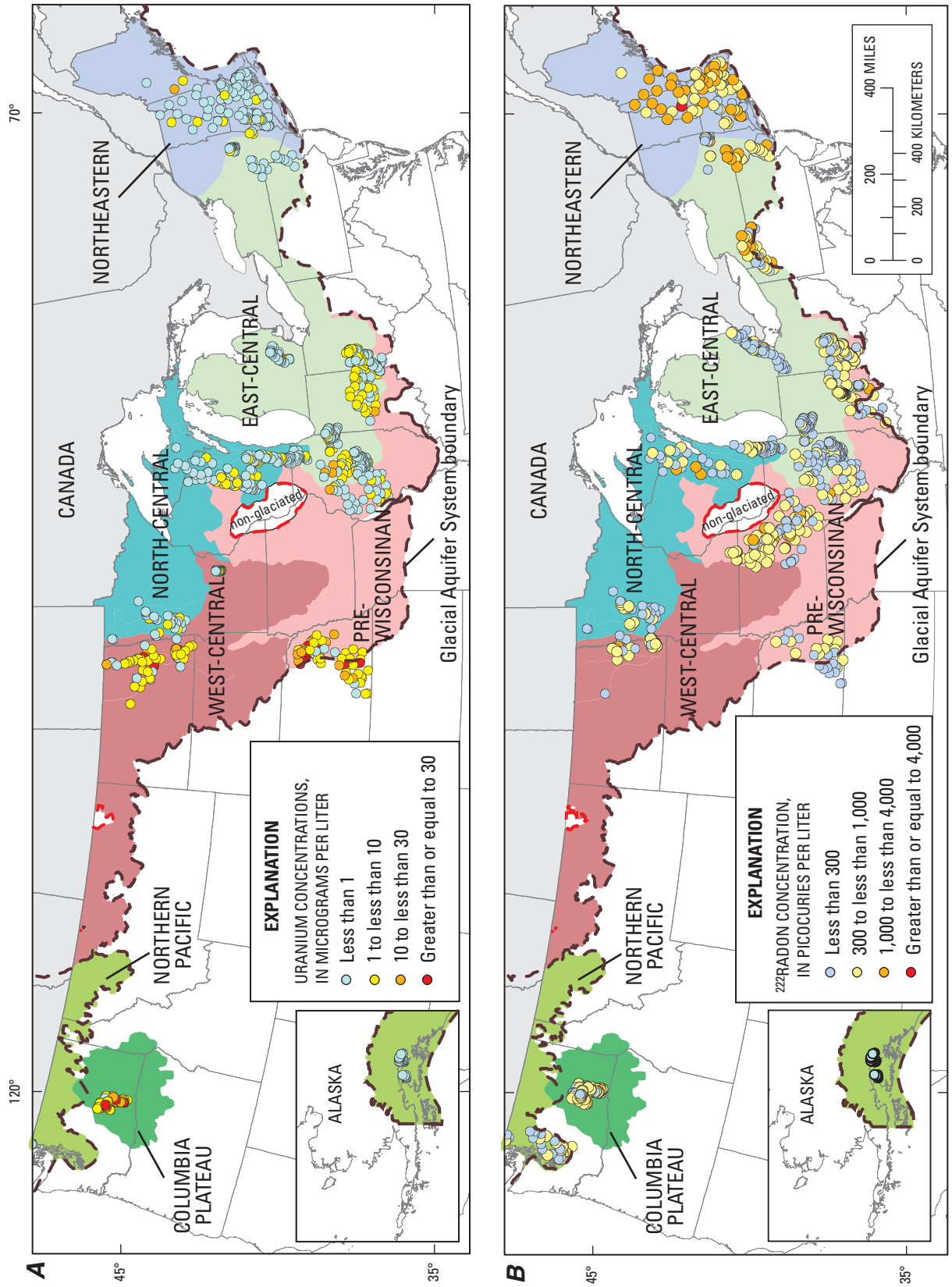


Figure 7. Distribution of (*A*) uranium and (*B*) ^{222}radon concentrations in sampled wells in the glacial aquifer groups in the northern United States, 1993–2003.

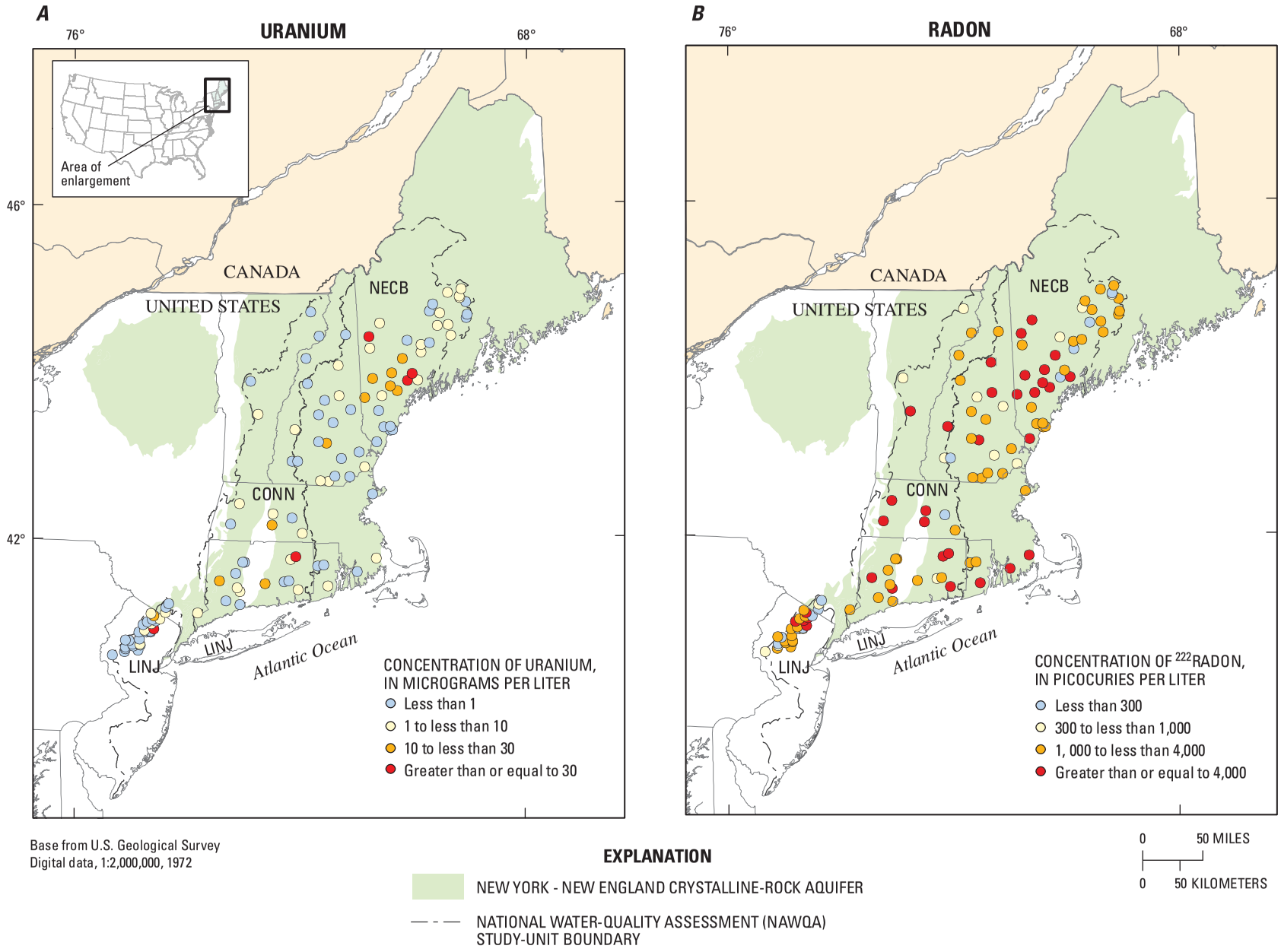


Figure 8. Distribution of (*A*) uranium and (*B*) ^{222}radon concentrations in sampled wells in the New York and New England crystalline aquifer group in the northern United States, 1993–2003.

Concentrations of uranium exceeded 10 µg/L in more than 50 percent of ground-water samples from wells in the CPG aquifers (table 4), and about 10 percent of the samples from the CPG and WCG aquifers exceeded the USEPA MCL of 30 µg/L. More than 10 percent of the wells sampled in the NEC aquifers had concentrations greater than 10 µg/L. The greatest concentration, 429 µg/L, was measured in a sample from a domestic bedrock well completed in the NEC aquifer group.

Concentrations of uranium in ground-water samples from North-Central glacial aquifer group (NCG), which are underlain mostly by Precambrian crystalline rocks, were less than 12 µg/L. The sediments that comprise the WCG aquifer group, immediately to the west of the NCG aquifers, were derived in part from the northwest and contain appreciable amounts of Cretaceous shale that is uraniferous. This difference may affect uranium source and(or) redox (Bohlke and others, 2002) and may contribute to the high concentrations of uranium in wells in the northern part of the WCG aquifers and the low concentrations of uranium in the wells in the NCG aquifers (figs. 5 and 7A). None of the samples from wells in Northern Pacific glacial aquifer group (NPG) (5 wells in Washington and 34 in Alaska) had uranium concentrations greater than 1 µg/L. The highest value reported for 76 wells in the Cambrian-Ordovician (COS) aquifer group was 5 µg/L (table 4, fig. 9A).

Results from a multiple comparison test showed that ground-water samples from wells in CPG aquifers had significantly higher uranium concentrations than samples from all other aquifer groups (table 4). Water samples from wells in WCG aquifers had significantly higher uranium concentrations than samples from all other aquifer groups, except for CPG aquifers. Whereas the NEC aquifer group had some individual samples with high uranium concentrations (greater than 30 µg/L), as a group, uranium concentrations in the NEC aquifer group were only significantly higher than those for NCG, Pre-Wisconsinan glacial (PWG), NPG, and NEG aquifer groups.

^{222}Radon by Aquifer Group

Concentrations of ^{222}radon in ground water from some of the nine aquifer groups also differed significantly. The highest ^{222}radon concentrations were present in samples from wells completed in NEC aquifers; the median value (2,122 pCi/L) was about 10 times the median values of all other aquifer groups (table 3; fig. 8B). More than 30 percent of the 110 samples from wells in NEC aquifers had ^{222}radon concentrations that exceeded the proposed USEPA AMCL of 4,000 pCi/L. The second highest median concentration (814 pCi/L) was in samples from the NEG aquifers, which were predominantly derived from and overlie the NEC aquifer. The NEG aquifer group was the only glacial aquifer group with a water sample having a ^{222}radon concentration exceeding the proposed USEPA AMCL of 4,000 pCi/L. In CPG aquifers, the median and 90th percentile concentrations of ^{222}radon were 530 and 1,100 pCi/L, respectively. For all other aquifer groups (WCG, ECG, COS, NCG, NPG, and the PWG), the median value of ^{222}radon was about 300 pCi/L and the 90th percentile values did not exceed 1,000 pCi/L (figs. 7B and 9B); these groups had similar ^{222}radon concentrations.

Comparison of Uranium and ^{222}Radon in Drinking-Water Supply and Monitoring Wells

Concentrations of uranium and ^{222}radon were evaluated for differences between monitoring wells representing particular land uses, and public- and domestic-supply wells used for drinking water (termed drinking-water wells). In this study, uranium concentrations were significantly higher in samples from monitoring wells than from drinking-water wells ($p < 0.0001$) in the ECG aquifers. However, uranium concentrations were significantly higher in drinking-water wells in the NEG ($p = 0.0374$) and the WCG ($p = 0.0210$) aquifer groups than in monitoring wells for these groups. Uranium concentrations did not differ significantly between samples from drinking-water and monitoring wells in the NCG, NPG, or PWG aquifer groups. This information is useful when evaluating uranium concentrations between aquifer groups that include a combination of drinking-water and monitoring-well data because it indicates that well type may also play a role in differences in uranium concentrations.

Concentrations of ^{222}radon also differed by well type within the aquifer groups. ^{222}Radon concentrations were significantly higher in samples from drinking-water wells than those from monitoring wells in the CPG aquifers and NEG aquifers ($p = 0.0007$ and 0.0078, respectively). ^{222}Radon concentrations were significantly higher in monitoring wells than in drinking-water wells in the PWG and WCG aquifers ($p = 0.0001$ and 0.0257, respectively). For the ECG, NCG, and NPG glacial aquifer groups, no significant difference was observed between concentrations of ^{222}radon in samples from drinking-water wells and monitoring wells.

Concentrations of uranium exceeded the USEPA maximum enforceable contaminant levels in some of the aquifer groups (table 6). Twelve percent of water samples from drinking-water wells in WCG aquifers and 4 percent of water samples from the wells in NEC aquifers exceeded the USEPA MCL of 30 µg/L for uranium. Eleven percent of water samples from monitoring wells in WCG aquifers and 9 percent of samples from the monitoring wells in CPG aquifers exceeded the USEPA MCL of 30 µg/L for uranium. Data for drinking-water wells were not available for the CPG aquifers and monitoring-well data were not available for the NEC or COS aquifers.

^{222}Radon was measured at concentrations near or above the proposed USEPA MCL of 300 pCi/L in nearly 50 percent or more of all water samples, regardless of well type or aquifer group. However, 33 of the 34 water samples with ^{222}radon concentrations greater than the proposed USEPA

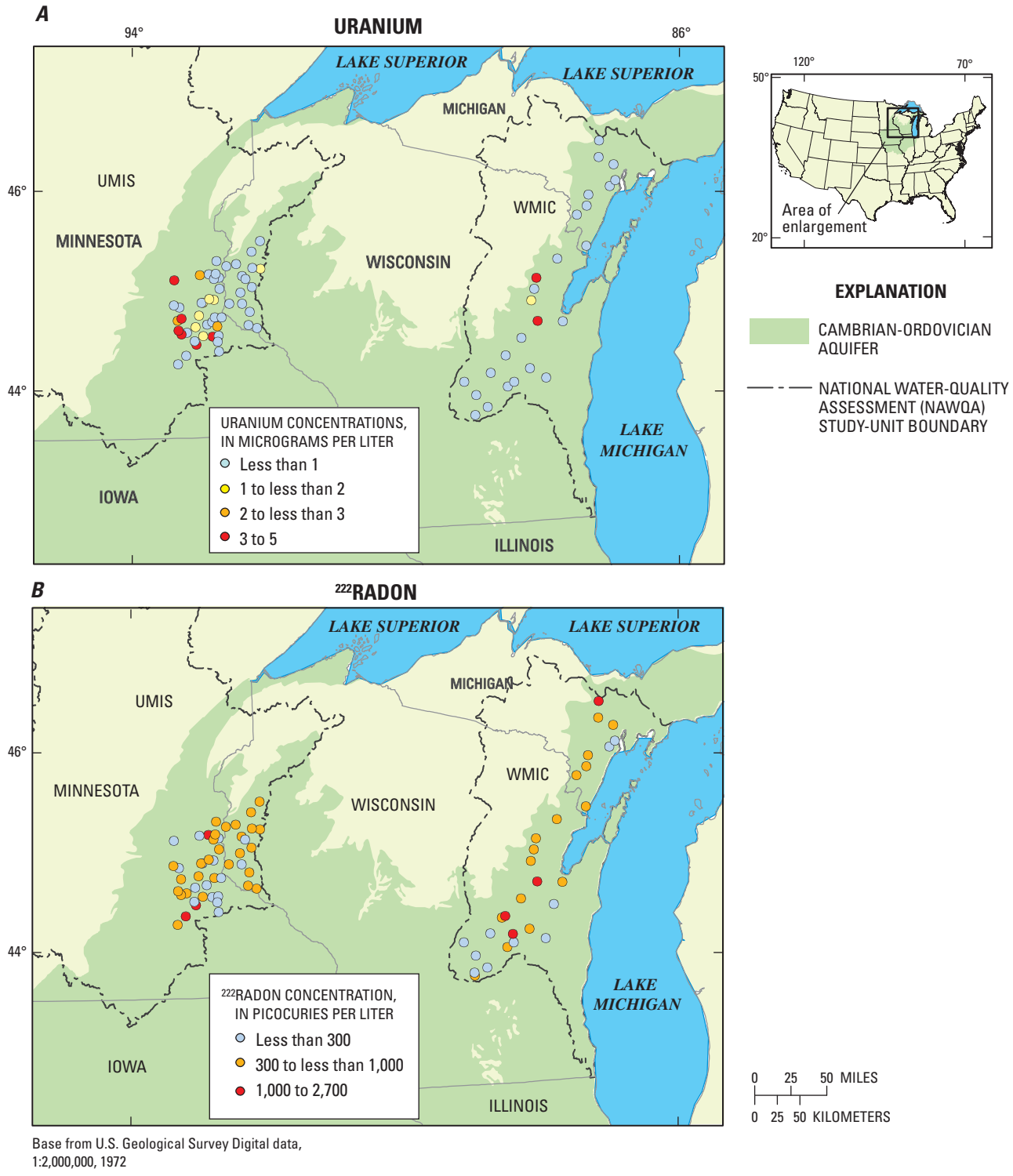


Figure 9. Distribution of (*A*) uranium and (*B*) ^{222}radon concentrations in sampled wells in the Cambrian-Ordovician aquifer group in the northern United States, 1993–2003.

Table 5. Summary statistics for concentrations of ^{222}radon, by aquifer group, in the glaciated northern United States, 1993–2003.

[See table 2 for descriptions of aquifer groups. Aquifer groups with the same Tukey group letter do not differ significantly at the 95-percent confidence level. N, number of samples; Max, maximum; Min, minimum; P, percentile (90, 75, 25, 10); <, less than]

Aquifer group (code)	Number of samples	Concentration of ^{222}radon, in picocuries per liter							
		Max	P90	P75	Median	P25	P10	Min	Tukey group (alpha = 0.05)
New York and New England crystalline (NEC)	110	215,210	10,950	4,738	2,122	1,200	565	< 80	A
Northeastern glacial (NEG)	93	8,056	2,087	1,269	814	508	344	< 80	B
Columbia Plateau glacial (CPG)	85	1,900	1,100	710	530	320	265	110	C
Cambrian-Ordovician (COS)	77	2,700	940	648	370	230	184	< 80	CD
West-Central glacial (WCG)	76	1,100	626	394	313	245	217	83	DE
Pre-Wisconsinan glacial (PWG)	175	2,146	767	454	322	210	150	< 80	DE
East-Central glacial (ECG)	337	2,800	810	522	302	187	138	< 80	E
Northern Pacific glacial (NPG)	77	860	540	439	290	200	146	100	E
North-Central glacial (NCG)	107	2,436	463	360	252	184	152	< 80	E

Table 6. Percentage of drinking water and monitoring wells with concentrations of uranium and ^{222}radon greater than the U.S. Environmental Protection Agency Maximum Contaminant Level (MCL) for uranium and proposed MCL and AMCL for ^{222}radon, by aquifer group and well type, in the northern United States.

[See table 2 for descriptions of aquifer groups. N, number; >, greater than; µg/L, micrograms per liter; pCi/L, picocuries per liter; –, no data]

Aquifer group (code)	Drinking water (public and domestic) wells					Monitoring (unused) wells				
	Uranium		^{222}Radon			Uranium		^{222}Radon		
	N	Percentage >30 µg/L	N	Percentage >4,000 pCi/L	Percentage >300 pCi/L	N	Percentage >30 µg/L	N	Percentage >4,000 pCi/L	Percentage >300 pCi/L
Northern Pacific glacial (NPG)	31	0	57	0	46	5	0	17	0	65
Columbia Plateau glacial (CPG)	–	–	44	0	89	46	9	39	0	72
West-Central glacial (WCG)	52	12	35	0	40	116	11	41	0	73
North-Central glacial (NCG)	74	0	72	0	33	93	0	31	0	32
East-Central glacial (ECG)	70	0	123	0	45	209	0	209	0	53
Pre-Wisconsinan glacial (PWG)	59	0	88	0	41	8	0	83	0	66
Cambrian-Ordovician (COS)	73	0	74	0	66	–	–	–	–	–
Northeastern glacial (NEG)	67	0	61	2	92	55	0	29	0	93
New York and New England crystalline (NEC)	113	4	107	30	94	–	–	–	–	–

AMCL of 4,000 pCi/L were from drinking-water wells in the northeastern United States. Thirty-two of the 33 samples were from domestic supply wells in the NEC aquifer group. The remaining water sample with high radon (8,056 pCi/L) was from a drinking-water well in the NEG aquifer group.

Data were available for five aquifer groups (ECG, WCG, NPG, COS, NEG) to evaluate differences in uranium and ^{222}radon concentrations in water samples between public and domestic wells used to supply drinking water. Concentrations of uranium did not differ significantly between public and domestic wells ($p = 0.1784$ to 0.7235) in any of the five aquifer groups. Similarly, ^{222}radon concentrations in public and domestic wells in the aquifer groups COS, ECG, NEG, and NPG were not significantly different ($p = 0.0670$ to 0.7344).

Relation of Uranium and ^{222}Radon in Ground Water to Terrestrial Gamma-Ray Emissions

National-scale data on the equivalent uranium (eU) and thorium (eTh) content of near-surface sediments, determined from gamma-ray emissions measured during an aerometric survey (Duval, 1990), were compared to uranium and ^{222}radon concentrations measured in the associated ground water. More than 50 percent of the uranium concentrations measured in ground water were below the reporting level; therefore, the 75th percentiles of uranium and ^{222}radon concentrations in ground water from each of the NAWQA well networks (appendix 2) were plotted against the 75th percentiles of eU and eTh concentrations from the aerometric gamma-ray surveys that were associated with each network (fig. 10). The eTh values may provide better correlations with uranium and(or) ^{222}radon concentrations in ground water than eU values because thorium is much less mobile than uranium in the environment and, thus, less susceptible to error related to secular disequilibrium in the sediment environment (Osmond and Ivanovich, 1992). Concentrations of uranium in ground water are somewhat related to eU and eTh concentrations in near-surface sediments. Where eU concentrations were greater than 1.25 ppm (parts per million) (fig. 10A), uranium concentrations in water varied and were often high (75th percentile > 10 µg/L). Similarly, where eTh concentrations were greater than 5 ppm (fig. 10B), uranium concentrations in ground water were high (75th percentile > 10 µg/L); where eTh concentrations were less than 5 ppm, uranium concentrations in ground water were consistently low. The concentrations of ^{222}radon generally increased with increasing eU and eTh concentrations, although ^{222}radon concentrations were consistently low where eU concentrations were less than about 2.0 ppm. Where eU concentrations were greater than 2.0 ppm, ^{222}radon concentrations increased sharply. This response is due largely to samples from New England in both the glacial (NEG) and crystalline (NEC) aquifer groups and from samples in the ECG (figs. 10C and 10D). Samples from the PWG aquifers had high eU and eTh values but consistently low concentrations of ^{222}radon, indicating that processes such as redox may affect intermediate radionuclides (for example, ^{226}radium) from which ^{222}radon is derived. Thus, the relation between uranium and ^{222}radon in ground water and terrestrial gamma-ray emissions is not consistent but provides an indication of potential for the presence of ^{222}radon and, less so, uranium, in ground water.

Correlations of Uranium and ^{222}Radon with Ancillary Data

Uranium and ^{222}radon concentrations were correlated with ancillary data, including water chemistry, streambed-sediment chemistry, terrestrial gamma-ray emissions, and physical and hydrologic properties. Significant correlations of uranium and ^{222}radon with ancillary data, by aquifer group, are listed in appendixes 3 and 4, respectively. Significant correlation coefficients for ground-water chemistry constituents that were commonly correlated with uranium, by aquifer group, are summarized in table 7. These correlations differed by aquifer group and may relate to large-scale hydrologic and geochemical processes that affect the concentrations of uranium and ^{222}radon in ground water.

Uranium and ^{222}radon concentrations in ground water correlated with concentrations of many other water-quality constituents; however, the constituents that correlated with uranium and ^{222}radon differed among the aquifer groups. Some of the correlations were similar among aquifer groups, whereas others were unique to a specific aquifer group. The differences in the types of ancillary data that correlated could be due to differences in geology or the source of the geologic materials but also may be affected by the geochemical behavior of uranium and ^{226}radium. Uranium readily forms complexes with several anions, including carbonate, sulfate, nitrate, chloride, and phosphate (Sorg, 1991), and correlations between uranium and anions may provide insights to the processes that affect uranium concentrations in the various aquifer groups. Major ions and trace elements were commonly correlated with uranium. Calcium correlated with uranium ($p < 0.05$) in eight of the nine aquifer groups, and sulfate correlated with uranium in seven of the nine aquifer groups. Total dissolved solids (TDS), acid neutralizing capacity (ANC), and bicarbonate (HCO_3) also correlated with uranium in most of the aquifer groups (table 7).

In the CPG and WCG glacial aquifer groups, uranium concentrations correlated with boron, lithium, selenium, and strontium (table 7). These correlations were strikingly similar to ones found in studies of uranium in surface waters in the western United States affected by irrigation (Seiler and others, 2003; Zielinski and others, 1995). Both studies cite the combination of geologic sources of uranium or selenium and heavy irrigation of agricultural land in a semiarid climate as possible explanations for mobilization of these trace elements. In the CPG and in the WCG aquifer groups, there are abundant natural sources of uranium in the aquifer sediments, and the re-use of irrigation waters from either ground water or surface water sources is a common practice.

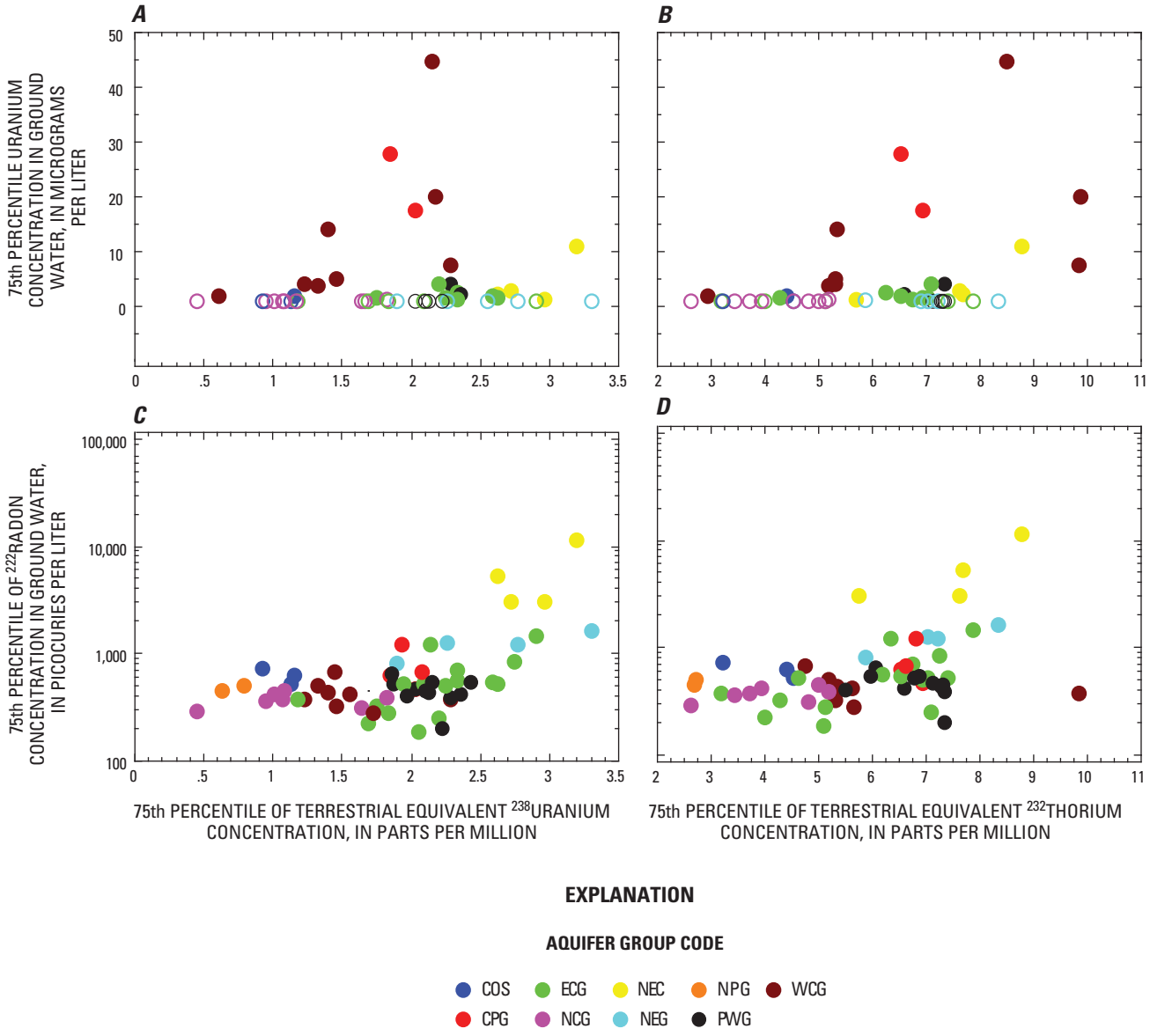


Figure 10. Relation of the 75th percentile of concentrations of uranium in ground water to the 75th percentile concentrations of terrestrial (*A*) equivalent ^{238}uranium and (*B*) equivalent ^{232}thorium; and 75th percentile of concentrations of ^{222}radon in ground water to 75th percentile concentrations of terrestrial (*C*) equivalent ^{238}uranium and (*D*) equivalent ^{232}thorium in ground-water samples from wells in glacial, Cambrian-Ordovician, and New York and New England crystalline aquifer groups in the northern United States. Open circles indicate that 75th percentile for uranium was <1 microgram per liter.

Table 7. Spearman correlation coefficients between uranium and selected water-chemistry constituents, by aquifer group, in the northern United States.

[Aquifer group codes are defined in table 2; Values in bold have *p*-values less than 0.05; –, no data; ANC, Acid neutralizing capacity; B, boron; Ca, calcium; HCO_3, bicarbonate; Li, lithium; Mn, manganese; Ni, Nickel; Se, selenium; SO_4, sulfate; Sr, strontium; TDS, total dissolved solids; ^{222}Rn, ^{222}radon; alpha, gross alpha concentration]

Aquifer group code	ANC	B	Ca	HCO_3	Li	Mn	Ni	Se	SO_4	Sr	TDS	^{222}Rn	alpha
NPG	–	–	–	–	–	–	–	–	–	–	–	–	–
CPG	**0.68**	**0.42**	**0.31**	**0.77**	**0.47**	0.22	**0.31**	**0.37**	**0.51**	**0.52**	**0.68**	0.18	–
WCG	**0.40**	**0.36**	**0.37**	**0.37**	**0.43**	**-0.31**	-0.01	**0.60**	**0.27**	**0.32**	**0.39**	0.06	–
NCG	0.18	0.04	**0.19**	**0.24**	**0.20**	**0.18**	**0.42**	**0.19**	**0.20**	0.14	**0.17**	0.10	0.06
ECG	**0.35**	**0.18**	**0.40**	0.20	0.11	**0.46**	**0.43**	**0.16**	**0.41**	**0.23**	**0.36**	-0.19	–
PWG	-0.16	-0.45	**0.47**	–	–	-0.04	**0.45**	0.13	**0.56**	**0.61**	**0.29**	**0.41**	–
NEG	**0.31**	-0.03	**0.29**	**0.30**	0.16	-0.01	-0.01	–	**0.37**	**0.22**	**0.19**	0.01	**0.54**
COS	**0.48**	-0.14	**0.42**	–	-0.22	**0.36**	**0.47**	0.06	**0.32**	0.02	**0.27**	0.09	–
NEC	0.18	-0.05	**0.25**	-0.03	0.24	-0.18	-0.01	-0.13	-0.03	0.10	0.14	**0.60**	**0.72**

Uranium correlated with nickel in glacial aquifer groups in the central United States (NCG, ECG, and PWG). Uranium also correlated with nickel in the COS aquifer group, although uranium concentrations were generally low in this aquifer group. The low uranium concentrations should be considered, however, in conjunction with information on other radionuclides, particularly ^{226}radium, which is known to be high in parts of this aquifer system (Gilkeson and Cowart, 1987; Michael and Jordana, 1987; Saad, 1996).

^{222}Radon correlated with uranium in the NEC and PWG aquifer groups, but not in any of the other aquifer groups. These correlations may be related to hydraulic properties of the NEC and PWG aquifers, such as the proximity of the sources to fractures that transmit water or by the geochemical behavior of uranium and ^{226}radium.

Many of the variables that did not correlate significantly, or did not correlate consistently, by aquifer group, with uranium or ^{222}radon are listed in appendixes 3 and 4. Examples of these include well depth, nitrate, dissolved oxygen, trace elements, and some of the NURE stream sediment data. There are a variety of possible explanations why significant correlations did not occur between uranium and ^{222}radon and other data. One reason may be that some of the ancillary data were not complete for the study area, such as the NURE streambed sediment chemistry data (Smith, 2001a; Smith, 2001b). For example, there were 283 uranium samples for the ECG aquifer group, but only 43 of these samples were from wells that intersected with areas containing NURE data. Another is that some trace elements, such as beryllium and cadmium, were not detected above laboratory reporting levels in 99 percent of the water samples. Also, some areas had no uranium or radon data or, as was the case in the Northern Pacific aquifer group, none of water samples had uranium concentrations above 1 µg/L.

Anomalously High Uranium and ^{222}Radon Concentrations and Related Factors

Uranium and ^{222}radon concentrations were anomalously high in samples from some aquifers in the northern United States. In this section, aquifer groups with large percentages of wells with uranium concentrations that exceeded the USEPA MCL of 30 µg/L and ^{222}radon concentrations that exceeded the proposed USEPA AMCL of 4,000 pCi/L are examined in more detail. Three areas in particular were examined—the NEC, WCG, and the CPG aquifers. The distributions of the concentrations, as well as correlation to other factors, are presented.

New York and New England Crystalline Aquifer Group

Wells in the New York and New England crystalline (NEC) aquifer group (figs. 6 and 8) are predominantly domestic wells that intersect water-bearing fractures at various depths in the bedrock (Flanagan and others, 1999). Land use near the sampled wells is predominantly rural, forested land with minor amounts of residential and agricultural lands. The NEC aquifer group followed only the CPG and WCG aquifer groups for highest uranium concentrations (table 4) and ranked the highest among all groups for ^{222}radon concentrations (table 5).

In the New England part of the NEC aquifer group, the uranium and ^{222}radon concentrations correlated with each other and with other radionuclide data such as gross alpha and gross beta particle activities, but not with most other constituent concentrations. Most notably, uranium concentrations correlated strongly with gross alpha (rho = 0.72, $p < 0.0001$) (appendix 3) and with ^{222}radon concentrations (rho = 0.60, $p < 0.0001$) (appendix 3). This relation was not found in other parts of the United States, and the primary reason is that ^{222}radon is not subject to the same geochemical controls as uranium. In a Finnish study, however, ^{222}radon concentrations in wells in similar bedrock formations, primarily granites or granitoid crystalline rocks, correlated with ^{238}uranium concentrations (rho = 0.57, $p < 0.0001$) (Vesterbacka and others, 2005).

Results of a recent study for the mobilization of ^{222}radon in fractured crystalline aquifers indicated that a diffusion/ion exchange model may help explain the anomalous concentrations of ^{222}radon in ground water; in this model, ^{226}radium diffuses toward the water-bearing fracture and decays to ^{222}radon (Wood and others, 2004). They noted that results from a brine injection test showed that the activity of ^{226}radium was 34 times greater than the activity of uranium at the fracture face. The correlation between uranium and ^{222}radon in ground water determined in this study, especially in the ground waters in granitoid rocks (appendix 5, necbsus2 NAWQA well network), indicates that at least some of the ^{226}radium, if present, may be derived from uranium at or near the fracture surface. Alternatively, ^{226}radium may be less soluble than uranium under slightly oxic or mixed geochemical conditions typical of these aquifers. Uranium in samples from wells in the NEC aquifer group also correlated with gross beta particle activity (0.33, $p = 0.0120$) and with concentrations of molybdenum (rho = 0.35, $p = 0.0001$) (appendix 3).

^{222}Radon also correlated with gross alpha particle activity (rho = 0.54, $p < 0.0001$; fig. 11B) and with total lead (rho = 0.38, $p = 0.0005$; fig. 11D). The correlation between ^{222}radon and total lead was strongest (rho = 0.52, $p = 0.004$) in samples from the granitic and metamorphic crystalline aquifers of eastern New England, part of the NEC aquifer group (fig. 11D; appendix 6). This result is similar to a study in Finland that found a strong correlation (rho = 0.74, $p < 0.0001$) between ^{222}radon and ^{210}lead in wells completed in crystalline aquifers (Vesterbacka, 2005; Vesterbacka and others, 2005). Lead can be present in ground water in two ways: it can be mobilized by the dissolution of the rock matrix or it can be formed in the water from the radioactive decay of ^{222}radon. Because ^{222}radon concentrations were anomalously high in the water from wells in this aquifer, the total lead concentrations measured in this study may be related, in part, to radiogenic lead (^{206}Pb and ^{208}Pb) dissolved, desorbed, or leached from labile phases in fractures or pore spaces in the rock, or alternatively, these rocks might simply be enriched in lead. In areas where ^{222}radon in ground water is particularly high, it is possible that a minor amount of the lead (^{210}Pb) associated with ^{222}radon decay may remain dissolved in the water (Focazio and others, 2001) although isotopic measurement, not simple mass measurement, is needed to confirm this hypothesis. Disequilibrium ratios could not be determined for this study because isotopic data for uranium and lead were not collected.

In New England, crystalline bedrock that is granitic, such as two-mica granites, as well as other high-grade metamorphic rocks, appears to contain abundant uranium that is soluble in the predominantly sub-oxic to oxic and high-pH geochemical conditions (Boudette, 1977). In New Hampshire, a study of concentration data from self-selected domestic well samples sent to the New Hampshire Department of Environmental Services laboratory for radon analysis showed results similar to those found in this study for the NEC aquifer group (Moore, 2004). The New Hampshire study found that 40 percent of the domestic well-water samples, primarily from the southern part of the state, exceeded the 4,000 pCi/L proposed USEPA AMCL for ^{222}radon; 30 percent of the public and domestic well-water samples from the NEC aquifer group exceeded the proposed AMCL (table 8).

Concentrations of uranium and ^{222}radon in drinking water from public and domestic wells in the NEC aquifer group were similar to those from domestic wells completed in bedrock in parts of several northern European countries, including Norway, Sweden, and Finland (Vesterbacka, 2005). In these countries, bedrock formations are similar to those found in the NEC. A comparison of radionuclide data from the NEC aquifer in this study with data from studies in these European countries is shown in table 9. In the Norwegian study, 3,494 domestic bedrock wells were sampled. The wells are completed in rock formations that include uranium-rich granites in the southeast part of Norway where the portion of the population obtaining drinking water from domestic bedrock wells has increased (Strand and others, 1998). In southeastern Sweden, the highest concentrations of ^{222}radon and uranium were in samples from drinking-water wells completed in primarily granite bedrock formations and granite-pegmatite mixes (Isam Salih and others, 2002).

West-Central Glacial Aquifer Group

Ground water in the West-Central glacial (WCG) aquifer group generally had high concentrations of uranium, and these high uranium concentrations may be affected by the source material of the glacial sediments. Land use near the sampled wells included urban, agricultural, and mixed land uses. The WCG aquifers are derived from Cretaceous-age rocks composed predominantly of shale and some sandstone and limestone. Parts of North and South Dakota, western Minnesota, and northeastern Nebraska are underlain by glacial materials deposited in association with the Des Moines, James, and Red River glacial lobes (Meinzer, 1923; Schumann, 1993b; Wayne, 1985). Despite the complexity of these glacial deposits, much of the material contained within them is derived from Cretaceous-age, uraniferous shale. The Pierre Shale, for example, contains higher amounts of uranium than the average crustal abundance of 2.5 mg/kg (Schumann,

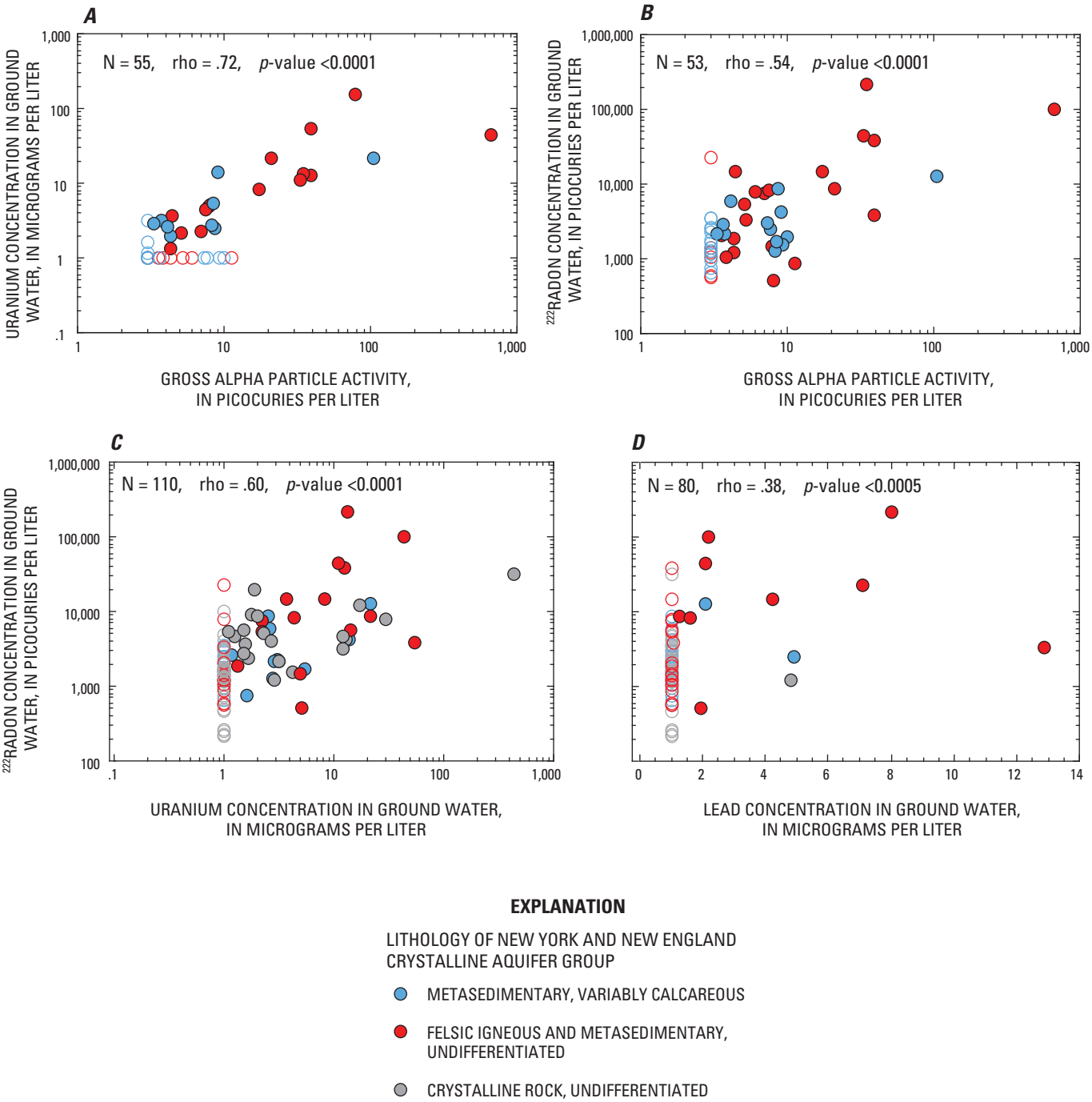


Figure 11. Relation of concentrations of (*A*) uranium and (*B*) ^{222}radon to gross alpha particle activity; and concentrations of ^{222}radon to (*C*) uranium and (*D*) lead in ground-water samples from wells in the New York and New England crystalline aquifer group in the northern United States, 1993–2003. Open circles indicate that the concentration is less than the laboratory reporting limit.

Table 8. Percentage of wells with uranium and ^{222}radon concentrations exceeding selected standards and proposed standards, by lithology, for the New York and New England crystalline aquifer group.

[See appendix 1 for description of National Water-Quality Assessment Program (NAWQA) networks. NA, not applicable]

Lithology	NAWQA well network code	Number of samples	Percentage of wells with uranium greater than (micrograms per liter)			
			30	20	10	1
Felsic igneous and undifferentiated metasedimentary rocks	necbsus2	30	10	13	27	57
Metasedimentary rocks, variably calcareous	necbsus1	28	0	4	7	50
Crystalline, undifferentiated	connsus1, linjsus1	59	3	3	10	37
Total	NA	117	4	6	13	45
Lithology	**NAWQA well network code**	**Number of samples**	**Percentage of wells with ^{222}radon greater than (picocuries per liter)**			
			20,000	**4,000**	**300**	**80**
Felsic igneous and undifferentiated metasedimentary rocks	necbsus2	28	18	46	96	96
Metasedimentary rocks, variably calcareous	necbsus1	26	0	15	100	100
Crystalline, undifferentiated	connsus1, linjsus1	56	4	29	91	100
Total	NA	110	6	30	94	99

Table 9. Comparison of maximum and mean concentrations of uranium and ^{222}radon in ground water from areas dominated by crystalline aquifers in New England, United States; Norway; Sweden; and Finland.

[–, no data; N, number of samples; µg/L, micrograms per liter; pCi/L, picocuries per liter]

Country	N	Maximum	Mean	Reference
		Uranium (µg/L)		
Finland	288	800	20.9	(Vesterbacka and others, 2005)
Sweden	328	427	14.3	(Isam Salih and others, 2002)
Norway	–	–	–	–
New York and New England crystalline aquifers group, United States	113	4,291	4.5[1]	This study
		^{222}Radon (pCi/L)		
Finland	288	232,432	12,432	(Vesterbacka and others, 2005)
Sweden	328	219,054	6,946	(Isam Salih and others, 2002)
Norway	3,494	864,864	10,541	(Strand and others, 1998)
New York and New England crystalline aquifers group, United States	107	215,210	7,360	This study

[1] Value represents total uranium rather than ^{238}uranium and the mean is estimated on the basis of a log-normal distribution because of censored data (Helsel, 1990).

1993b). Thus, glacial aquifers in this region may contain appreciable amounts of uranium that is available for dissolution in ground water.

In addition, much of eastern Nebraska was occupied by pre-Wisconsinan ice of the Dakota and Minnesota lobes (Colgan, 1999; Meinzer, 1923; Srhoba and others, 2001; Wayne, 1985). The Dakota lobe in particular may have carried and deposited uraniferous shale to eastern Nebraska and northeastern Kansas. Loess deposits from the western United States (Muhs and Bettis, 2000) may also have contributed uranium to aquifers that resulted in high concentrations of uranium in ground water in the Nebraska wells (fig. 7A).

Ten percent (17 of 177) of samples in the WCG aquifer group contained uranium concentrations greater than the USEPA MCL of 30 µg/L; the highest uranium concentration was 162.3 µg/L. Although this aquifer group had significantly higher uranium concentrations than other aquifer groups studied (table 4), it had one of the lowest ^{222}radon distributions (table 5). The highest ^{222}radon concentration measured in this aquifer group was 1,100 pCi/L.

The strongest correlations for uranium were with selenium (rho = 0.60), carbonate (CO_3) ion (rho = 0.52), potassium, lithium, and calcium (rho = 0.52, 0.43, and 0.37, respectively), acid neutralizing capacity (rho = 0.40), and total dissolved solids (rho = 0.39) (appendix 3). Uranium correlated somewhat with sodium (rho = 0.40) and nitrate (rho = 0.34). Uranium was inversely correlated with total iron (rho = -0.46), indicating redox controls. Uranium also correlated with terrestrial gamma-ray emissions: ^{40}potassium (rho = 0.46) and eTh (rho = 0.43).

^{222}Radon in the WCG aquifer group inversely correlated with well depth, depth to top of open interval, and depth to bottom of open interval (rho = -0.35, -0.36, and -0.35, respectively) (appendix 4). Also, ^{222}radon correlated positively with tritium (rho = 0.35), and inversely with ^{18}oxygen (^{18}O) (rho = -0.34). These correlations indicate that water in these aquifers may be young. Young ground water may be an indication of high transmissivities (high hydraulic conductivity) and may indicate that there is a pathway for ^{222}radon, thus increasing concentrations in ground water. Alternatively, young ground water may have the redox properties necessary to mobilize uranium, or the water may be affected by agricultural practices such as irrigation. Inverse correlations were observed between ^{222}radon and terrestrial gamma-ray measurements of ^{40}potassium and eTh (-0.32 and -0.34, respectively).

Within the WCG aquifer group, concentrations of uranium in ground water generally were higher in samples from the wells in Nebraska (NAWQA well networks cnbrluscr1and hpgwdwgs1; appendix 2) than in the wells in eastern North Dakota and western Minnesota (NAWQA well networks rednlusag2, rednsus1, rednsus3, and rednsus5; appendix 2). This may be a result of available uranium in aquifer materials in combination with enhanced mobility from evaporative concentration associated with agricultural irrigation. In general, high uranium concentrations correlated with high total dissolved solids concentrations. This correlation was strongest for the ground water in shallow wells in an agricultural cropland setting in northeastern Nebraska (NAWQA well network cnbrluscr1; appendix 5). These wells tap shallow ground water in predominantly corn and soybeans croplands (appendix 1). Uranium in ground water from these wells correlated most strongly with major ions, including lithium (rho = 0.81), boron (rho = 0.79), potassium (rho = 0.71), sodium (rho = 0.57), strontium (rho = 0.51), and selenium (rho = 0.50) (appendix 5). In general, the samples from wells in eastern North Dakota, South Dakota, and Minnesota had lower uranium concentrations than those from the northeastern Nebraska wells, but several of the wells had samples with concentrations exceeding or approaching the USEPA MCL of 30 µg/L. Uranium concentrations in these wells also correlated significantly with total dissolved solids, magnesium, potassium, and other major ions (appendix 5).

The relations of uranium to other dissolved constituents in the samples from the WCG aquifers were similar to those in surface water in the Arkansas River in eastern Colorado (Zielinski and others, 1995). In this study, the ground water discharging to the river (as irrigation return flow) was affected by geologic sources of uranium in shale bedrock, enhanced uranium leaching from irrigation water, and evaporative concentration from the semiarid climate. For the WCG aquifer samples, graphs of uranium with calcium, lithium, boron, sodium, strontium, and selenium illustrate significant correlations (fig. 12) among those constituents and, except for sulfate and chloride, the correlations were similar to those for surface waters in the Arkansas River study.

In the Arkansas River study, uranium concentrations increased in the river with increasing distance from its source in the Rocky Mountains and with increasing inputs of ground-water discharge from aquifers that underlie irrigated agricultural lands (Zielinski and others, 1995). It is possible that one factor related to the high uranium concentrations in ground water in the WCG aquifer group also is recharge from irrigated agricultural lands.

Columbia Plateau Glacial Aquifer Group

Columbia Plateau glacial aquifers (CPG) (fig. 6) are composed of shallow to deep glaciofluvial sediments overlying sequences of lava flows interbedded with unconsolidated paleo-lakebed deposits (U.S. Geological Survey, 2000). Wells in the CPG aquifer group are located in predominantly agricultural land. Shallow monitoring wells in this group have associated uranium data (appendixes 1 and 2). Uranium data are not available for the deep domestic wells (appendix 2). CPG aquifers are affected by irrigation for agriculture where surface-water irrigation is a main source of recharge to underlying aquifers (Embrey, 1988). This may indirectly affect the concentrations of uranium in shallow ground water because agricultural irrigation usually results in increased concentrations of dissolved solids, nitrate, and salts in the underlying aquifer.

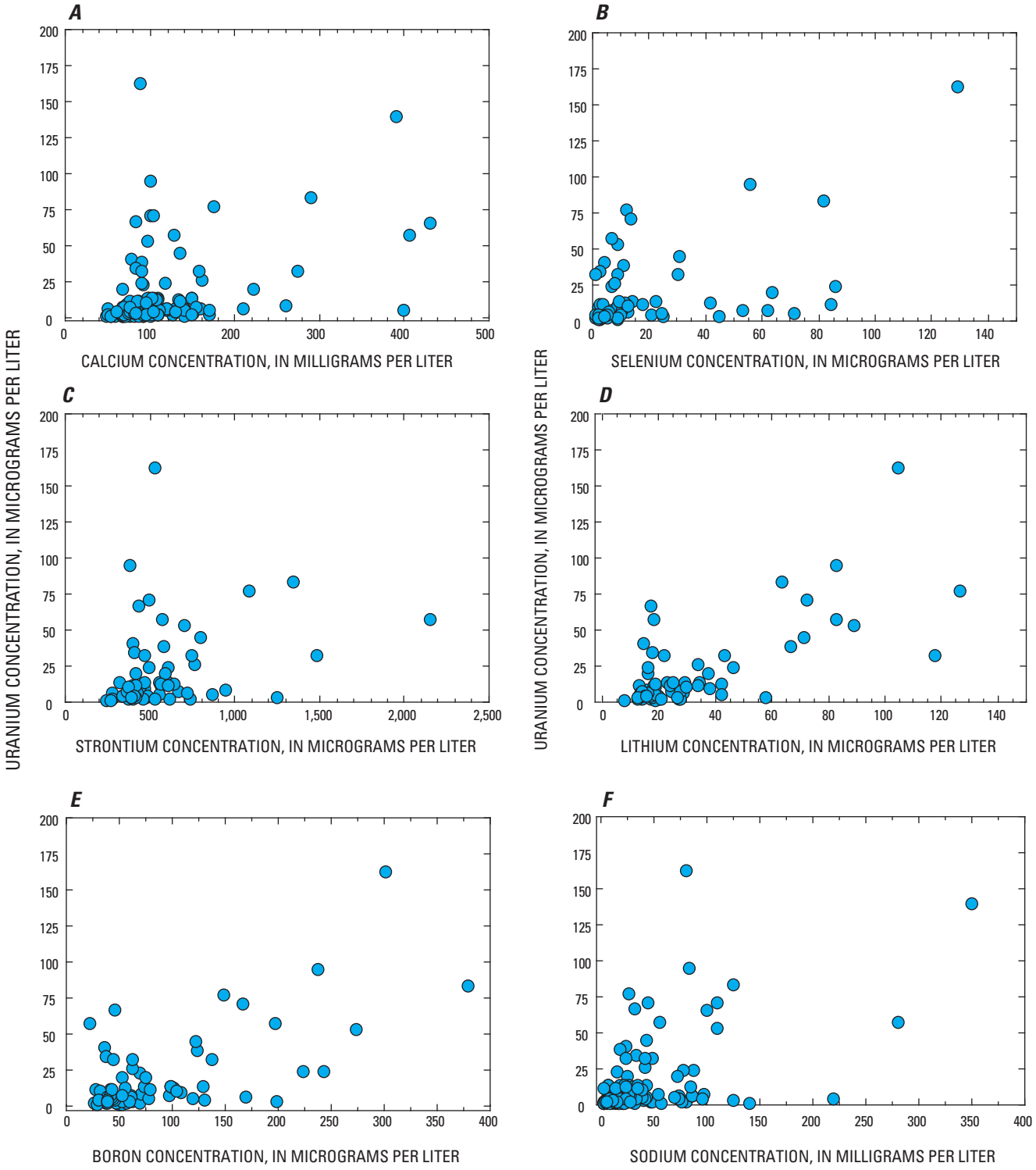


Figure 12. Relation of concentrations of uranium to concentrations of (*A*) calcium, (*B*) selenium, (*C*) strontium, (*D*) lithium, (*E*) boron, and (*F*) sodium in ground-water samples from the West-Central glacial aquifer group in the northern United States, 1993–2003.

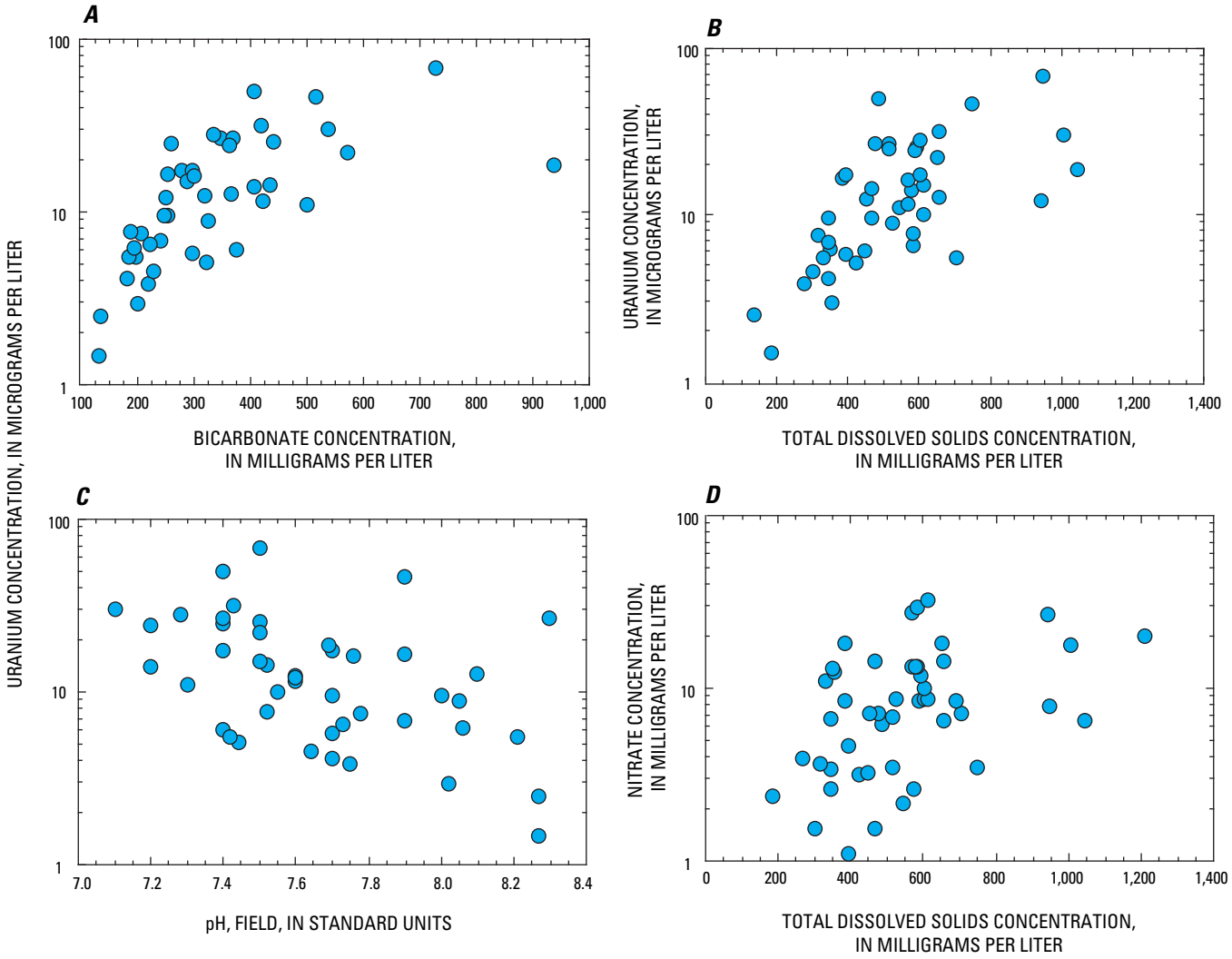


Figure 13. Relation of concentrations of uranium to concentrations of (*A*) bicarbonate, (*B*) total dissolved solids, and (*C*) pH, and (*D*) relation of concentrations of nitrate to concentrations of total dissolved solids in ground-water samples from wells in the Columbia Plateau glacial aquifer group in the northern United States, 1993–2003.

Nine percent of the samples from the CPG aquifers contained uranium concentrations that exceeded the USEPA MCL of 30 µg/L (table 6). The maximum uranium concentration was 67.9 µg/L (table 4). The concentrations of uranium in ground water from this aquifer group were higher than in any of the other aquifer groups studied (table 4). The maximum ^{222}radon concentration for 85 samples in the CPG aquifer group was 1,900 pCi/L (table 5).

The strongest uranium correlations in CPG aquifers were with bicarbonate (HCO_3) ion (rho = 0.77), field specific conductance (rho = 0.71), sodium (rho = 0.69), total dissolved solids (rho = 0.68), and acid neutralizing capacity (rho = 0.68) (appendix 3). Other strong correlations include sulfate (rho = 0.51) and pH (rho = -0.48). Uranium also correlated with some trace elements in this aquifer, including copper (rho = 0.47), lithium (rho = 0.47), magnesium (rho = 0.44), and boron (rho = 0.42). Significant uranium correlations are listed by individual well networks in the CPG aquifer group in appendix 5.

These correlations are consistent with the complexation of uranium with bicarbonate and sulfate ions (Gascoyne, 1992; Hem, 1985), and indicate that this process may be a major control on uranium occurrence in ground water in the CPG aquifer group. Concentrations of TDS that exceed 500 mg/L in shallow aquifers are indicative of irrigation (Whitehead, 2000). Wells in CPG aquifers had a median TDS concentration of 441 mg/L and a mean of 494 mg/L. TDS also correlated strongly with nitrate concentrations, further indicating that TDS is related to irrigated agriculture in this aquifer group (fig. 13). The inverse correlation of uranium with pH may be related to the age of the water, indicating that less chemically evolved water had correspondingly high uranium concentrations (fig. 13).

Lithium, bromide, and nickel were the only elements that correlated positively with ^{222}radon in CPG aquifers (rho = 0.51, 0.35, and 0.32, respectively) (appendix 4). Vanadium and phosphorus were inversely correlated to ^{222}radon (rho = -0.31 and -0.33, respectively). Well depth and radon were positively correlated (rho = 0.37).

Summary and Conclusions

Uranium and ^{222}radon in ground water have long been a concern throughout the United States. Radionuclide concentrations were compared among the glacial, Cambrian-Ordovician, and the New York and New England crystalline aquifer systems of the northern United States. In these aquifer systems, uranium and ^{222}radon concentrations differed greatly. In certain aquifers, concentrations also exceeded human-health standards in ground water used for drinking water and for agriculture.

In this study, water-quality data collected during 1993 to 2003 from 56 well networks in the U.S. Geological Survey National Water-Quality Assessment (NAWQA) program were evaluated to determine the occurrence of uranium and ^{222}radon in water in aquifers in the northern United States. The well networks, generally consisting of about 30 wells in similar aquifers and(or) land-use settings, were used in this investigation if the wells were completed in one of the three aquifer systems described above and had a measurement for uranium and(or) ^{222}radon. A total of 1,426 wells sampled as part of the NAWQA program met the above criteria. About 60 percent of these wells had water-quality data for both uranium and ^{222}radon.

The glacial aquifer system is geographically extensive and the composition of aquifer materials differs across the Unites States. For this reason, the glacial aquifer system was further divided into seven aquifer groups on the basis of the origin of the glacial deposits from which they were formed. Comparisons were made among the seven glacial aquifer groups and the Cambrian-Ordovician and New York and New England Crystalline aquifer systems. The chemical composition of samples from the resulting nine aquifer groups was compared, and concentrations of uranium and ^{222}radon were found to differ significantly. In general, uranium concentrations were highest in the glacial aquifer group of the Columbia Plateau, the West-Central glacial aquifer group, and the New York and New England crystalline aquifer group. About 10 percent of the wells in the Columbia Plateau glacial and the West-Central glacial aquifer groups had water with concentrations of uranium that exceeded the U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL) of 30 µg/L. For the New York and New England crystalline aquifer group, samples from 4 percent of the wells sampled exceeded the MCL of 30 µg/L for uranium.

In areas with high concentrations of uranium, the link to uranium-enriched geologic material is a common feature. In the Columbia Plateau glacial aquifer group, the deposits were derived in part from basaltic lava flows, with some felsic volcanic rocks and probably some paleo lakebeds that may be rich in uranium. In the West-Central glacial aquifer group, rocks such as Cretaceous marine shale that contain abundant uranium probably contribute to the high concentrations of uranium in ground water; in the southern part of this area, including northern Nebraska, the glacial or glacial-related sediment may be interbedded with uranium-rich materials that originated in the Rocky Mountains. These areas coincide with some of the highest terrestrial gamma-ray measurements in the United States, further indicating that a geologic source of uranium is a major factor controlling ground-water concentrations. In New England, crystalline bedrock that is granitic, such as two-mica granites, as well as other high-grade metamorphic rocks, appears to contain abundant uranium that is soluble in the predominant sub-oxic to oxic and high-pH geochemical conditions. In the Columbia Plateau and West-Central glacial aquifers, uranium correlated with total dissolved solids and bicarbonate as well as with boron, lithium, selenium, and strontium. In the New York and New England crystalline aquifer group, uranium correlated

primarily with other radionuclides, such as gross alpha particle activity, and with ^{222}radon. In addition to having a geologic source of uranium, factors that affect oxidation-reduction potential (redox) or ground-water flow could have an effect on uranium concentrations in ground water. For example, irrigation agriculture is particularly prevalent in the glacial aquifers of the Columbia Plateau and West-Central glacial aquifer groups, and irrigation return flows might enhance the mobility of uranium.

Median concentrations of ^{222}radon were 10 times higher in the New York and New England crystalline aquifer group than in the glacial aquifer group and the Cambrian-Ordovician aquifer group. Concentrations of ^{222}radon in New England were similar to those found in other countries (mainly Scandinavia) with similar geologic histories and(or) similar bedrock geology. In the New York and New England crystalline aquifer group, uranium and ^{222}radon concentrations strongly correlated with each other and with gross alpha particle activity. This was not found in any other aquifers studied in this investigation.

Also, ^{222}radon correlated with lead in water from wells completed in felsic igneous and undifferentiated metasedimentary rocks in the New York and New England crystalline aquifer group—a finding that is similar to findings in studies in Finland. Some of the lead concentrations associated with high ^{222}radon concentrations (greater than 10,000 pCi/L) in these wells are at levels near the USEPA action level for lead of 15 µg/L.

Although water-quality data for 1,426 wells were evaluated in this investigation, spatial coverage of areas where water is used for drinking-water supply was limited. Additional data from the state drinking-water programs or other sources could provide the necessary spatial coverage to validate findings presented in this report as well as to refine or develop new models of uranium and ^{222}radon occurrence.

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Appendixes 1–6

Appendix 1. Abbreviations and descriptions of the National Water Quality Assessment (NAWQA) program well networks used to study water quality in glacial, Cambrian-Ordovician, and New York and New England crystalline aquifer systems in the northern United States, 1993–2003.

[NAWQA, National Water Quality Assessment Program; SUID, Study-Unit Identifier. NAWQA summary reports provide more detailed information on the individual study units and their well networks used in this study. Access to these reports can be found online at *http://water.usgs.gov/nawqa/nawqa_sumr.html*]

NAWQA Study Unit Identifiers

ALMN	Allegheny and Monongahela River Basins (Pennsylvania, West Virginia, New York, and Maryland)
CCYK	Central Columbia Plateau (Washington and Idaho) combined with the Yakima River Basin (Washington)
CNBR	Central Nebraska Basins (Nebraska)
CONN	Connecticut, Housatonic, and Thames Rivers Basins (Connecticut, Massachusetts, New Hampshire, and Vermont)
COOK	Cook Inlet Basin (Alaska)
DELR	Delaware River Basin (Delaware, Maryland, New Jersey, Pennsylvania, and Virginia)
EIWA	Eastern Iowa Basins (Iowa and Minnesota)
HDSN	Hudson River Basin (New York and adjacent states)
HPGW	High Plains Regional ground-water study (Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, and Texas)
LERI	Lake Erie-Lake Saint Clair Drainages (Michigan, Ohio, Indiana, New York, and Pennsylvania)
LINJ	Long Island-New Jersey Coastal Drainages (New Jersey and New York)
LIRB	Lower Illinois River Basin (Illinois)
NECB	New England Coastal Basins (New Hampshire, Massachusetts, Maine, and Rhode Island)
PUGT	Puget Sound Basin (Washington and British Columbia, Canada)
REDN	Red River of the North Basin (Minnesota, North Dakota, and South Dakota)
UIRB	Upper Illinois River Basin (Illinois, Indiana, and Wisconsin)
UMIS	Upper Mississippi River Basin (Minnesota, Wisconsin, South Dakota, Iowa, and North Dakota)
WHMI	White River Basin (Indiana) combined with the Great and Little Miami River Basins (Ohio and Indiana)
WMIC	Western Lake Michigan Drainages (Michigan and Wisconsin)

Aquifer Group Codes

CPG	Columbia Plateau glacial
COS	Cambrian-Ordovician (sandstone and dolomite)
ECG	East-Central glacial
NEC	New York and New England crystalline (fractured bedrock)
NEG	Northeastern glacial
NCG	North-Central glacial (deposits of the Red River and Wadena, Rainy, Lake Superior, and Green Bay glacial lobes)
WCG	West-Central glacial (deposits of the Dakota, James, Des Moines, and eastern Red River glacial lobes)
NPG	Northern Pacific glacial
PWG	Pre-Wisconsinan glacial

Appendix 1. Abbreviations and descriptions of the National Water Quality Assessment (NAWQA) program well networks used to study water quality in glacial, Cambrian-Ordovician, and New York and New England crystalline aquifer systems in the northern United States, 1993–2003.—Continued

NAWQA SUID (see figure 2)	NAWQA well network	Aquifer group code	Predominant land-use setting	Aquifer setting	NAWQA summary report reference
			Cambrian-Ordovician aquifer system		
UMIS	umissus3	COS	Mixed	Unconfined (dolomite and sandstone) aquifers in Minnesota and Wisconsin	Stark and others, 2000
UMIS	umissus4	COS	Mixed	Confined (dolomite and sandstone) aquifers in Minnesota and Wisconsin	Do.
WMIC	wmicsus1	COS	Mixed	(Sandstone) aquifers, west of Maquoketa shale in Michigan and Wisconsin	Peters and others, 1998
			New York and New England crystalline aquifer system		
CONN	connsus1	NEC	Mixed	Fractured, crystalline-bedrock (undifferentiated) aquifers in Connecticut, Vermont, Massachusetts, New Hampshire	Garabedian and others, 1998
LINJ	linjsus1	NEC	Mixed	Fractured, crystalline-bedrock (undifferentiated) aquifers in New Jersey and New York	Ayers and others, 2000
NECB	necbsus1	NEC	Mixed	Fractured, crystalline-bedrock (metasedimentary, variably calcareous) aquifers in New Hampshire and Maine	Robinson and others, 2004
NECB	necbsus2	NEC	Mixed	Fractured, crystalline-bedrock (felsic igneous and metasedimentary, undifferentiated) aquifers in New Hampshire, Maine, and Massachusetts	Do.
			Glacial aquifer system		
ALMN	almnsus2	ECG	Mixed	Glacial (coarse-grained glaciofluvial sediments) aquifers in northwestern Pennsylvania and western New York	Anderson and others, 2000
CCYK	ccptlusag2a	CPG	Potatoes and corn	Deep, basin-fill glacial aquifers in eastern Washington State	Williamson and others, 1998
CCYK	ccptlusag2b	CPG	Potatoes and corn	Shallow, basin-fill glacial aquifers in eastern Washington State	Do.
CCYK	ccptlusor1a	CPG	Orchards and vineyards	Deep, basin-fill glacial aquifers in eastern Washington	Do.
CCYK	ccptlusor1b	CPG	Orchards and vineyards	Shallow, basin-fill glacial aquifers in eastern Washington	Do.
CNBR	cnbrluscr1	WCG	Corn and soybeans	Loess-mantled glacial till aquifers in eastern Nebraska	Unpublished data [1]
CONN	conndwgs1	NEG	Mixed	Glacial (sand and gravel) aquifers in Connecticut	Do.
CONN	connlusrc1	NEG	New residential and commercial	Glacial (sand and gravel) aquifers in Connecticut and Massachusetts	Do.
CONN	connsus2	NEG	Mixed	Unconsolidated glacial aquifers in western New England	Do.
COOK	cooksus1	NPG	Mixed	Glacial aquifers in Cook Inlet area, Alaska	Glass and others, 2004

Appendix 1. Abbreviations and descriptions of the National Water Quality Assessment (NAWQA) program well networks used to study water quality in glacial, Cambrian-Ordovician, and New York and New England crystalline aquifer systems in the northern United States, 1993–2003.—Continued

NAWQA SUID (see figure 2)	NAWQA well network	Aquifer group code	Predominant land-use setting	Aquifer setting	NAWQA summary report reference
			Glacial aquifer system—Continued		
DELR	delrsus3	ECG	Mixed	Coarse-grained, glacial outwash aquifers in New York, New Jersey, and Pennsylvania	Fischer and others, 2004
EIWA	eiwaluscr1	PWG, WCG	Corn and soybeans	Unconsolidated glacial aquifers in Iowa and Minnesota	Kalkhoff and others, 2000
EIWA	eiwalusrc1	PWG, WCG	Residential, commercial, and industrial	Unconsolidated glacial aquifers in Iowa and Minnesota	Do.
EIWA	eiwasus2	PWG, WCG	Mixed	Alluvial glacial aquifers in Iowa	Do.
HDSN	hdsnlusag1	ECG	Unknown	Unconsolidated glacial aquifers in New York	Wall and others, 1998
HDSN	hdsnlusur1	ECG	Urban	Unconsolidated glacial aquifers in New York	Do.
HPGW	hpgwdwgs1	WCG	Mixed	Quaternary (glacial) aquifers in southeastern Nebraska	Unpublished data [1]
HPGW	hpgwsus4	WCG	Mixed	Unconfined glacial aquifers in Nebraska (northern high plains)	Do.
LERI	lerilusrc1	ECG	Urban	Unconfined glacial aquifers outside Detroit, Michigan	Myers and others, 2000
LERI	lerisus1	ECG	Mixed	Glacial aquifers overlain by fractured clay-till in Michigan and Ohio	Do.
LIRB	lirbluscr1	ECG	Corn and soybeans	Shallow glacial aquifers, Bloomington Ridged Till Plains not overlying buried bedrock valley in Illinois	Groschen and others, 2000
LIRB	lirbluscr2	ECG	Corn and soybeans	Shallow glacial aquifers, Bloomington Ridged Till Plains, overlying Mahomet-Teays buried bedrock valley, in Illinois	Do.
LIRB	lirbsus1	PWG	Mixed	Deep glacial aquifers, Bloomington Ridged Till Plains, overlying Mahomet-Teays buried bedrock valley, in Illinois	Do.
LIRB	lirbsus2	PWG	Mixed	Shallow glacial aquifers, Galesburg/Springfield Till Plains, not overlying buried bedrock valley, in Illinois	Do.
WHMI	miamluscr1	ECG, PWG	Corn and soybeans	Glacial (outwash) aquifers in Indiana and Ohio	Rowe and others, 2004
WHMI	miamlusrc1	ECG, PWG	Urban	Glacial (outwash) aquifers in Ohio	Do.
WHMI	miamsus1	ECG, PWG	Mixed	Confined glacial (buried valley) aquifers in Indiana and Ohio	Do.
NECB	necblusrc1	NEG	New residential and commercial	Coarse-grained, glacial aquifers in Massachusetts and New Hampshire	Robinson and others, 2004
NECB	necbsus3	NEG	Mixed	Shallow and deep glacial aquifers in eastern New England	Do.

Appendix 1. Abbreviations and descriptions of the National Water Quality Assessment (NAWQA) program well networks used to study water quality in glacial, Cambrian-Ordovician, and New York and New England crystalline aquifer systems in the northern United States, 1993–2003.—Continued

NAWQA SUID (see figure 2)	NAWQA well network	Aquifer group code	Predominant land-use setting	Aquifer setting	NAWQA summary report reference
			Glacial aquifer system—Continued		
PUGT	pugtluscr1	NPG	Raspberries cropland	Coarse-grained, glacial aquifers in western Washington State	Ebbert and others, 2000
PUGT	pugtlusrs1	NPG	New residential	Coarse-grained, glacial aquifers in western Washington State	Do.
PUGT	pugtsus1	NPG	Mixed	Unconfined (Fraser) glacial aquifers in western Washington State	Do.
REDN	rednlusag1	NCG	Irrigated cropland	Glacial outwash (Otter Tail) aquifer in Minnesota	Stoner and others, 1998
REDN	rednlusag2	WCG	Agriculture	Glacial (Sheyenne Delta) aquifer in South Dakota	Do.
REDN	rednsus1	WCG, NCG	Mixed	Confined and unconfined glacial aquifers in North Dakota and Minnesota	Do.
REDN	rednsus2	NCG	Mixed	Unconfined glacial aquifers in North Dakota and Minnesota	Do.
REDN	rednsus3	WCG, NCG	Mixed	Unconfined glacial aquifers in North Dakota	Do.
REDN	rednsus5	WCG, NCG	Mixed	Buried glacial aquifers in North Dakota and Minnesota	Do.
					Do.
UIRB	uirbluscr1	ECG	Irrigated rowcrops	Coarse-grained, glacial aquifers in Illinois and Indiana	Groschen and others, 2004
UIRB	uirblusrc1	NCG	Hi-density suburban	Thin sand and gravel lenses in till, overlying Silurian-Devonian aquifers, in Illinois and Wisconsin	Do.
UIRB	uirbsus1	NCG	Mixed	Shallow, coarse-grained, glacial aquifers in Illinois and Wisconsin	Do.
UIRB	uirbsus2	ECG	Mixed	Deep, coarse-grained glacial aquifers in Illinois and Indiana	Do.
UMIS	umislusrc1	WCG	New residential	Coarse-grained, unconfined, glacial aquifers in Minnesota	Stark and others, 2000
WHMI	whitluscr1	ECG	Croplands	Unconfined sand and gravel, and glacial till, aquifers in Indiana	Fenelon, 1998
WHMI	whitluscr3	PWG, ECG	Croplands	Coarse-grained glacial aquifers in Indiana	Do.
WHMI	whitlusur1	ECG, PWG	Urban lands	Coarse-grained, glacial aquifers in Indiana	Do.
WMIC	wmiclusag1a	NCG	Corn and alfalfa	Glacial till (sand, gravel, and clay) aquifers in Wisconsin	Peters and others, 1998
WMIC	wmiclusag2	NCG	Corn and alfalfa	Coarse-grained glacial (sand and gravel) aquifers in Wisconsin	Do.
WMIC	wmicsus2	NCG	Mixed	Glacial aquifers in Wisconsin and Michigan	Unpublished data [1]

[1] Unpublished data collected during the second assessment period of the National Water QualityAssessment Program. Public access to this data is available from the NAWQA Data Warehouse (Bell and Williamson, 2006; Williamson, 2006).

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Appendix 2. Statistical summary of uranium and ^{222}radon concentrations in ground water in the NAWQA well networks used to study water quality in glacial, Cambrian-Ordovician, and New York and New England crystalline aquifer systems in the northern United States, 1993–2003.

[N, number of samples; Min, minimum; 10th, tenth percentile; 25th, twenty-fifth percentile; Med, median; 75th, seventy-fifth percentile; 90th, ninetieth percentile; Max, maximum; <, less than; –, no data available; e, estimated concentration; Domestic, drinking-water well used for private (or household) supply; Monitor, observation well installed in a specific land-use setting for monitoring water quality; Public supply, drinking-water well used for municipal supply]

NAWQA well network	Water use	Sample years	Number of wells in network	Median well depth, in feet	N	Uranium concentrations, in micrograms per liter							N	^{222}Radon concentrations, in picocuries per liter						
						Min	10th	25th	Med	75th	90th	Max		Min	10th	25th	Med	75th	90th	Max
Cambrian-Ordovician aquifer system																				
umissus3	Domestic	1996	25	180	25	< 1	< 1	< 1	< 1	1	1	5	24	100	190	230	340	530	730	2,700
umissus4	Domestic	1996	25	200	25	< 1	< 1	< 1	< 1	2	3	4	23	74	190	250	420	630	900	2,600
wmicsus1	Domestic/public supply	2002	30	155	26	e .01	< .01	0.1	0.28	0.73	1.8	4.7	30	140	180	230	523	730	1,072	1,957
New York and New England crystalline aquifer system																				
connsus1	Domestic	1995	30	235	30	< .4	< .4	< .4	0.75	2.3	12	30	30	220	730	1,300	2,150	5,400	9,500	20,000
linjsus1	Domestic	1997	29	201	29	< 1	< 1	< 1	< 1	1.24	6.4	429	26	218	245	554	1,547	3,124	4,738	31,820
necbsus1	Domestic	1999–00	28	188	28	< 1	< 1	< 1	< 1	2.8	6.1	21.8	26	663	947	1,404	2,185	3,027	5,920	12,776
necbsus2	Domestic	2000	30	303	30	e .01	< 1	< 1	1.9	11	32.4	151.5	28	75	556	1,115	3,567	11,740	45,290	215,210
Glacial aquifer system																				
almnsus2	Domestic	1996	30	73	0	–	–	–	–	–	–	–	30	180	195	330	665	1,200	1,700	2,800
ccptlusag2a	Domestic	1993–94	30	133	0	–	–	–	–	–	–	–	28	210	240	388	555	690	885	1,250
ccptlusag2b	Monitor	1993–94	32	38	27	0.92	2.5	5.7	10.1	17.5	26.6	50.5	19	110	230	270	395	476	831	980
ccptlusor1a	Domestic	1994–95	18	165	0	–	–	–	–	–	–	–	18	310	310	600	915	1,200	1,800	1,900
ccptlusor1b	Monitor	1994–95	22	29.5	19	3.8	4.1	6	14.5	27.9	46.2	68	20	210	250	340	505	620	705	850
cnbrluscr1	Monitor	2003	30	–	29	0.76	2.9	10.9	19.3	44.8	83.8	162	0	–	–	–	–	–	–	–
conndwgs1	Public supply	2002–03	15	70	10	e .01	.01	0.07	0.24	0.38	.97	1.4	5	577	–	762	1,103	1,208	–	1,292
connlusrc1	Monitor	2003	28	22	28	e .01	< .02	0.02	0.024	0.44	.92	13.6	0	–	–	–	–	–	–	–
connsus2	Domestic	2002	30	110	30	e .01	< .02	0.07	0.31	0.97	2.9	6.2	29	166	270	484	758	1,247	2,244	8,056
cooksus1	Domestic	1999	34	97.5	34	< 1	< 1	< 1	< 1	< 1	< 1	< 1	31	139	151	197	256	382	454	609
delrsus3	Domestic	2001	16	114	16	e .01	< .02	< .02	< 0.02	0.2	0.59	0.9	16	373	497	771	1,011	1,483	1,644	2,282
eiwaluscr1	Monitor	1997	31	–	0	–	–	–	–	–	–	–	31	187	221	266	396	488	861	1,500
eiwalusrc1	Monitor	1997	30	–	0	–	–	–	–	–	–	–	30	172	236	281	378	657	987	1,221
eiwasus2	Domestic	1998	32	52	0	–	–	–	–	–	–	–	32	53	196	245	340	515	692	2,146

Appendix 2. Statistical summary of uranium and ^{222}radon concentrations in ground water in the NAWQA well networks used to study water quality in glacial, Cambrian-Ordovician, and New York and New England crystalline aquifer systems in the northern United States, 1993–2003.—Continued

[N, number of samples; Min, minimum; 10th, tenth percentile; 25th, twenty-fifth percentile; Med, median; 75th, seventy-fifth percentile; 90th, ninetieth percentile; Max, maximum; <, less than; –, no data available; e, estimated concentration; Domestic, drinking-water well used for private (or household) supply; Monitor, observation well installed in a specific land-use setting for monitoring water quality; Public supply, drinking-water well used for municipal supply]

NAWQA well network	Water use	Sample years	Number of wells in network	Median well depth, in feet	N	Uranium concentrations, in micrograms per liter							N	^{222}Radon concentrations, in picocuries per liter						
						Min	10th	25th	Med	75th	90th	Max		Min	10th	25th	Med	75th	90th	Max
Glacial aquifer system—Continued																				
hdsnlusag1	Monitor	1993–94	14	19.5	0	–	–	–	–	–	–	–	3	110	–	–	672	–	–	841
hdsnlusur1	Unused/public supply	1993–94	28	27.5	27	< 1	< 1	< 1	< 1	< 1	2	2	18	69	82	102	169	281	531	1,086
hpgwdwgs1	Public supply	2002	15	292	15	0.19	0.5	2.21	6.4	19.9	34.4	66.6	0	–	–	–	–	–	–	–
hpgwsus4	Domestic	2003	30	187.5	27	0.09	0.43	1.8	4.2	7.56	12.2	57.4	26	162	187	233	276	372	626	900
lerilusrc1	Monitor	1996–97	30	25.5	29	< 1	< 1	< 1	< 1	< 1	4	7	21	93	140	170	310	380	520	690
lerisus1	Domestic	1998	27	90	0	–		–	–	–	–	–	27	104	128	145	171	188	245	302
lirbluscr1	Monitor	1997	28	27.5	28	< 1	< 1	< 1	1.7	4	10.2	15	28	< 80	< 80	158	216	251	605	677
lirbluscr2	Monitor	1997	29	20	29	< 1	< 1	< 1	1.2	1.6	4.1	11.6	29	< 80	143	200	348	472	738	1,301
lirbsus1	Domestic	1996	30	245	30	< 1	< 1	< 1	< 1	< 1	< 1	<1	30	110	120	140	160	200	260	730
lirbsus2	Domestic	1996	30	50	30	< 1	< 1	< 1	< 1	1	3.5	17	29	< 52	130	210	340	500	790	1,200
miamluscr1	Monitor	2000	34	27.5	34	< 1	< 1	< 1	< 1	1.75	4.2	14	34	98	215	308	384	506	651	791
miamlusrc1	Monitor	2001	27	38	25	0.23	.42	0.5	0.8	1.1	1.24	1.8	25	199	210	392	449	619	867	1,013
miamsus1	Domestic	1999	30	60	30	< 1	< 1	< 1	< 1	1.7	2.5	3.7	30	163	181	222	359	529	670	1,386
necblusrc1	Monitor	1999	29	23	29	< 1	< 1	< 1	< 1	< 1	< 1	< 2	29	165	344	454	683	822	1,253	1,289
necbsus3	Public supply	2001	30	56	30	< .02	< .02	0.026	0.13	0.39	1.4	15.8	30	311	442	671	1,165	1,627	2,407	3,745
pugtluscr1	Monitor	–	22	–	5	< 1	< 1	< 1	< 1	< 1	< 1	< 1	0	–	–	–	–	–	–	–
pugtlusrs1	Monitor	1996	27	–	0	–	–	–	–	–	–	–	16	160	180	240	385	510	550	630
pugtsus1	Domestic	1996	30	–	0	–	–	–	–	–	–	–	30	100	125	180	290	450	625	860
rednlusag1	Monitor	1994	29	25.5	3	< .4	–	–	< .4	–	–	<.4	3	< 80	–	–	250	–	–	290
rednlusag2	Monitor	1993	29	15	25	< .4	< .4	0.7	1.4	4	11	71	21	217	222	264	341	383	469	940

Appendix 2. Statistical summary of uranium and ^{222}radon concentrations in ground water in the NAWQA well networks used to study water quality in glacial, Cambrian-Ordovician, and New York and New England crystalline aquifer systems in the northern United States, 1993–2003.—Continued

[N, number of samples; Min, minimum; 10th, tenth percentile; 25th, twenty-fifth percentile; Med, median; 75th, seventy-fifth percentile; 90th, ninetieth percentile; Max, maximum; <, less than; –, no data available; e, estimated concentration; Domestic, drinking-water well used for private (or household) supply; Monitor, observation well installed in a specific land-use setting for monitoring water quality; Public supply, drinking-water well used for municipal supply]

NAWQA well network	Water use	Sample years	Number of wells in network	Median well depth, in feet	N	Uranium concentrations, in micrograms per liter							N	^{222}Radon concentrations, in picocuries per liter						
						Min	10th	25th	Med	75th	90th	Max		Min	10th	25th	Med	75th	90th	Max
Glacial aquifer system—Continued																				
rednsus1	Monitor/ domestic	1993–95	29	35	17	< .4	< .4	0.7	1.9	6.7	23	66	14	190	217	230	325	640	670	1,100
rednsus2	Monitor/ domestic	1993	25	58	22	< .4	< .4	< .4	< 0.4	0.7	2.1	5.5	20	130	160	189	267	361	452	594
rednsus3	Monitor/ domestic	1993–95	24	41	24	< .4	< .4	1.2	2.1	3.5	6.7	140	5	290	–	290	469	500	–	820
rednsus5	Domestic	1994	34	121	19	< .4	< .4	< .4	2.7	5	6	7.5	8	83	83	220	305	380	390	390
uirbluscr1	Monitor	1999	29	14	29	< 1	< 1	< 1	< 1	1.7	7.8	21.1	29	137	143	182	260	323	569	695
uirblusrc1	Monitor	2000	27	29	26	< 1	< 1	< 1	< 1	1.3	4.4	5.9	21	149	182	210	265	388	456	587
uirbsus1	Domestic	2001	27	72	27	e .02	< .02	0.11	0.27	0.42	.98	2.5	27	145	153	171	221	310	377	418
uirbsus2	Domestic	2000	23	45	23	e .01	< 1	< 1	< 1	< 1	.53	1.2	23	99	128	131	166	228	259	422
umislusrc1	Monitor	1996	30	19	30	< 1	< 1	< 1	< 1	2	5.5	13	0	–	–	–	–	–	–	–
whitluscr1	Monitor	1994	26	28	23	0.2	.46	0.68	1.7	2.4	6.4	12.1	0	–	–	–	–	–	–	–
whitluscr3	Monitor	1995	30	22.5	0	–	–	–	–	–	–	–	29	160	170	210	310	540	790	1,600
whitlusur1	Monitor	1995	28	29	0	–	–	–	–	–	–	–	28	140	190	300	405	505	690	920
wmiclusag1a	Monitor	1993–94	26	28	25	< .4	< 1	0.4	0.7	1	2.1	5.5	0	–	–	–	–	–	–	–
wmiclusag2	Monitor	1994	32	42	32	e .01	< .02	0.06	0.25	0.83	2.5	11.9	0	–	–	–	–	–	–	–
wmicsus2	Domestic	2002	28	–	28	e .01	< .01	0.06	0.28	0.75	1.9	3.3	28	132	144	173	249	424	1,115	2,436

Appendix 3. Selected rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and ancillary data with uranium concentrations in ground water, by aquifer group, in the northern United States, 1993–2003.

For each aquifer group, the order of the correlation variable is listed by the highest correlation (either negative or positive) value to the lowest correlation value. Spearman's coefficients (rho) are significant when the *P*-values are less than or equal to 0.05; a negative rho value indicates an inverse relation. The following variables consist of geochemical data for the United States based primarily on streambed sediments and analyzed for using a consistent set of methods as part of the USGS National Geochemical Survey (U.S. Geological Survey Open-File Report 2004–1001). Most of the original samples were collected as part of the U.S. Geological Survey's National Uranium Resource Evaluation (NURE) Program from 1975 to 1983 and re-analyzed (data were accessed online May 2005, at *http://tin.er.usgs.gov/geochem/doc/home.htm*).

The variables are expressed in parts per million, unless stated otherwise:

Calcium (NURE)	in percent weight
Molybdenum (NURE)	
Selenium (NURE)	
Sodium (NURE)	in percent weight
Lithium (NURE)	
Lead (NURE)	
Potassium (NURE)	
Iron (NURE)	
Uranium (NURE)	
<	less than
U	uranium
Runoff	mean annual runoff, for 1951 to 1980, in inches (Wolock, D.M., 2003)
precip90	mean annual precipitation, for 1961 through 1990 (Source of data is at Oregon State University in Corvallis, OR, accessed online December 2006, at *http://www.ocs.oregonstate.edu/prism/index.phtml*)
Population Density	population density from the 2000 Census, in persons per square kilometer within 500 meters of sampled wells
^{18}Oxygen	a stable isotope, reported as the ratio per mill (‰, or per thousand) of $^{18}O/^{16}O$ ($\delta^{18}O$)
Deuterium	a stable isotope, reported as the ratio per mill (‰, or per thousand) of $^{2}H/^{1}H$ (δD)
^{40}Potassium	aerial gamma-ray survey across the conterminous United States that measured the gamma-ray flux produced by the radioactive decay of the naturally-occurring element ^{40}Potassium in the top few centimeters of rock and soil, expressed in units of percent potassium (Phillips and others, 1993)
^{232}Thorium	aerial gamma-ray survey across the conterminous United States that measure the gamma-ray flux produced by the radioactive decay of the naturally-occurring element ^{232}Thorium in the top few centimeters of rock and soil, expressed as parts per million equivalent thorium (eTh) (Phillips and others, 1993).

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Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	Cambrian-Ordovician (COS) aquifer			
U	Sodium (NURE)	11	0.501	0.116
U	Acid neutralizing capacity (water)	74	0.478	<0.0001
U	Nickel (water)	76	0.472	<0.0001
U	Molybdenum (NURE)	19	-0.443	0.058
U	Calcium (water)	75	0.415	<0.0001
U	Calcium (NURE)	11	-0.400	0.223
U	Magnesium (water)	75	0.392	<0.0001
U	Specific conductance, field (water)	76	0.358	0.001
U	Manganese (water)	76	0.355	0.002
U	Runoff	75	-0.336	0.003
U	Selenium (NURE)	19	-0.327	0.171
U	Sulfate (water)	75	0.320	0.005
U	Molybdenum (water)	76	0.308	0.007
U	precip90	75	-0.306	0.008
U	Dissolved oxygen (water)	76	-0.280	0.014
U	Thallium (water)	26	0.277	0.171
U	Aluminum (water)	74	0.273	0.019
U	Total dissolved solids (water)	75	0.271	0.019
U	Ammonia + organic nitrogen (water)	38	0.243	0.142
U	Potassium (water)	75	0.226	0.051
U	Turbidity (water)	74	0.223	0.056
U	Tritium (water)	49	-0.219	0.130
U	Zinc (water)	76	0.218	0.058
U	Lithium (water)	26	-0.215	0.291
U	^{232}Thorium (gamma-ray)	73	0.201	0.089
U	Cobalt (water)	76	0.190	0.100
U	Population density	76	0.187	0.106
U	Silica (water)	75	0.183	0.116
U	ortho-phosphate (water)	75	-0.182	0.117
U	Water temperature	76	0.175	0.131
U	Barium (water)	76	0.148	0.202
U	Sodium (water)	75	0.147	0.207
U	Age of water (time of recharge)	62	0.140	0.278
U	Copper (water)	76	-0.139	0.232
U	Boron	26	-0.135	0.510
U	Depth to water table	75	-0.128	0.272
U	^{40}Potassium (gamma-ray)	76	0.119	0.303
U	Chloride (water)	75	-0.117	0.318
U	Arsenic (water)	76	-0.114	0.327
U	Fluoride (water)	75	0.110	0.346
U	Radon (water)	73	0.087	0.463
U	Depth to top of open interval	75	0.081	0.490
U	Phosphorus (water)	74	-0.069	0.561
U	Nitrate (water)	75	0.064	0.586

Appendix 3. Selected rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and ancillary data with uranium concentrations in ground water, by aquifer group, in the northern United States, 1993–2003. —Continued

Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	Cambrian-Ordovician (COS) aquifer—Continued			
U	Dissolved organic carbon (water)	73	0.063	0.596
U	Selenium (water)	76	0.062	0.594
U	pH, field (water)	76	-0.061	0.598
U	Well depth	76	-0.029	0.808
U	Lead (water)	76	-0.020	0.866
U	Strontium (water)	26	0.015	0.940
	Columbia Plateau Glacial (CPG) aquifer			
U	Bicarbonate (water)	45	0.765	<0.0001
U	Calcium (NURE)	10	0.745	0.013
U	Specific conductance, field (water)	46	0.711	<0.0001
U	Sodium (water)	46	0.692	<0.0001
U	Total dissolved solids (water)	46	0.683	<0.0001
U	Acid neutralizing capacity (water)	35	0.680	<0.0001
U	Ammonia + organic nitrogen (water)	46	0.658	<0.0001
U	Molybdenum (NURE)	12	-0.544	0.068
U	Strontium (water)	46	0.518	<0.0001
U	Sulfate (water)	46	0.513	<0.0001
U	Field pH (water)	46	-0.485	<0.0001
U	Dissolved organic carbon (water)	46	0.473	<0.0002
U	Copper (water)	46	0.472	<0.0002
U	Lithium (water)	46	0.469	0.001
U	Sodium (NURE)	12	-0.452	0.140
U	Magnesium (water)	46	0.442	0.002
U	Iron (NURE)	12	0.424	0.170
U	Boron (water)	46	0.418	0.004
U	Chloride (water)	46	0.375	0.010
U	Selenium (water)	46	0.369	0.012
U	Uranium (NURE)	12	0.354	0.259
U	Nickel (water)	46	0.310	0.036
U	Calcium (water)	46	0.309	0.037
U	Bromide (water)	46	0.300	0.043
U	Nitrate (water)	46	0.291	0.050
U	Ortho-phosphate (water)	46	0.284	0.056
U	Depth to water table	35	-0.269	0.119
U	Phosphorus (water)	35	0.255	0.139
U	Iron (water)	46	0.253	0.090
U	Molybdenum (water)	46	0.247	0.098
U	Water temperature	44	-0.232	0.130
U	Ammonia + organic nitrogen (water)	46	-0.230	0.124
U	Manganese (water)	46	0.215	0.151
U	Zinc (water)	46	0.212	0.157
U	Thallium (water)	46	-0.203	0.175
U	Aluminum (water)	46	-0.186	0.215
U	Radon (water)	33	0.176	0.327

Appendix 3. Selected rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and ancillary data with uranium concentrations in ground water, by aquifer group, in the northern United States, 1993–2003. —Continued

Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	Columbia Plateau Glacial (CPG) aquifer—Continued			
U	Population density	46	0.141	0.348
U	Dissolved oxygen (water)	46	-0.140	0.354
U	Depth to top of open interval	46	0.139	0.356
U	Well depth	46	0.126	0.404
U	Depth to bottom of open interval	46	0.125	0.406
U	Fluoride (water)	46	0.099	0.511
U	Vanadium (water)	46	-0.077	0.609
U	^{232}Thorium (gamma-ray)	46	-0.076	0.617
U	Potassium (water)	46	0.063	0.680
U	Turbidity (water)	31	-0.044	0.813
U	Barium (water)	46	0.043	0.777
U	Silica (water)	46	-0.042	0.780
U	precip90	35	0.042	0.812
U	^{40}Potassium (gamma-ray)	46	-0.036	0.813
U	Arsenic (water)	46	-0.012	0.937
	East-Central Glacial (ECG) aquifer			
U	Manganese (water)	283	0.460	<0.0001
U	Magnesium (water)	282	0.452	<0.0001
U	Nickel (water)	283	0.425	<0.0001
U	Sulfate (water)	279	0.414	<0.0001
U	Calcium (water)	282	0.400	<0.0001
U	Molybdenum (water)	283	0.380	<0.0001
U	Sodium (NURE)	43	0.375	0.013
U	Turbidity (water)	179	0.371	<0.0001
U	Total dissolved solids (water)	280	0.361	<0.0001
U	Acid neutralizing capacity (water)	131	0.353	<0.0001
U	Thallium (water)	68	0.342	0.004
U	Carbonate (water)	45	0.329	0.027
U	Cobalt (water)	283	0.316	<0.0001
U	Fluoride (water)	282	0.297	<0.0001
U	Calcium (NURE)	39	0.288	0.076
U	Dissolved organic carbon (water)	277	0.278	<0.0001
U	Specific conductance, field (water)	282	0.271	<0.0001
U	Phosphorus (water)	259	-0.264	<0.0001
U	Depth to water table	280	-0.262	<0.0001
U	Depth to bottom of open interval	275	-0.260	<0.0001
U	Well depth	283	-0.259	<0.0001
U	Depth to top of open interval	279	-0.258	<0.0001
U	Strontium (water)	157	0.227	0.004
U	Nitrite (water)	282	0.224	0.000
U	^{232}Thorium (gamma-ray)	266	0.213	0.001
U	Ortho-phosphate (water)	282	-0.211	0.000
U	Barium (water)	283	0.209	0.000
U	Potassium (NURE)	43	0.209	0.179

Appendix 3. Selected rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and ancillary data with uranium concentrations in ground water, by aquifer group, in the northern United States, 1993–2003. —Continued

Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	East-Central Glacial (ECG) aquifer—Continued			
U	Runoff	280	-0.205	0.001
U	Iron (NURE)	43	0.202	0.193
U	Bicarbonate (water)	73	0.197	0.095
U	Radon (water)	241	-0.191	0.003
U	^{40}Potassium (gamma-ray)	283	0.189	0.001
U	Lithium (NURE)	43	-0.185	0.235
U	Boron (water)	167	0.184	0.017
U	Selenium (NURE)	30	0.176	0.353
U	Potassium (water)	282	0.174	0.003
U	Dissolved oxygen (water)	277	-0.166	0.006
U	Uranium (NURE)	43	-0.158	0.311
U	Selenium (water)	282	0.157	0.008
U	Molybdenum (NURE)	43	-0.158	0.317
U	Population density	283	-0.155	0.009
U	Water temperature	280	0.137	0.021
U	Lead (water)	283	-0.132	0.026
U	Antimony (water)	282	0.129	0.030
U	^{228}Radium (water)	26	0.118	0.566
U	^{18}Oxygen (water)	36	0.115	0.504
U	Arsenic (water)	282	0.114	0.055
U	Lithium (water)	157	0.113	0.159
U	Deuterium (water)	36	0.109	0.528
U	Copper (water)	283	0.088	0.139
U	Bromide (water)	280	0.085	0.155
U	Ammonia (water)	282	0.068	0.257
U	Vanadium (water)	157	-0.060	0.456
U	Chloride (water)	282	-0.059	0.325
U	Aluminum (water)	282	0.045	0.454
U	pH, field (water)	281	-0.044	0.461
U	Zinc (water)	282	0.043	0.469
U	Ammonia + organic nitrogen (water)	209	0.025	0.715
U	Sodium (water)	282	-0.024	0.693
U	Tritium (water)	116	-0.022	0.810
U	precip90	280	-0.013	0.822
U	Silica (water)	282	-0.011	0.856
U	Nitrate (water)	282	-0.009	0.877
U	Iron (water)	282	0.002	0.973
	North-Central Glacial (NCG) aquifer			
U	Cobalt (water)	116	0.463	<0.0001
U	Nickel (water)	114	0.420	<0.0001
U	Nitrite (water)	167	0.330	<0.0001
U	^{224}Radium (water)	27	0.313	0.112
U	^{228}Radium (water)	27	-0.313	0.112
U	Uranium (NURE)	57	0.272	0.040

Appendix 3. Selected rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and ancillary data with uranium concentrations in ground water, by aquifer group, in the northern United States, 1993–2003. —Continued

Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	North-Central Glacial (NCG) aquifer—Continued			
U	Magnesium (water)	171	0.259	<0.0001
U	Fluoride (water)	170	0.250	0.001
U	Potassium (water)	166	0.237	0.002
U	Bicarbonate (water)	74	0.235	0.044
U	Specific conductance, field (water)	170	0.207	0.007
U	Gross beta particle activity (water)	45	0.199	0.190
U	Lithium (water)	119	0.198	0.031
U	Sulfate (water)	166	0.200	0.011
U	Tritium (water)	50	0.190	0.186
U	Calcium (water)	171	0.188	0.014
U	Selenium (water)	124	0.186	0.039
U	Acid neutralizing capacity (water)	87	0.183	0.090
U	Manganese (water)	171	0.175	0.022
U	Total dissolved solids (water)	169	0.174	0.023
U	Chloride (water)	170	0.170	0.027
U	Copper (water)	115	0.162	0.084
U	^{226}Radium (water)	77	-0.161	0.161
U	Calcium (NURE)	26	0.158	0.440
U	Thallium (water)	83	-0.156	0.159
U	Molybdenum (water)	114	0.152	0.107
U	Strontium (water)	119	0.143	0.121
U	Barium (water)	124	0.141	0.117
U	Potassium (NURE)	26	-0.141	0.492
U	Well depth	143	-0.137	0.103
U	Molybdenum (NURE)	57	-0.136	0.311
U	^{18}Oxygen (water)	55	-0.131	0.339
U	Depth to top of open interval	143	-0.127	0.129
U	Depth to bottom of open interval	143	-0.125	0.135
U	Dissolved organic carbon (water)	163	0.120	0.126
U	Deuterium (water)	55	-0.120	0.383
U	Carbonate (water)	73	0.117	0.325
U	Zinc (water)	107	0.111	0.252
U	Nitrate (water)	152	0.109	0.181
U	Sodium (water)	171	0.107	0.165
U	Radon (water)	107	0.102	0.297
U	Phosphorus (water)	137	-0.099	0.249
U	pH, field (water)	170	-0.095	0.216
U	Ortho-phosphate (water)	166	-0.091	0.241
U	Iron (water)	171	-0.091	0.236
U	Aluminum (water)	74	0.089	0.453
U	Water temperature	170	0.085	0.268
U	^{232}Thorium (gamma-ray)	171	0.077	0.318
U	Bromide (water)	170	0.074	0.341
U	Lead (water)	114	0.069	0.465

Appendix 3. Selected rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and ancillary data with uranium concentrations in ground water, by aquifer group, in the northern United States, 1993–2003. —Continued

Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	North-Central Glacial (NCG) aquifer—Continued			
U	Turbidity (water)	108	0.063	0.515
U	Gross alpha particle activity (water)	49	0.058	0.693
U	Ammonia (water)	167	-0.053	0.491
U	Selenium (NURE)	57	0.051	0.705
U	Arsenic (water)	116	-0.050	0.594
U	Population density	143	0.047	0.573
U	Cadmium (water)	124	-0.045	0.620
U	Age of water (time of recharge)	54	-0.045	0.749
U	Dissolved oxygen (water)	162	-0.044	0.580
U	Boron (water)	110	0.044	0.650
U	Silica (water)	171	-0.043	0.578
U	precip90	141	0.026	0.767
U	Runoff	141	0.025	0.767
U	Ammonia + organic nitrogen (water)	146	-0.024	0.776
U	^{40}Potassium (gamma-ray)	171	-0.020	0.800
U	Depth to water table	141	-0.014	0.872
U	Lithium (NURE)	57	-0.007	0.960
	New York and New England Crystalline (NEC) aquifer			
U	Gross alpha particle activity (water)	55	0.719	<0.0001
U	Radon (water)	110	0.598	<0.0001
U	Molybdenum (water)	87	0.350	<0.0001
U	Gross beta particle activity (water)	56	0.333	0.012
U	Calcium (NURE)	52	0.281	0.044
U	Iron (water)	117	-0.266	0.004
U	Lead (water)	87	0.257	0.016
U	Calcium (water)	117	0.254	0.006
U	^{226}Radium (water)	56	0.243	0.071
U	Lithium (water)	58	0.237	0.073
U	Barium (water)	87	-0.233	0.030
U	Antimony (water)	86	0.211	0.050
U	Arsenic (water)	110	0.188	0.049
U	Manganese (water)	117	-0.181	0.050
U	Iron (NURE)	117	-0.178	0.054
U	^{224}Radium (water)	53	-0.177	0.203
U	Acid neutralizing capacity (water)	116	0.176	0.058
U	Depth to water table	117	-0.170	0.066
U	Deuterium (water)	58	-0.167	0.210
U	Cadmium (water)	87	0.165	0.127
U	Potassium (water)	117	0.162	0.081
U	Specific conductance, field (water)	117	0.160	0.085
U	Population density	117	-0.156	0.093
U	Selenium (NURE)	29	-0.154	0.425
U	Well depth	117	0.153	0.100
U	^{18}Oxygen (water)	58	-0.150	0.260

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Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	New York and New England Crystalline (NEC) aquifer—Continued			
U	Fluoride (water)	117	0.144	0.120
U	Total dissolved solids (water)	117	0.143	0.125
U	Potassium (NURE)	116	-0.141	0.132
U	Sodium (water)	117	0.138	0.138
U	Water temperature	117	0.137	0.141
U	Selenium (water)	76	-0.134	0.250
U	Aluminum (water)	86	-0.130	0.231
U	Silica (water)	117	-0.113	0.227
U	Sodium (NURE)	117	0.112	0.230
U	Beryllium (water)	87	0.109	0.314
U	pH, field (water)	117	0.107	0.251
U	^{228}Radium (water)	58	-0.100	0.453
U	Uranium (NURE)	117	0.100	0.284
U	Ammonia (water)	117	-0.098	0.292
U	Strontium (water)	58	0.097	0.467
U	Runoff	117	0.089	0.336
U	^{40}Potassium (gamma-ray)	117	0.088	0.343
U	Ammonia + organic nitrogen (water)	65	-0.080	0.526
U	Magnesium (water)	117	0.078	0.405
U	Zinc (water)	86	0.066	0.548
U	Dissolved organic carbon (water)	81	0.064	0.569
U	Ortho-phosphate (water)	117	-0.060	0.521
U	precip90	117	-0.059	0.528
U	Dissolved oxygen (water)	115	-0.054	0.566
U	Boron (water)	53	-0.049	0.730
U	Age of water (time of recharge)	55	0.042	0.760
U	Molybdenum (NURE)	116	-0.039	0.673
U	Lithium (NURE)	116	-0.036	0.697
U	Bromide (water)	117	-0.032	0.729
U	Bicarbonate (water)	88	-0.029	0.786
U	Sulfate (water)	116	-0.025	0.789
U	Phosphorus (water)	117	-0.024	0.800
U	Depth to top of open interval	117	-0.022	0.814
U	Nitrate (water)	117	-0.015	0.868
U	Copper (water)	87	-0.012	0.911
U	Nickel (water)	87	-0.007	0.948
U	Chloride (water)	117	0.001	0.990
	Northeastern Glacial (NEG) aquifer			
U	Gross alpha particle activity (water)	63	0.543	<0.0001
U	Sulfate (water)	126	0.368	<0.0001
U	Field pH (water)	126	0.345	<0.0001
U	Acid neutralizing capacity (water)	124	0.310	<0.0001
U	Molybdenum (water)	126	0.306	<0.0001

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Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	Northeastern Glacial (NEG) aquifer—Continued			
U	Well depth	125	0.303	<0.0001
U	Bicarbonate (water)	126	0.302	<0.0001
U	Depth to bottom of open interval	116	0.291	0.002
U	Calcium (water)	126	0.287	0.001
U	Depth to top of open interval	116	0.286	0.002
U	^{18}Oxygen (water)	38	-0.262	0.111
U	Deuterium (water)	38	-0.262	0.112
U	Aluminum (water)	104	-0.249	0.011
U	Arsenic (water)	126	0.248	0.005
U	Strontium (water)	125	0.220	0.014
U	Chloride (water)	126	-0.207	0.020
U	Dissolved oxygen (water)	126	-0.204	0.022
U	precip90	58	-0.200	0.131
U	Gross beta particle activity (water)	63	0.196	0.124
U	Potassium (water)	126	0.190	0.033
U	Total dissolved solids (water)	123	0.187	0.039
U	^{226}Radium (water)	50	0.176	0.220
U	Specific conductance, field (water)	126	0.167	0.061
U	Calcium (NURE)	61	0.164	0.207
U	Lithium (water)	125	0.160	0.074
U	Magnesium (water)	126	0.155	0.082
U	Population density	125	-0.139	0.120
U	Cobalt (water)	126	-0.124	0.166
U	Depth to water table	58	-0.124	0.355
U	Selenium (NURE)	55	0.120	0.382
U	Lithium (NURE)	119	0.116	0.208
U	Sodium (water)	126	-0.111	0.217
U	Iron (water)	126	0.108	0.229
U	Sodium (NURE)	125	-0.106	0.241
U	^{40}Potassium (gamma-ray)	124	0.095	0.292
U	Iron (NURE)	125	0.087	0.337
U	Bromide (water)	126	0.086	0.341
U	Dissolved organic carbon (water)	120	-0.082	0.373
U	Molybdenum (NURE)	119	0.080	0.385
U	^{228}Radium (water)	53	0.074	0.597
U	Uranium (NURE)	125	-0.073	0.419
U	Ortho-phosphate (water)	126	0.071	0.429
U	Barium (water)	126	-0.054	0.748
U	^{224}Radium (water)	42	0.051	0.748
U	Lead (water)	126	-0.042	0.639
U	Water temperature	126	-0.042	0.641
U	Ammonia (water)	126	-0.040	0.659
U	^{232}Thorium (gamma-ray)	108	0.038	0.695
U	Runoff	58	-0.038	0.776

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Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	Northeastern Glacial (NEG) aquifer—Continued			
U	Zinc (water)	126	-0.034	0.704
U	Vanadium (water)	125	-0.031	0.735
U	Beryllium (water)	126	-0.030	0.736
U	Boron (water)	113	-0.028	0.771
U	Copper (water)	126	-0.028	0.759
U	Ammonia + organic nitrogen (water)	126	-0.027	0.763
U	Silica (water)	126	0.016	0.861
U	Radon (water)	92	0.014	0.890
U	Potassium (NURE)	119	-0.014	0.883
U	Phosphorus (water)	58	0.008	0.952
U	Nitrate (water)	116	-0.008	0.933
U	Turbidity (water)	38	0.008	0.964
U	Thallium (water)	98	0.007	0.944
U	Nickel (water)	126	-0.007	0.941
U	Manganese (water)	126	-0.005	0.952
U	Fluoride (water)	126	-0.009	0.991
	Northern Pacific Glacial (NPG) aquifer			
U	No correlations between uranium in ground water and other variables.			
	Pre-Wisconsinan glacial (PWG) aquifer			
U	Strontium (water)	11	0.607	0.048
U	Sulfate (water)	71	0.560	<0.0001
U	Field pH (water)	71	-0.519	<0.0001
U	Calcium (water)	70	0.467	<0.0001
U	Nickel (water)	71	0.453	<0.0001
U	Phosphorus (water)	66	-0.449	<0.0001
U	Dissolved oxygen (water)	71	0.448	<0.0001
U	Ammonia (water)	71	-0.442	<0.0001
U	Depth to top of open interval	71	-0.441	<0.0001
U	Nitrate (water)	71	0.434	<0.0001
U	Ortho-phosphate (water)	71	-0.434	<0.0001
U	Iron (water)	71	-0.424	<0.0001
U	Well depth	71	-0.422	<0.0001
U	Depth to bottom of open interval	71	-0.421	<0.0001
U	Barium (water)	71	-0.410	<0.0001
U	Radon (water)	70	0.406	<0.0001
U	Copper (water)	71	0.390	<0.0001
U	Bromide (water)	69	0.376	0.001
U	Magnesium (water)	71	0.358	0.002
U	Runoff	71	-0.356	0.002
U	Molybdenum (water)	71	-0.347	0.003
U	Potassium (water)	71	-0.327	0.005
U	Tritium (water)	34	0.326	0.060
U	Aluminum (water)	71	0.319	0.007
U	Cobalt (water)	71	0.314	0.008

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Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	Pre-Wisconsinan glacial (PWG) aquifer—Continued			
U	Turbidity (water)	63	-0.312	0.013
U	Sodium (water)	71	-0.307	0.009
U	Total dissolved solids (water)	70	0.288	0.015
U	Antimony (water)	71	0.285	0.016
U	Ammonia + organic nitrogen (water)	53	-0.276	0.046
U	Arsenic (water)	71	-0.275	0.020
U	Dissolved organic carbon (water)	70	-0.242	0.044
U	Zinc (water)	71	0.240	0.044
U	Fluoride (water)	71	-0.226	0.057
U	Nitrite (water)	71	0.188	0.116
U	precip90	71	-0.176	0.141
U	Acid neutralizing capacity (water)	60	-0.163	0.213
U	Water temperature	71	0.149	0.214
U	Selenium (water)	71	0.131	0.277
U	Specific conductance, field (water)	71	0.122	0.311
U	^{40}Potassium (gamma-ray)	71	-0.080	0.507
U	^{232}Thorium (gamma-ray)	69	-0.073	0.553
U	Depth to water table	71	-0.067	0.580
U	Lead (water)	71	-0.056	0.641
U	Manganese (water)	71	-0.042	0.730
U	Chloride (water)	70	0.029	0.809
U	Population density	71	-0.023	0.852
U	Silica (water)	71	0.010	0.937
	West-Central Glacial (WCG) aquifer			
U	Selenium (water)	116	0.598	<0.0001
U	Carbonate (water)	135	0.524	<0.0001
U	Potassium (water)	169	0.521	<0.0001
U	Aluminum (water)	52	-0.483	<0.0001
U	^{40}Potassium (gamma-ray)	175	0.462	<0.0001
U	Iron (water)	174	-0.458	<0.0001
U	Lithium (water)	72	0.431	<0.0001
U	Fluoride (water)	176	0.428	<0.0001
U	^{232}Thorium (gamma-ray)	175	0.425	<0.0001
U	Lithium (NURE)	132	0.416	<0.0001
U	Acid neutralizing capacity (water)	96	0.402	<0.0001
U	Sodium (water)	176	0.398	<0.0001
U	Total dissolved solids (water)	176	0.390	<0.0001
U	Bicarbonate (water)	176	0.373	<0.0001
U	Calcium (water)	176	0.372	<0.0001
U	Potassium (NURE)	132	0.368	<0.0001
U	Ammonia + organic nitrogen (water)	133	-0.363	<0.0001
U	Boron (water)	78	0.357	0.001
U	Nitrate (water)	161	0.335	<0.0001
U	Tritium (water)	56	-0.328	0.014

Appendix 3. Selected rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and ancillary data with uranium concentrations in ground water, by aquifer group, in the northern United States, 1993–2003. —Continued

Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	West-Central Glacial (WCG) aquifer—Continued			
U	Specific conductance, field (water)	175	0.328	<0.0001
U	Strontium (water)	72	0.315	0.007
U	Manganese (water)	176	-0.311	<0.0001
U	Calcium (NURE)	132	-0.304	<0.0001
U	Vanadium (water)	72	-0.303	0.010
U	Ammonia (water)	172	-0.301	<0.0001
U	Depth to bottom of open interval	124	0.300	<0.0001
U	Turbidity (water)	30	-0.292	0.118
U	Well depth	131	0.280	0.001
U	Sulfate (water)	175	0.265	<0.0001
U	Depth to top of open interval	125	0.258	0.004
U	Phosphorus (water)	100	-0.250	0.012
U	Runoff	105	-0.248	0.011
U	Copper (water)	116	0.243	0.009
U	Bromide (water)	176	0.229	0.002
U	Dissolved oxygen (water)	175	0.218	0.004
U	Selenium (NURE)	132	0.214	0.014
U	Zinc (water)	116	-0.195	0.036
U	Barium (water)	116	0.194	0.037
U	Magnesium (water)	176	0.193	0.010
U	Silica (water)	176	0.181	0.016
U	Molybdenum (water)	116	0.177	0.057
U	Uranium (NURE)	132	0.176	0.043
U	precip90	105	-0.176	0.073
U	Age of water (time of recharge)	28	-0.169	0.390
U	Arsenic (water)	122	0.157	0.084
U	Thallium (water)	72	-0.155	0.193
U	Cobalt (water)	115	-0.150	0.110
U	Water temperature	175	0.127	0.094
U	Ortho-phosphate (water)	169	0.126	0.103
U	Molybdenum (NURE)	132	0.116	0.185
U	Sodium (NURE)	132	-0.113	0.195
U	Dissolved organic carbon (water)	162	-0.111	0.160
U	Radon (water)	60	0.064	0.627
U	pH, field (water)	177	-0.060	0.424
U	Chloride (water)	175	0.058	0.444
U	Nitrite (water)	172	0.050	0.516
U	Depth to water table	105	-0.050	0.613
U	Iron (NURE)	132	0.041	0.640
U	Population density	177	0.014	0.851
U	Lead (water)	115	0.013	0.892
U	Antimony (water)	116	0.012	0.901
U	Nickel (water)	116	-0.010	0.916

References

Phillips, J.D., Duval, J.S., and Ambroziak, R.A., 1993, National Geophysical Data Grids: Gamma-ray, gravity, magnetic, and topographic data for the conterminous United States: U.S. Geological Survey Digital Data Series DDS-9, accessed online May 2005, at *ftp://ftpext.usgs.gov/pub/cr/co/denver/musette/pub/GEOPHYSICAL_DATA/cdrom_DDS-9/*

Wolock, D.M., 2003, Estimated mean annual natural ground-water recharge in the conterminous United States: U.S. Geological Survey Open-File Report 03–311, online at *http://water.usgs.gov/lookup/getspatial?rech48grd*.

Appendix 4. Selected rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and other ancillary data with ^{222}radon concentrations in ground water, by aquifer group, in the northern United States, 1993–2003.

For each aquifer group, the order of the correlation variable is listed by the highest correlation (either negative or positive) value to the lowest correlation value. Spearman's coefficients (rho) are significant when the *P*-values are less than or equal to 0.05; a negative rho value indicates an inverse relation. The following variables consist of geochemical data for the United States based primarily on streambed sediments and analyzed for using a consistent set of methods as part of the USGS National Geochemical Survey (U.S. Geological Survey Open-File Report 2004–1001). Most of the original samples were collected as part of the U.S. Geological Survey's National Uranium Resource Evaluation (NURE) Program from 1975 to 1983 and re-analyzed (data were accessed online May 2005, at *http://tin.er.usgs.gov/geochem/doc/home.htm*).

The variables are expressed in parts per million, unless stated otherwise:

Calcium (NURE)	in percent weight
Molybdenum (NURE)	
Selenium (NURE)	
Sodium (NURE)	in percent weight
Lithium (NURE)	
Lead (NURE)	
Potassium (NURE)	
Iron (NURE)	
Uranium (NURE)	
<	less than
^{222}Rn	radon
Runoff	mean annual runoff, for 1951 to 1980, in inches (Wolock, D.M., 2003)
precip90	mean annual precipitation, for 1961 through 1990 (Source of data is at Oregon State University in Corvallis, OR, accessed online December 2006, at *http://www.ocs.oregonstate.edu/prism/index.phtml*)
Population Density	population density from the 2000 Census, in persons per square kilometer within 500 meters of sampled wells
^{18}Oxygen	a stable isotope, reported as the ratio per mill (‰, or per thousand) of $^{18}O/^{16}O$ ($\delta^{18}O$)
Deuterium	a stable isotope, reported as the ratio per mill (‰, or per thousand) of $^{2}H/^{1}H$ (δD)
^{40}Potassium	aerial gamma-ray survey across the conterminous United States that measured the gamma-ray flux produced by the radioactive decay of the naturally-occurring element ^{40}Potassium in the top few centimeters of rock and soil, expressed in units of percent potassium (Phillips and others, 1993)
^{232}Thorium	aerial gamma-ray survey across the conterminous United States that measure the gamma-ray flux produced by the radioactive decay of the naturally-occurring element ^{232}Thorium in the top few centimeters of rock and soil, expressed as parts per million equivalent thorium (eTh) (Phillips and others, 1993).

Appendix 4. Selected rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and other ancillary data with ^{222}radon concentrations in ground water, by aquifer group, in the northern United States, 1993–2003. —Continued

Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	Cambrian-Ordovician (COS) aquifer			
^{222}Rn	Sodium (NURE)	11	0.474	0.141
^{222}Rn	Thallium (water)	26	0.393	0.047
^{222}Rn	Depth to water table	76	-0.278	0.015
^{222}Rn	Dissolved organic carbon (water)	74	0.215	0.066
^{222}Rn	precip90	76	0.200	0.083
^{222}Rn	Nickel (water)	73	-0.179	0.129
^{222}Rn	Runoff	76	0.175	0.130
^{222}Rn	Nitrite (water)	76	0.174	0.133
^{222}Rn	Aluminum (water)	71	-0.170	0.155
^{222}Rn	Age of water (recharge date)	64	0.167	0.186
^{222}Rn	Water temperature	77	-0.167	0.146
^{222}Rn	Lead (water)	73	-0.166	0.161
^{222}Rn	Strontium (water)	26	0.164	0.424
^{222}Rn	Silica (water)	76	0.162	0.162
^{222}Rn	Zinc (water)	73	-0.149	0.210
^{222}Rn	Well depth	77	-0.123	0.288
^{222}Rn	Depth to top of open interval	76	-0.114	0.328
^{222}Rn	pH, field (water)	77	-0.108	0.348
^{222}Rn	Potassium (water)	76	0.107	0.357
^{222}Rn	^{40}Potassium (gamma-ray)	77	0.105	0.365
^{222}Rn	Arsenic (water)	73	-0.103	0.384
^{222}Rn	Iron (water)	76	-0.093	0.424
^{222}Rn	Barium (water)	73	0.087	0.463
^{222}Rn	Uranium (water)	73	0.087	0.463
^{222}Rn	Acid neutralizing capacity (water)	75	0.080	0.498
^{222}Rn	Cobalt (water)	73	-0.078	0.512
^{222}Rn	Nitrate (water)	76	0.073	0.529
^{222}Rn	Turbidity (water)	71	0.066	0.582
^{222}Rn	Dissolved oxygen (water)	76	-0.057	0.623
^{222}Rn	Lithium (water)	26	-0.056	0.784
^{222}Rn	Calcium (water)	76	-0.052	0.654
^{222}Rn	Fluoride (water)	76	0.051	0.663
^{222}Rn	Molybdenum (water)	73	-0.047	0.691
^{222}Rn	Total dissolved solids (water)	76	0.045	0.697
^{222}Rn	Sodium (water)	76	0.045	0.699
^{222}Rn	Ammonia + organic nitrogen (water)	39	0.042	0.802
^{222}Rn	Selenium (water)	73	0.035	0.772
^{222}Rn	^{232}Thorium (gamma-ray)	73	0.032	0.787
^{222}Rn	Ortho-phosphate (water)	76	-0.032	0.784
^{222}Rn	Magnesium (water)	76	0.031	0.790
^{222}Rn	Ammonia (water)	76	0.023	0.844
^{222}Rn	Copper (water)	73	-0.022	0.855
^{222}Rn	Tritium (water)	50	0.021	0.887

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Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	Cambrian-Ordovician (COS) aquifer—Continued			
^{222}Rn	Population density	77	-0.016	0.888
^{222}Rn	Chloride (water)	76	-0.013	0.914
^{222}Rn	Specific conductance, field (water)	77	-0.006	0.957
^{222}Rn	Boron (water)	26	0.004	0.982
^{222}Rn	Phosphorus (water)	75	-0.003	0.982
^{222}Rn	Sulfate (water)	76	0.002	0.984
^{222}Rn	Manganese (water)	77	0.001	0.991
	Columbia Plateau Glacial (CPG) aquifer			
^{222}Rn	Lithium (water)	33	0.510	0.002
^{222}Rn	Lead (NURE)	21	-0.417	0.060
^{222}Rn	Depth to bottom of screen interval	83	0.370	0.001
^{222}Rn	Well depth	85	0.368	0.001
^{222}Rn	Bromide (water)	85	0.348	0.001
^{222}Rn	Phosphorus (water)	85	-0.326	0.002
^{222}Rn	Nickel (water)	33	0.323	0.067
^{222}Rn	Vanadium (water)	33	-0.311	0.078
^{222}Rn	Thallium (water)	33	-0.301	0.089
^{222}Rn	Iron (water)	85	0.298	0.006
^{222}Rn	Calcium (NURE)	21	-0.279	0.220
^{222}Rn	Zinc (water)	33	0.274	0.123
^{222}Rn	Arsenic (water)	33	-0.258	0.147
^{222}Rn	Ortho-phosphate (water)	85	-0.247	0.023
^{222}Rn	Molybdenum (water)	33	0.231	0.197
^{222}Rn	Depth to top of open interval	84	0.225	0.040
^{222}Rn	Selenium (water)	33	0.216	0.228
^{222}Rn	Boron (water)	33	-0.202	0.256
^{222}Rn	Bicarbonate (water)	76	-0.188	0.104
^{222}Rn	Depth to water table	85	0.187	0.087
^{222}Rn	^{40}Potassium (gamma-ray)	85	0.186	0.088
^{222}Rn	Uranium (water)	33	0.176	0.327
^{222}Rn	Sulfate (water)	85	0.158	0.148
^{222}Rn	Chloride (water)	85	0.156	0.155
^{222}Rn	Manganese (water)	85	0.142	0.196
^{222}Rn	Nitrate (water)	85	-0.132	0.227
^{222}Rn	Copper (water)	33	0.122	0.498
^{222}Rn	Ammonia + organic nitrogen (water)	44	0.100	0.518
^{222}Rn	Water temperature	81	0.097	0.389
^{222}Rn	Magnesium (water)	85	-0.095	0.387
^{222}Rn	Potassium (water)	85	0.076	0.491
^{222}Rn	Calcium (water)	85	-0.065	0.554
^{222}Rn	Specific conductance, field (water)	85	-0.065	0.556
^{222}Rn	Strontium (water)	33	-0.053	0.767
^{222}Rn	Total dissolved solids (water)	85	-0.051	0.641
^{222}Rn	^{232}Thorium (gamma-ray)	85	0.047	0.667

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Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	Columbia Plateau Glacial (CPG) aquifer—Continued			
^{222}Rn	Fluoride (water)	85	0.046	0.673
^{222}Rn	Barium (water)	33	-0.037	0.836
^{222}Rn	Nitrite (water)	85	0.037	0.737
^{222}Rn	Silica (water)	85	0.029	0.790
^{222}Rn	Dissolved organic carbon (water)	61	-0.029	0.827
^{222}Rn	Aluminum (water)	33	-0.017	0.927
^{222}Rn	Acid neutralizing capacity (water)	61	-0.015	0.907
^{222}Rn	Population density	85	-0.015	0.888
^{222}Rn	Ammonia (water)	85	0.012	0.914
^{222}Rn	precip90	85	0.012	0.916
^{222}Rn	Sodium (water)	85	-0.012	0.917
^{222}Rn	Dissolved oxygen (water)	85	-0.010	0.926
^{222}Rn	pH, field (water)	85	-0.003	0.979
	East-Central Glacial (ECG) aquifer			
^{222}Rn	Calcium (NURE)	35	-0.707	<0.0001
^{222}Rn	Sodium (NURE)	39	-0.672	<0.0001
^{222}Rn	Lithium (NURE)	39	0.583	0.000
^{222}Rn	Uranium (NURE)	39	0.570	0.000
^{222}Rn	Nitrate (water)	336	0.554	<0.0001
^{222}Rn	Iron (water)	336	-0.507	<0.0001
^{222}Rn	precip90	337	0.500	<0.0001
^{222}Rn	Ammonia (water)	336	-0.486	<0.0001
^{222}Rn	Selenium (NURE)	23	-0.464	0.026
^{222}Rn	Dissolved oxygen (water)	331	0.440	<0.0001
^{222}Rn	Arsenic (water)	241	-0.430	<0.0001
^{222}Rn	Manganese (water)	337	-0.428	<0.0001
^{222}Rn	Ammonia + organic nitrogen (water)	216	-0.398	<0.0001
^{222}Rn	Runoff	337	0.381	<0.0001
^{222}Rn	^{228}Radium (water)	26	-0.357	0.074
^{222}Rn	Sulfate (water)	333	-0.349	<0.0001
^{222}Rn	Molybdenum (NURE)	39	0.348	0.030
^{222}Rn	Molybdenum (water)	241	-0.341	<0.0001
^{222}Rn	^{232}Thorium (gamma-ray)	296	0.337	<0.0001
^{222}Rn	Potassium (NURE)	39	-0.334	0.038
^{222}Rn	Silica (water)	336	-0.327	<0.0001
^{222}Rn	Dissolved organic carbon (water)	330	-0.301	<0.0001
^{222}Rn	Iron (NURE)	39	-0.301	0.063
^{222}Rn	Bicarbonate (water)	70	0.282	0.018
^{222}Rn	Fluoride (water)	336	-0.278	<0.0001
^{222}Rn	Deuterium (water)	36	0.264	0.120
^{222}Rn	Thallium (water)	43	-0.264	0.088
^{222}Rn	^{18}Oxygen (water)	36	0.249	0.143
^{222}Rn	Copper (water)	241	0.248	0.000
^{222}Rn	Acid neutralizing capacity (water)	189	-0.239	0.001

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Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	East-Central Glacial (ECG) aquifer—Continued			
^{222}Rn	Lithium (water)	132	-0.239	0.006
^{222}Rn	pH, field (water)	335	-0.225	<0.0001
^{222}Rn	Total dissolved solids (water)	334	-0.199	0.000
^{222}Rn	Boron (water)	139	-0.198	0.019
^{222}Rn	Uranium (water)	241	-0.191	0.003
^{222}Rn	Nickel (water)	242	-0.188	0.003
^{222}Rn	Magnesium (water)	336	-0.172	0.002
^{222}Rn	Cobalt (water)	241	-0.161	0.013
^{222}Rn	Selenium (water)	241	0.141	0.029
^{222}Rn	Strontium (water)	132	-0.139	0.113
^{222}Rn	Calcium (water)	336	-0.136	0.012
^{222}Rn	Specific conductance, field (water)	336	-0.134	0.014
^{222}Rn	Aluminum (water)	241	-0.132	0.041
^{222}Rn	Nitrite (water)	336	-0.131	0.016
^{222}Rn	Potassium (water)	336	-0.124	0.023
^{222}Rn	Chloride (water)	336	0.102	0.062
^{222}Rn	Depth to water table	337	0.097	0.076
^{222}Rn	Antimony (water)	240	-0.087	0.178
^{222}Rn	Turbidity (water)	182	0.085	0.256
^{222}Rn	Water temperature	334	-0.068	0.213
^{222}Rn	Zinc (water)	240	-0.046	0.477
^{222}Rn	Ortho-phosphate (water)	336	-0.043	0.427
^{222}Rn	Well depth	337	-0.041	0.449
^{222}Rn	Tritium (water)	120	0.037	0.686
^{222}Rn	Depth to bottom of open interval	329	-0.034	0.535
^{222}Rn	Sodium (water)	336	-0.031	0.575
^{222}Rn	Vanadium (water)	132	-0.026	0.764
^{222}Rn	^{232}Thorium (gamma-ray)	337	-0.025	0.651
^{222}Rn	Barium (water)	242	-0.024	0.708
^{222}Rn	Population density	337	0.023	0.669
^{222}Rn	Lead (water)	241	0.017	0.788
^{222}Rn	Total phosphorus (water)	316	-0.006	0.910
	North-Central Glacial (NCG) aquifer			
^{222}Rn	Sodium (NURE)	22	0.348	0.113
^{222}Rn	Gross alpha particle activity (water)	48	-0.344	0.017
^{222}Rn	Nitrate (water)	88	0.342	0.001
^{222}Rn	Iron (water)	107	-0.329	0.001
^{222}Rn	precip90	79	-0.303	0.007
^{222}Rn	Bicarbonate (water)	30	0.284	0.128
^{222}Rn	^{224}Radium (water)	27	-0.282	0.153
^{222}Rn	Gross beta particle activity (water)	44	-0.279	0.067
^{222}Rn	Manganese (water)	107	-0.270	0.005
^{222}Rn	Total phosphorus (water)	75	0.256	0.027
^{222}Rn	Runoff	79	-0.249	0.027

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Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
North-Central Glacial (NCG) aquifer—Continued				
^{222}Rn	^{228}Radium (water)	27	-0.233	0.242
^{222}Rn	^{226}Radium (water)	76	-0.226	0.050
^{222}Rn	Selenium (water)	91	0.220	0.036
^{222}Rn	Zinc (water)	76	0.215	0.062
^{222}Rn	Nickel (water)	81	0.212	0.058
^{222}Rn	^{232}Thorium (gamma-ray)	107	0.211	0.029
^{222}Rn	Ortho-phosphate (water)	102	0.209	0.035
^{222}Rn	Turbidity (water)	76	0.207	0.072
^{222}Rn	Depth to top of open interval	79	-0.200	0.077
^{222}Rn	Lithium (NURE)	29	0.195	0.311
^{222}Rn	Copper (water)	82	0.188	0.090
^{222}Rn	Acid neutralizing capacity (water)	31	0.185	0.320
^{222}Rn	Ammonia (water)	103	-0.178	0.072
^{222}Rn	Depth to bottom of open interval	79	-0.173	0.128
^{222}Rn	Well depth	79	-0.170	0.133
^{222}Rn	Thallium (water)	55	-0.170	0.215
^{222}Rn	Molybdenum (NURE)	29	0.169	0.380
^{222}Rn	Cobalt (water)	83	0.169	0.127
^{222}Rn	Depth to water table	79	-0.155	0.173
^{222}Rn	Sodium (water)	107	0.141	0.149
^{222}Rn	Lithium (water)	86	-0.133	0.223
^{222}Rn	Molybdenum (water)	81	-0.127	0.260
^{222}Rn	Potassium (water)	102	0.121	0.227
^{222}Rn	^{40}Potassium (gamma-ray)	107	0.110	0.261
^{222}Rn	pH, field (water)	107	-0.109	0.263
^{222}Rn	Dissolved organic carbon (water)	100	0.102	0.313
^{222}Rn	Uranium (water)	107	0.102	0.297
^{222}Rn	Specific conductance, field (water)	107	0.096	0.326
^{222}Rn	Lead (water)	81	0.094	0.403
^{222}Rn	Strontium (water)	86	-0.086	0.430
^{222}Rn	Dissolved oxygen (water)	103	0.078	0.436
^{222}Rn	Barium (water)	91	-0.076	0.473
^{222}Rn	Total dissolved solids (water)	105	0.071	0.472
^{222}Rn	Chloride (water)	106	0.069	0.484
^{222}Rn	Selenium (NURE)	29	-0.062	0.751
^{222}Rn	Ammonia + organic nitrogen (water)	97	-0.058	0.574
^{222}Rn	Calcium (water)	107	0.042	0.669
^{222}Rn	Magnesium (water)	107	0.040	0.679
^{222}Rn	Arsenic (water)	83	0.040	0.721
^{222}Rn	Silica (water)	107	0.039	0.689
^{222}Rn	Cadmium (water)	91	0.036	0.734
^{222}Rn	Nitrite (water)	103	-0.032	0.749
^{222}Rn	Water temperature	107	-0.024	0.804
^{222}Rn	Fluoride (water)	106	-0.018	0.855

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Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	North-Central Glacial (NCG) aquifer—Continued			
^{222}Rn	Uranium (NURE)	29	0.016	0.935
^{222}Rn	Population density	79	0.012	0.916
^{222}Rn	Sulfate (water)	102	0.008	0.933
^{222}Rn	Aluminum (water)	43	-0.007	0.965
^{222}Rn	Boron (water)	77	0.001	0.100
	New York and New England Crystalline (NEC) aquifer			
^{222}Rn	Uranium (water)	110	0.598	<0.0001
^{222}Rn	Gross alpha particle activity (water)	53	0.537	<0.0001
^{222}Rn	Gross beta particle activity (water)	54	0.424	0.001
^{222}Rn	Lead (water)	80	0.378	0.001
^{222}Rn	Strontium (water)	54	-0.347	0.010
^{222}Rn	Barium (water)	80	-0.347	0.002
^{222}Rn	Sulfate (water)	109	-0.328	0.001
^{222}Rn	Calcium (NURE)	45	0.325	0.029
^{222}Rn	Bicarbonate (water)	84	-0.324	0.003
^{222}Rn	^{226}Radium (water)	54	0.257	0.060
^{222}Rn	Beryllium (water)	47	0.245	0.028
^{222}Rn	Boron (water)	47	-0.242	0.102
^{222}Rn	^{232}Thorium (gamma-ray)	106	0.228	0.019
^{222}Rn	Iron (NURE)	110	-0.222	0.020
^{222}Rn	^{40}Potassium (gamma-ray)	110	0.224	0.020
^{222}Rn	Lithium (water)	54	0.200	0.148
^{222}Rn	Cadmium (water)	80	0.192	0.087
^{222}Rn	Fluoride (water)	110	0.188	0.049
^{222}Rn	Molybdenum (water)	80	0.187	0.097
^{222}Rn	Sodium (NURE)	110	0.184	0.054
^{222}Rn	^{18}Oxygen (water)	54	0.171	0.217
^{222}Rn	Antimony (water)	79	-0.158	0.164
^{222}Rn	Age of water (recharge date)	51	0.154	0.282
^{222}Rn	Acid neutralizing capacity (water)	109	-0.139	0.148
^{222}Rn	Deuterium (water)	54	0.138	0.320
^{222}Rn	Zinc (water)	79	0.133	0.244
^{222}Rn	Water temperature	110	0.126	0.190
^{222}Rn	Total dissolved solids (water)	110	-0.122	0.203
^{222}Rn	Iron (water)	110	-0.122	0.203
^{222}Rn	Phosphorus (water)	110	0.118	0.219
^{222}Rn	Copper (water)	80	0.118	0.219
^{222}Rn	Runoff	110	0.113	0.239
^{222}Rn	Dissolved oxygen (water)	108	0.109	0.264
^{222}Rn	Dissolved organic carbon (water)	75	-0.101	0.386
^{222}Rn	Potassium (water)	110	0.097	0.315
^{222}Rn	Specific conductance, field (water)	110	-0.096	0.317
^{222}Rn	^{224}Radium (water)	51	0.089	0.536
^{222}Rn	Lithium (NURE)	109	-0.086	0.374

Appendix 4. Selected rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and other ancillary data with ^{222}radon concentrations in ground water, by aquifer group, in the northern United States, 1993–2003. —Continued

Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
New York and New England Crystalline (NEC) aquifer—Continued				
^{222}Rn	Nickel (water)	80	-0.080	0.481
^{222}Rn	Nitrite (water)	110	-0.080	0.409
^{222}Rn	Molybdenum (NURE)	110	-0.069	0.473
^{222}Rn	Uranium (NURE)	110	0.068	0.483
^{222}Rn	Manganese (water)	110	-0.064	0.507
^{222}Rn	Magnesium (water)	110	-0.060	0.530
^{222}Rn	Well depth	110	-0.059	0.537
^{222}Rn	Population density	110	-0.059	0.537
^{222}Rn	Ammonia (water)	110	-0.058	0.548
^{222}Rn	Silica (water)	110	-0.058	0.550
^{222}Rn	Ortho-phosphate (water)	110	0.045	0.639
^{222}Rn	Calcium (water)	110	-0.042	0.665
^{222}Rn	Chloride (water)	110	-0.038	0.690
^{222}Rn	precip90	110	0.037	0.703
^{222}Rn	pH, field (water)	110	-0.037	0.705
^{222}Rn	Ammonia + organic nitrogen (water)	59	-0.021	0.874
^{222}Rn	Arsenic (water)	104	-0.019	0.846
^{222}Rn	Sodium (water)	110	0.018	0.853
^{222}Rn	^{228}Radium (water)	56	0.017	0.901
^{222}Rn	Potassium (NURE)	109	0.016	0.872
^{222}Rn	Nitrate (water)	110	-0.013	0.893
^{222}Rn	Aluminum (water)	79	0.008	0.943
^{222}Rn	Depth to top of open interval	110	-0.008	0.936
^{222}Rn	Depth to water table	110	-0.003	0.976
^{222}Rn	Selenium (water)	71	-0.001	0.994
Northeastern Glacial (NEG) aquifer				
^{222}Rn	Water temperature, in deg. C	93	-0.461	<0.0001
^{222}Rn	Barium (water)	93	-0.414	<0.0001
^{222}Rn	Deuterium (water)	39	-0.286	0.078
^{222}Rn	Nickel (water)	93	-0.285	0.006
^{222}Rn	Fluoride (water)	93	0.265	0.010
^{222}Rn	^{18}Oxygen (water)	39	-0.263	0.105
^{222}Rn	^{224}Radium (water)	43	-0.258	0.095
^{222}Rn	Nitrite (water)	93	-0.248	0.017
^{222}Rn	^{228}Radium (water)	54	-0.221	0.108
^{222}Rn	Dissolved organic carbon (water)	89	-0.209	0.049
^{222}Rn	Silica (water)	93	0.208	0.045
^{222}Rn	Potassium (NURE)	86	0.198	0.067
^{222}Rn	Sodium (NURE)	92	0.192	0.067
^{222}Rn	Well depth	93	0.191	0.066
^{222}Rn	Ammonia + organic nitrogen (water)	93	-0.191	0.067
^{222}Rn	Cobalt (water)	93	-0.181	0.083
^{222}Rn	Aluminum (water)	85	-0.176	0.108
^{222}Rn	Uranium (NURE)	92	0.170	0.106

Appendix 4. Selected rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and other ancillary data with ^{222}radon concentrations in ground water, by aquifer group, in the northern United States, 1993–2003. —Continued

Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	Northeastern Glacial (NEG) aquifer—Continued			
^{222}Rn	Iron (water)	93	-0.168	0.107
^{222}Rn	Population density	93	-0.168	0.106
^{222}Rn	pH, field (water)	93	0.167	0.111
^{222}Rn	Boron (water)	80	-0.161	0.153
^{222}Rn	^{40}Potassium (gamma-ray)	91	0.161	0.128
^{222}Rn	Manganese (water)	93	-0.161	0.124
^{222}Rn	Specific conductance, field (water)	93	-0.159	0.128
^{222}Rn	Sodium (water)	93	-0.158	0.130
^{222}Rn	Molybdenum (water)	92	0.150	0.154
^{222}Rn	Potassium (water)	93	0.148	0.156
^{222}Rn	Gross alpha particle activity (water)	63	-0.143	0.265
^{222}Rn	Thallium (water)	64	-0.142	0.262
^{222}Rn	Depth to water table	59	-0.138	0.299
^{222}Rn	Lithium (water)	92	0.136	0.197
^{222}Rn	^{232}Thorium (gamma-ray)	75	0.135	0.248
^{222}Rn	Age of water (recharge date)	33	0.129	0.476
^{222}Rn	Total dissolved solids (water)	90	-0.125	0.240
^{222}Rn	Zinc (water)	93	-0.122	0.242
^{222}Rn	Strontium (water)	92	0.122	0.247
^{222}Rn	Dissolved oxygen (water)	93	0.122	0.246
^{222}Rn	Phosphorus (water)	59	-0.120	0.363
^{222}Rn	Vanadium (water)	91	-0.116	0.272
^{222}Rn	Magnesium (water)	93	0.112	0.286
^{222}Rn	Turbidity (water)	39	-0.104	0.527
^{222}Rn	Bicarbonate (water)	93	0.102	0.330
^{222}Rn	Arsenic (water)	93	-0.102	0.333
^{222}Rn	Depth to top of open interval	84	0.097	0.382
^{222}Rn	Beryllium (water)	92	0.093	0.379
^{222}Rn	Chloride (water)	93	-0.086	0.411
^{222}Rn	Ammonia (water)	93	-0.083	0.429
^{222}Rn	^{226}Radium (water)	51	0.080	0.576
^{222}Rn	Acid neutralizing capacity (water)	93	0.059	0.572
^{222}Rn	Selenium (NURE)	47	-0.058	0.698
^{222}Rn	Molybdenum (NURE)	86	0.055	0.614
^{222}Rn	Lithium (NURE)	86	0.049	0.655
^{222}Rn	Nitrate (water)	87	-0.046	0.675
^{222}Rn	precip90	59	-0.036	0.789
^{222}Rn	Sulfate (water)	93	-0.035	0.738
^{222}Rn	Iron (NURE)	92	0.028	0.790
^{222}Rn	Gross beta particle activity (water)	63	-0.025	0.847
^{222}Rn	Calcium (NURE)	50	0.020	0.893
^{222}Rn	Lead (water)	92	0.017	0.871
^{222}Rn	Ortho-phosphate (water)	93	0.016	0.882
^{222}Rn	Copper (water)	93	0.015	0.887

Appendix 4. Selected rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and other ancillary data with ^{222}radon concentrations in ground water, by aquifer group, in the northern United States, 1993–2003. —Continued

Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	Northeastern Glacial (NEG) aquifer—Continued			
^{222}Rn	Uranium (water)	92	0.014	0.892
^{222}Rn	Runoff	59	0.013	0.921
^{222}Rn	Calcium (water)	93	0.012	0.908
	Northern Pacific Glacial (NPG) aquifer			
^{222}Rn	^{232}Thorium (gamma-ray)	42	0.535	0.000
^{222}Rn	^{40}Potassium (gamma-ray)	43	0.501	0.001
^{222}Rn	Aluminum (water)	31	-0.421	0.018
^{222}Rn	Potassium (NURE)	24	0.420	0.041
^{222}Rn	Arsenic (water)	30	-0.401	0.028
^{222}Rn	Field pH (water)	77	-0.326	0.004
^{222}Rn	Iron (water)	77	-0.323	0.004
^{222}Rn	Depth to bottom of screen interval	50	-0.305	0.031
^{222}Rn	Depth to water table	77	0.304	0.007
^{222}Rn	Molybdenum (water)	31	-0.291	0.112
^{222}Rn	Nitrate (water)	77	0.266	0.019
^{222}Rn	Barium (water)	31	-0.263	0.152
^{222}Rn	Calcium (NURE)	31	-0.241	0.191
^{222}Rn	precip90	46	-0.239	0.110
^{222}Rn	^{226}Radium (water)	31	-0.218	0.240
^{222}Rn	Manganese (water)	77	-0.208	0.069
^{222}Rn	Gross alpha particle activity (water)	31	0.191	0.303
^{222}Rn	Runoff	45	-0.169	0.141
^{222}Rn	Bicarbonate (water)	62	-0.155	0.230
^{222}Rn	Population density	46	0.151	0.314
^{222}Rn	Gross beta particle activity (water)	31	0.148	0.425
^{222}Rn	Cobalt	31	0.143	0.443
^{222}Rn	Water temperature	77	0.142	0.218
^{222}Rn	Iron (NURE)	31	-0.142	0.448
^{222}Rn	Chloride	76	0.137	0.239
^{222}Rn	Well depth	77	-0.136	0.238
^{222}Rn	Sodium (NURE)	31	-0.135	0.467
^{222}Rn	Phosphorus (water)	77	-0.130	0.260
^{222}Rn	Silica (water)	77	0.128	0.269
^{222}Rn	Magnesium (water)	77	-0.125	0.277
^{222}Rn	Depth to top of open interval	77	-0.120	0.297
^{222}Rn	Zinc (water)	31	0.115	0.537
^{222}Rn	Sodium (water)	77	0.114	0.322
^{222}Rn	Copper (water)	31	0.099	0.595
^{222}Rn	Ortho-phosphate	77	-0.098	0.398
^{222}Rn	Acid neutralizing capacity (water)	46	-0.097	0.523
^{222}Rn	Lithium (NURE)	30	0.095	0.617
^{222}Rn	Nitrite (water)	77	0.088	0.447
^{222}Rn	Nickel (water)	31	-0.083	0.655
^{222}Rn	Potassium (water)	77	0.081	0.486

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Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	Northern Pacific Glacial (NPG) aquifer—Continued			
^{222}Rn	Specific conductance (water)	77	-0.074	0.521
^{222}Rn	Uranium (NURE)	31	-0.073	0.696
^{222}Rn	Ammonia (water)	77	-0.047	0.682
^{222}Rn	Dissolved oxygen (water)	77	0.046	0.694
^{222}Rn	Lead (water)	31	0.041	0.827
^{222}Rn	Sulfate (water)	76	0.036	0.757
^{222}Rn	^{18}Oxygen (water)	28	-0.036	0.857
^{222}Rn	Deuterium (water)	28	-0.029	0.883
^{222}Rn	Dissolved organic carbon (water)	77	-0.025	0.831
^{222}Rn	Total dissolved soilds (water)	76	-0.022	0.850
^{222}Rn	^{224}Radium (water)	21	-0.020	0.933
^{222}Rn	^{228}Radium (water)	29	0.019	0.923
^{222}Rn	Ammonia + organic nitrogen (water)	34	-0.018	0.918
^{222}Rn	Calcium (water)	77	0.012	0.919
^{222}Rn	Fluoride (water)	76	-0.012	0.921
^{222}Rn	Selenium (water)	29	-0.008	0.968
	Pre-Wisconsinan Glacial (PWG) aquifer			
^{222}Rn	Copper (water)	70	0.558	<0.0001
^{222}Rn	Dissolved oxygen (water)	173	0.541	<0.0001
^{222}Rn	Depth to bottom of screen interval	157	-0.535	<0.0001
^{222}Rn	Barium (water)	70	-0.519	<0.0001
^{222}Rn	Depth to top of screen interval	157	-0.503	<0.0001
^{222}Rn	Molybdenum (water)	70	-0.477	<0.0001
^{222}Rn	Ammonia (water)	175	-0.473	<0.0001
^{222}Rn	Well depth	175	-0.449	<0.0001
^{222}Rn	Iron (water)	175	-0.408	<0.0001
^{222}Rn	Uranium (water)	70	0.406	0.000
^{222}Rn	Ammonia + organic nitrogen (water)	95	-0.404	<0.0001
^{222}Rn	^{228}Radium (water)	4	0.400	0.600
^{222}Rn	Arsenic (water)	70	-0.344	0.004
^{222}Rn	Ortho-phosphate (water)	175	-0.330	<0.0001
^{222}Rn	Runoff	175	-0.328	<0.0001
^{222}Rn	Selenium (water)	70	0.319	0.007
^{222}Rn	Nitrate (water)	175	0.308	<0.0001
^{222}Rn	^{40}Potassium (gamma-ray)	175	-0.300	0.000
^{222}Rn	Sulfate (water)	175	0.295	0.000
^{222}Rn	precip90	175	-0.293	0.000
^{222}Rn	Acid neutralizing capacity (water)	164	-0.290	0.000
^{222}Rn	Field pH (water)	175	-0.289	0.000
^{222}Rn	Fluoride (water)	175	-0.287	0.000
^{222}Rn	Phosphorus (water)	170	-0.281	0.000
^{222}Rn	Sodium (water)	175	-0.281	0.000
^{222}Rn	Dissolved organic carbon (DOC)	174	-0.274	0.000
^{222}Rn	^{18}Oxygen (water)	83	-0.260	0.017

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Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	Pre-Wisconsinan Glacial (PWG) aquifer—Continued			
^{222}Rn	Deuterium (water)	69	-0.228	0.059
^{222}Rn	Population density	175	0.190	0.012
^{222}Rn	Calcium (water)	174	0.164	0.031
^{222}Rn	Specific conductance (water)	175	-0.160	0.034
^{222}Rn	Potassium (water)	175	-0.159	0.035
^{222}Rn	Magnesium (water)	175	-0.152	0.044
^{222}Rn	^{232}Thorium (gamma-ray)	173	-0.145	0.057
^{222}Rn	Cobalt (water)	70	0.144	0.233
^{222}Rn	Bicarbonate (water)	90	0.130	0.222
^{222}Rn	Lead (water)	70	0.128	0.290
^{222}Rn	Manganese (water)	166	-0.117	0.132
^{222}Rn	Turbidity (water)	161	0.111	0.162
^{222}Rn	Water temperature	173	-0.100	0.189
^{222}Rn	Nickel (water)	70	0.091	0.455
^{222}Rn	Total dissolved solids (water)	174	-0.087	0.255
^{222}Rn	Zinc (water)	70	-0.075	0.539
^{222}Rn	Tritium (water)	133	-0.072	0.411
^{222}Rn	Antimony (water)	70	0.057	0.641
^{222}Rn	Chloride (water)	174	-0.045	0.558
^{222}Rn	Aluminum (water)	70	-0.032	0.791
^{222}Rn	Carbonate (water)	90	-0.026	0.805
^{222}Rn	Nitrite (water)	175	-0.013	0.862
^{222}Rn	Silica (water)	175	-0.004	0.959
^{222}Rn	Depth to water table	175	-0.002	0.980
	West-Central Glacial (WCG) aquifer			
^{222}Rn	Depth to top of screen interval	63	-0.364	0.003
^{222}Rn	Tritium (water)	34	0.352	0.041
^{222}Rn	Depth to bottom of screen interval	62	-0.348	0.006
^{222}Rn	Well depth	70	-0.345	0.003
^{222}Rn	^{18}Oxygen (water)	17	-0.338	0.184
^{222}Rn	^{232}Thorium (gamma-ray)	76	-0.337	0.003
^{222}Rn	^{40}Potassium (gamma-ray)	76	-0.322	0.005
^{222}Rn	Depth to water table	50	0.321	0.023
^{222}Rn	Thallium (water)	26	0.307	0.127
^{222}Rn	Potassium (NURE)	64	-0.298	0.017
^{222}Rn	Iron (water)	68	-0.249	0.040
^{222}Rn	Bromide (water)	70	-0.267	0.026
^{222}Rn	Boron (water)	32	0.234	0.198
^{222}Rn	Phosphorus (water)	44	-0.221	0.149
^{222}Rn	Molybdenum (NURE)	64	-0.206	0.102
^{222}Rn	Lead (water)	30	0.204	0.280
^{222}Rn	Nickel (water)	31	0.188	0.312
^{222}Rn	Selenium (water)	31	0.179	0.334
^{222}Rn	Calcium (NURE)	64	0.172	0.173

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Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
	West-Central Glacial (WCG) aquifer—Continued			
^{222}Rn	Lithium (NURE)	64	-0.165	0.191
^{222}Rn	Ammonia (water)	70	-0.160	0.187
^{222}Rn	Dissolved organic carbon (water)	69	0.159	0.193
^{222}Rn	Water temperature	70	-0.153	0.207
^{222}Rn	Carbonate (water)	69	-0.147	0.227
^{222}Rn	Nitrite (water)	70	0.142	0.241
^{222}Rn	Nitrate (water)	66	0.134	0.282
^{222}Rn	Molybdenum (water)	31	0.132	0.479
^{222}Rn	Magnesium (water)	69	0.125	0.306
^{222}Rn	Selenium (NURE)	64	-0.121	0.341
^{222}Rn	Fluoride (water)	70	-0.112	0.356
^{222}Rn	Ortho-phosphate (water)	70	-0.110	0.366
^{222}Rn	Copper (water)	31	0.106	0.569
^{222}Rn	Vanadium (water)	26	0.106	0.608
^{222}Rn	Chloride (water)	70	-0.102	0.400
^{222}Rn	Population density	76	-0.097	0.405
^{222}Rn	Silica (water)	69	-0.096	0.434
^{222}Rn	Potassium (water)	70	-0.092	0.449
^{222}Rn	Arsenic (water)	37	0.089	0.602
^{222}Rn	Runoff	50	0.089	0.54
^{222}Rn	Strontium (water)	26	0.074	0.719
^{222}Rn	Iron (NURE)	64	-0.071	0.577
^{222}Rn	Lithium (water)	26	0.070	0.735
^{222}Rn	Sodium (NURE)	64	-0.067	0.597
^{222}Rn	Barium (water)	31	0.064	0.731
^{222}Rn	Uranium (water)	60	0.064	0.627
^{222}Rn	Specific conductance (water)	68	-0.059	0.634
^{222}Rn	precip90	50	-0.057	0.693
^{222}Rn	Turbidity (water)	10	0.055	0.881
^{222}Rn	Ammonia + organic nitrogen (water)	54	0.053	0.703
^{222}Rn	Sodium (water)	69	-0.051	0.680
^{222}Rn	Dissolved oxygen (water)	69	-0.050	0.683
^{222}Rn	pH, field (water)	70	0.050	0.683
^{222}Rn	Sulfate (water)	70	-0.045	0.709
^{222}Rn	Manganese (water)	69	0.044	0.719
^{222}Rn	Bicarbonate (water)	70	0.030	0.803
^{222}Rn	Zinc (water)	31	-0.014	0.942
^{222}Rn	Acid neutralizing capacity (water)	43	0.012	0.938
^{222}Rn	Calcium (water)	69	-0.011	0.929
^{222}Rn	Total dissolved solids (water)	70	-0.010	0.932
^{222}Rn	Uranium (NURE)	64	-0.005	0.970

References

Phillips, J.D., Duval, J.S., and Ambroziak, R.A., 1993, National Geophysical Data Grids: Gamma-ray, gravity, magnetic, and topographic data for the conterminous United States: U.S. Geological Survey Digital Data Series DDS-9, accessed online May 2005, at *ftp://ftpext.usgs.gov/pub/cr/co/denver/musette/pub/GEOPHYSICAL_DATA/cdrom_DDS-9/*

Wolock, D.M., 2003, Estimated mean annual natural ground-water recharge in the conterminous United States: U.S. Geological Survey Open-File Report 03–311, online at *http://water.usgs.gov/lookup/getspatial?rech48grd*

Appendix 5. Significant rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and other ancillary data with uranium concentrations in selected NAWQA well networks in the Columbia Plateau glacial, West-Central glacial, and New York and New England crystalline aquifer groups, in the northern United States, 1993–2003.

For each aquifer group, the order of the correlation variable is listed by the highest correlation (either negative or positive) value to the lowest correlation value. Spearman's coefficients (rho) are significant when the *P*-values are less than or equal to 0.05; a negative rho value indicates an inverse relation. The following variables consist of geochemical data for the United States based primarily on streambed sediments and analyzed for using a consistent set of methods as part of the USGS National Geochemical Survey (U.S. Geological Survey Open-File Report 2004–1001). Most of the original samples were collected as part of the U.S. Geological Survey's National Uranium Resource Evaluation (NURE) Program from 1975 to 1983 and re-analyzed (data were accessed online May 2005, at *http://tin.er.usgs.gov/geochem/doc/home.htm*).

The variables are expressed in parts per million, unless stated otherwise:

Calcium (NURE) in percent weight

Molybdenum (NURE)

Selenium (NURE)

Sodium (NURE) in percent weight

Lithium (NURE)

Lead (NURE)

Potassium (NURE)

Iron (NURE)

Uranium (NURE)

<	less than
U	uranium
deg. C	degrees Celsius
precip90	mean annual precipitation, for 1961 through 1990 (Source of data is at Oregon State University in Corvallis, OR, accessed online December 2006, at *http://www.ocs.oregonstate.edu/prism/index.phtml*)
^{18}Oxygen	a stable isotope, reported as the ratio per mill (‰, or per thousand) of $^{18}O/^{16}O$ ($\delta^{18}O$)
Deuterium	a stable isotope, reported as the ratio per mill (‰, or per thousand) of $^{2}H/^{1}H$ (δD)
^{40}Potassium	aerial gamma-ray survey across the conterminous United States that measured the gamma-ray flux produced by the radioactive decay of the naturally-occurring element ^{40}Potassium in the top few centimeters of rock and soil, expressed in units of percent potassium (Phillips and others, 1993)
^{232}Thorium	aerial gamma-ray survey across the conterminous United States that measure the gamma-ray flux produced by the radioactive decay of the naturally-occurring element ^{232}Thorium in the top few centimeters of rock and soil, expressed as parts per million equivalent thorium (eTh) (Phillips and others, 1993).

Appendix 5. Significant rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and other ancillary data with uranium concentrations in selected NAWQA well networks in the Columbia Plateau glacial, West-Central glacial, and New York and New England crystalline aquifer groups, in the northern United States, 1993–2003.—Continued

NAWQA well network (See appendix 1 for definition)	Aquifer group code	Radionuclide	Variable name	Number of samples	Spearman's coefficient (rho)	*P*-value
ccptlusag2b	CPG	U	Bicarbonate (water)	26	0.826	<0.0001
ccptlusag2b	CPG	U	Calcium (NURE)	10	0.745	0.013
ccptlusag2b	CPG	U	Sodium (water)	27	0.737	<0.0001
ccptlusag2b	CPG	U	Ammonia + organic nitrogen (water)	27	0.664	0.000
ccptlusag2b	CPG	U	Acid neutralizing capacity (water)	16	0.664	0.005
ccptlusag2b	CPG	U	Boron (water)	27	0.638	–
ccptlusag2b	CPG	U	Lithium (water)	27	0.616	0.001
ccptlusag2b	CPG	U	Specific conductance, field (water)	27	0.595	0.001
ccptlusag2b	CPG	U	Molybdenum (NURE)	12	-0.544	0.068
ccptlusag2b	CPG	U	Total dissolved solids (water)	27	0.531	0.004
ccptlusag2b	CPG	U	Copper (water)	27	0.527	0.005
ccptlusag2b	CPG	U	Field pH (water)	27	-0.500	0.008
ccptlusag2b	CPG	U	Dissolved organic carbon (water)	27	0.471	0.013
ccptlusag2b	CPG	U	Strontium (water)	27	0.463	0.015
ccptlusag2b	CPG	U	Sodium (NURE)	12	-0.452	0.140
ccptlusag2b	CPG	U	Iron (NURE)	12	0.424	0.170
ccptlusag2b	CPG	U	^{222}Radon (water)	16	0.421	0.105
ccptlusag2b	CPG	U	Magnesium (water)	27	0.403	0.037
ccptlusag2b	CPG	U	Sulfate (water)	27	0.386	0.046
ccptlusag2b	CPG	U	Thallium (water)	27	-0.373	0.055
ccptlusag2b	CPG	U	Manganese (water)	27	0.371	0.057
ccptlusag2b	CPG	U	Uranium (NURE)	12	0.354	0.259
ccptlusag2b	CPG	U	Molybdenum (water)	27	0.344	0.079
ccptlusag2b	CPG	U	Fluoride (water)	27	0.326	0.097
ccptlusag2b	CPG	U	precip90	16	0.298	0.263
ccptlusag2b	CPG	U	Barium (water)	27	0.284	0.150
ccptlusag2b	CPG	U	^{40}Potassium (gamma-ray)	27	0.279	0.158
ccptlusag2b	CPG	U	Ammonia (water)	27	-0.277	0.162
ccptlusag2b	CPG	U	Selenium (water)	27	0.264	0.184
ccptlusor1b	CPG	U	Specific conductance, field (water)	19	0.914	<0.0001
ccptlusor1b	CPG	U	Total dissolved solids (water)	19	0.909	<0.0001
ccptlusor1b	CPG	U	Acid neutralizing capacity (water)	19	0.719	0.001
ccptlusor1b	CPG	U	Bicarbonate (water)	19	0.705	0.001
ccptlusor1b	CPG	U	Sodium (water)	19	0.691	0.001
ccptlusor1b	CPG	U	Ammonia + organic nitrogen (water)	19	0.681	0.001
ccptlusor1b	CPG	U	Sulfate (water)	19	0.644	0.003
ccptlusor1b	CPG	U	Dissolved organic carbon (water)	19	0.558	0.013
ccptlusor1b	CPG	U	Strontium (water)	19	0.540	0.017
ccptlusor1b	CPG	U	Nitrate (water)	19	0.467	0.044
ccptlusor1b	CPG	U	Selenium (water)	19	0.455	0.050
ccptlusor1b	CPG	U	Field pH (water)	19	-0.441	0.059
ccptlusor1b	CPG	U	Depth to water table	19	-0.437	0.061

Appendix 5. Significant rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and other ancillary data with uranium concentrations in selected NAWQA well networks in the Columbia Plateau glacial, West-Central glacial, and New York and New England crystalline aquifer groups, in the northern United States, 1993–2003.—Continued

NAWQA well network (See appendix 1 for definition)	Aquifer group code	Radionuclide	Variable name	Number of samples	Spearman's coefficient (rho)	*P*-value
ccptlusor1b	CPG	U	Nickel (water)	19	0.434	0.063
ccptlusor1b	CPG	U	Chloride (water)	19	0.433	0.064
ccptlusor1b	CPG	U	Water temperature, in deg. C	19	-0.433	0.064
ccptlusor1b	CPG	U	Magnesium (water)	19	0.432	0.065
ccptlusor1b	CPG	U	Ortho phosphate (water)	19	0.404	0.086
ccptlusor1b	CPG	U	Phosphorus (water)	19	0.401	0.089
ccptlusor1b	CPG	U	Calcium (water)	19	0.396	0.093
ccptlusor1b	CPG	U	Iron (water)	19	0.387	0.101
ccptlusor1b	CPG	U	Copper (water)	19	0.346	0.147
ccptlusor1b	CPG	U	Thallium (water)	19	0.344	0.149
ccptlusor1b	CPG	U	Zinc (water)	19	0.295	0.221
cnbrluscr1	WCG	U	Lithium (water)	29	0.810	<0.0001
cnbrluscr1	WCG	U	Boron (water)	29	0.790	–
cnbrluscr1	WCG	U	Potassium (water)	26	0.714	<0.0001
cnbrluscr1	WCG	U	Sodium (water)	29	0.574	0.001
cnbrluscr1	WCG	U	Strontium (water)	29	0.510	0.005
cnbrluscr1	WCG	U	Selenium (water)	29	0.504	0.005
cnbrluscr1	WCG	U	Total dissolved solids (water)	29	0.486	0.007
cnbrluscr1	WCG	U	Uranium (NURE)	28	-0.471	0.011
cnbrluscr1	WCG	U	Fluoride (water)	29	0.459	0.012
cnbrluscr1	WCG	U	^{232}Thorium (gamma-ray)	28	-0.449	0.016
cnbrluscr1	WCG	U	Specific conductance, field (water)	29	0.437	0.018
cnbrluscr1	WCG	U	Sulfate (water)	28	0.425	0.024
cnbrluscr1	WCG	U	Bicarbonate (water)	28	0.420	0.026
cnbrluscr1	WCG	U	Calcium (water)	29	0.353	0.060
cnbrluscr1	WCG	U	Cabonate (water)	28	0.339	0.078
cnbrluscr1	WCG	U	Aluminum (water)	6	-0.338	0.512
cnbrluscr1	WCG	U	Iron (water)	28	-0.332	0.084
cnbrluscr1	WCG	U	Chloride (water)	29	0.324	0.086
cnbrluscr1	WCG	U	Silica (water)	29	0.304	0.109
cnbrluscr1	WCG	U	Calcium (NURE)	28	0.297	0.125
cnbrluscr1	WCG	U	^{40}Potassium (gamma-ray)	28	-0.277	0.154
cnbrluscr1	WCG	U	Arsenic (water)	29	0.271	0.155
cnbrluscr1	WCG	U	Manganese (water)	29	-0.264	0.166
cnbrluscr1	WCG	U	Potassium (NURE)	28	0.263	0.176
cnbrluscr1	WCG	U	Lithium (NURE)	28	0.258	0.184
hpgwdwgs1	WCG	U	Ammonia + organic nitrogen (water)	15	-0.718	0.003
hpgwdwgs1	WCG	U	Ammonia (water)	15	-0.659	0.008
hpgwdwgs1	WCG	U	Iron (water)	15	-0.643	0.010
hpgwdwgs1	WCG	U	Copper (water)	15	0.620	0.014
hpgwdwgs1	WCG	U	Iron (NURE)	15	0.532	0.041

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NAWQA well network (See appendix 1 for definition)	Aquifer group code	Radionuclide	Variable name	Number of samples	Spearman's coefficient (rho)	*P*-value
hpgwdwgs1	WCG	U	Sodium (NURE)	15	-0.509	0.053
hpgwdwgs1	WCG	U	Manganese (water)	15	-0.464	0.082
hpgwdwgs1	WCG	U	Arsenic (water)	15	-0.452	0.091
hpgwdwgs1	WCG	U	Barium (water)	15	0.398	0.142
hpgwdwgs1	WCG	U	Ortho phosphate (water)	15	0.384	0.158
hpgwdwgs1	WCG	U	Nitrite (water)	15	0.379	0.163
hpgwdwgs1	WCG	U	Molybdenum (NURE)	15	-0.376	0.168
hpgwdwgs1	WCG	U	Thallium (water)	15	-0.372	0.172
hpgwdwgs1	WCG	U	Fluoride (water)	15	-0.370	0.175
hpgwdwgs1	WCG	U	Selenium (water)	15	0.359	0.189
hpgwdwgs1	WCG	U	Boron (water)	15	-0.330	–
hpgwdwgs1	WCG	U	Selenium (NURE)	15	-0.321	0.243
hpgwdwgs1	WCG	U	Calcium (NURE)	15	-0.316	0.252
hpgwdwgs1	WCG	U	Sodium (water)	15	0.315	0.252
hpgwdwgs1	WCG	U	Dissolved organic carbon (water)	15	0.297	0.282
hpgwdwgs1	WCG	U	Cabonate (water)	13	0.291	0.335
hpgwsus4	WCG	U	Selenium (water)	27	0.589	0.001
hpgwsus4	WCG	U	Iron (water)	27	-0.487	0.010
hpgwsus4	WCG	U	Ammonia (water)	27	-0.464	0.015
hpgwsus4	WCG	U	Nitrite (water)	27	0.455	0.017
hpgwsus4	WCG	U	Tritium (water)	12	0.366	0.241
hpgwsus4	WCG	U	Sulfate (water)	27	0.364	0.062
hpgwsus4	WCG	U	Cabonate (water)	27	0.349	0.075
hpgwsus4	WCG	U	Ammonia + organic nitrogen (water)	27	-0.344	0.079
hpgwsus4	WCG	U	Depth to bottom of screen interval	27	-0.330	0.093
hpgwsus4	WCG	U	Well depth	27	-0.324	0.099
hpgwsus4	WCG	U	Calcium (water)	27	0.305	0.122
hpgwsus4	WCG	U	Copper (water)	27	0.300	0.129
hpgwsus4	WCG	U	Selenium (NURE)	27	-0.262	0.187
hpgwsus4	WCG	U	^{222}Radon (water)	26	0.258	0.202
hpgwsus4	WCG	U	Depth to top of screen interval	27	-0.256	0.198
rednlusag2	WCG	U	Tritium (water)	9	-0.586	0.097
rednlusag2	WCG	U	Total dissolved solids (water)	25	0.553	0.004
rednlusag2	WCG	U	Specific conductance, field (water)	25	0.523	0.007
rednlusag2	WCG	U	Magnesium (water)	24	0.506	0.012
rednlusag2	WCG	U	Bicarbonate (water)	25	0.501	0.011
rednlusag2	WCG	U	Acid neutralizing capacity (water)	25	0.460	0.021
rednlusag2	WCG	U	Well depth	17	-0.408	0.104
rednlusag2	WCG	U	Silica (water)	24	-0.394	0.057
rednlusag2	WCG	U	Sodium (water)	24	0.385	0.063
rednlusag2	WCG	U	Sulfate (water)	25	0.384	0.058

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NAWQA well network (See appendix 1 for definition)	Aquifer group code	Radionuclide	Variable name	Number of samples	Spearman's coefficient (rho)	*P*-value
rednlusag2	WCG	U	Calcium (water)	24	0.377	0.069
rednlusag2	WCG	U	Depth to bottom of screen interval	17	-0.348	0.171
rednlusag2	WCG	U	Chloride (water)	24	0.330	0.115
rednlusag2	WCG	U	Depth to top of screen interval	17	-0.317	0.216
rednlusag2	WCG	U	Calcium (NURE)	25	-0.308	0.134
rednlusag2	WCG	U	Deuterium (water)	9	-0.285	0.458
rednlusag2	WCG	U	^{18}Oxygen (water)	9	-0.285	0.458
rednlusag2	WCG	U	Depth to water table	25	-0.272	0.189
rednlusag2	WCG	U	Ortho phosphate (water)	25	-0.269	0.193
rednlusag2	WCG	U	Molybdenum (NURE)	25	0.254	0.220
rednlusag2	WCG	U	Potassium (NURE)	25	0.254	0.220
rednsus1	WCG	U	Magnesium (water)	11	0.890	0.000
rednsus1	WCG	U	Total dissolved solids (water)	11	0.793	0.004
rednsus1	WCG	U	Specific conductance, field (water)	10	0.736	0.015
rednsus1	WCG	U	Acid neutralizing capacity (water)	11	0.724	0.012
rednsus1	WCG	U	^{40}Potassium (gamma-ray)	11	0.724	0.012
rednsus1	WCG	U	Arsenic (water)	5	-0.700	0.188
rednsus1	WCG	U	Dissolved oxygen (water)	11	0.676	0.022
rednsus1	WCG	U	Bicarbonate (water)	11	0.661	0.027
rednsus1	WCG	U	Sulfate (water)	11	0.648	0.031
rednsus1	WCG	U	Calcium (water)	11	0.600	0.051
rednsus1	WCG	U	Potassium (water)	11	0.533	0.091
rednsus1	WCG	U	^{232}Thorium (gamma-ray)	11	0.492	0.124
rednsus1	WCG	U	Iron (NURE)	11	-0.442	0.174
rednsus1	WCG	U	Iron (water)	10	-0.427	0.219
rednsus1	WCG	U	Silica (water)	11	-0.425	0.193
rednsus1	WCG	U	Selenium (NURE)	11	-0.401	0.222
rednsus1	WCG	U	Sodium (water)	11	0.392	0.233
rednsus1	WCG	U	Calcium (NURE)	11	0.351	0.290
rednsus1	WCG	U	Uranium (NURE)	11	0.287	0.392
rednsus1	WCG	U	Depth to water table	11	-0.279	0.406
rednsus1	WCG	U	Chloride (water)	11	0.269	0.424
rednsus3	WCG	U	Potassium (water)	26	0.794	<0.0001
rednsus3	WCG	U	Acid neutralizing capacity (water)	17	0.741	0.001
rednsus3	WCG	U	Sodium (water)	26	0.725	<0.0001
rednsus3	WCG	U	Specific conductance, field (water)	25	0.715	0.000
rednsus3	WCG	U	Magnesium (water)	26	0.701	0.000
rednsus3	WCG	U	Total dissolved solids (water)	25	0.701	0.000
rednsus3	WCG	U	Calcium (water)	26	0.694	0.000
rednsus3	WCG	U	Sulfate (water)	25	0.681	0.000
rednsus3	WCG	U	Fluoride (water)	25	0.665	0.000

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NAWQA well network (See appendix 1 for definition)	Aquifer group code	Radionuclide	Variable name	Number of samples	Spearman's coefficient (rho)	*P*-value
rednsus3	WCG	U	Dissolved organic carbon (water)	17	0.650	0.005
rednsus3	WCG	U	Lithium (NURE)	19	0.641	0.003
rednsus3	WCG	U	Bicarbonate (water)	26	0.544	0.004
rednsus3	WCG	U	Chloride (water)	25	0.464	0.019
rednsus3	WCG	U	Ortho phosphate (water)	26	-0.452	0.020
rednsus3	WCG	U	Ammonia + organic nitrogen (water)	15	0.429	0.111
rednsus3	WCG	U	Uranium (NURE)	19	0.415	0.077
rednsus3	WCG	U	Selenium (NURE)	19	0.366	0.124
rednsus3	WCG	U	Depth to water table	26	0.321	0.110
rednsus3	WCG	U	Phosphorus (water)	26	-0.313	0.119
rednsus3	WCG	U	Potassium (NURE)	19	0.281	0.243
rednsus3	WCG	U	Sodium (NURE)	19	-0.253	0.296
rednsus5	WCG	U	Sodium (NURE)	7	0.800	0.031
rednsus5	WCG	U	Fluoride (water)	13	-0.794	0.001
rednsus5	WCG	U	Iron (water)	13	-0.646	0.017
rednsus5	WCG	U	Dissolved organic carbon (water)	8	0.634	0.092
rednsus5	WCG	U	Selenium (NURE)	7	-0.600	0.154
rednsus5	WCG	U	Phosphorus (water)	8	-0.584	0.129
rednsus5	WCG	U	Lithium (NURE)	7	-0.564	0.187
rednsus5	WCG	U	Ammonia (water)	8	-0.503	0.204
rednsus5	WCG	U	Ortho phosphate (water)	8	-0.500	0.207
rednsus5	WCG	U	Potassium (water)	8	0.491	0.217
rednsus5	WCG	U	Zinc (water)	13	0.468	0.107
rednsus5	WCG	U	Copper (water)	13	0.455	0.118
rednsus5	WCG	U	Ammonia + organic nitrogen (water)	7	-0.411	0.359
rednsus5	WCG	U	Arsenic (water)	13	0.404	0.172
rednsus5	WCG	U	Depth to top of screen interval	13	-0.382	0.198
rednsus5	WCG	U	Depth to bottom of screen interval	13	-0.362	0.224
rednsus5	WCG	U	Well depth	13	-0.362	0.224
rednsus5	WCG	U	Molybdenum (water)	13	0.347	0.246
rednsus5	WCG	U	Potassium (NURE)	7	0.346	0.448
rednsus5	WCG	U	Uranium (NURE)	7	0.346	0.448
rednsus5	WCG	U	Manganese (water)	13	0.296	0.326
rednsus5	WCG	U	Molybdenum (NURE)	7	0.295	0.521
rednsus5	WCG	U	^{40}Potassium (gamma-ray)	13	0.294	0.329
rednsus5	WCG	U	precip90	13	0.275	0.363
rednsus5	WCG	U	Calcium (water)	13	0.269	0.374
rednsus5	WCG	U	Nickel (water)	13	0.262	0.387
rednsus5	WCG	U	Nitrite (water)	8	0.260	0.534
umislusrc1	WCG	U	Nitrite (water)	30	0.516	0.003
umislusrc1	WCG	U	Aluminum (water)	30	-0.448	0.013

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NAWQA well network (See appendix 1 for definition)	Aquifer group code	Radionuclide	Variable name	Number of samples	Spearman's coefficient (rho)	*P*-value
umislusrc1	WCG	U	Potassium (water)	30	0.434	0.017
umislusrc1	WCG	U	Cobalt (water)	30	0.409	0.025
umislusrc1	WCG	U	Antimony (water)	30	0.376	0.041
umislusrc1	WCG	U	Manganese (water)	30	0.369	0.045
umislusrc1	WCG	U	Sodium (water)	30	0.348	0.059
umislusrc1	WCG	U	Specific conductance, field (water)	30	0.345	0.062
umislusrc1	WCG	U	Phosphorus (water)	30	-0.327	0.078
umislusrc1	WCG	U	Dissolved oxygen (water)	30	-0.317	0.088
umislusrc1	WCG	U	Sulfate (water)	30	0.315	0.090
umislusrc1	WCG	U	Magnesium (water)	30	0.313	0.093
umislusrc1	WCG	U	Total dissolved solids (water)	30	0.305	0.101
umislusrc1	WCG	U	Chloride (water)	30	0.303	0.103
umislusrc1	WCG	U	Nickel (water)	30	0.295	0.114
umislusrc1	WCG	U	Turbidity (water)	30	-0.292	0.118
umislusrc1	WCG	U	Depth to water table	30	0.286	0.125
umislusrc1	WCG	U	Barium (water)	30	0.270	0.149
umislusrc1	WCG	U	Calcium (water)	30	0.263	0.160
umislusrc1	WCG	U	Tritium (water)	30	0.261	0.164
umislusrc1	WCG	U	Bicarbonate (water)	30	0.252	0.179
connsus1	NEC	U	Calcium (NURE)	7	-0.709	0.074
connsus1	NEC	U	^{222}Radon (water)	30	0.621	0.000
connsus1	NEC	U	Selenium (NURE)	6	0.522	0.288
connsus1	NEC	U	Iron (water)	30	-0.491	0.006
connsus1	NEC	U	^{40}Potassium (gamma-ray)	30	0.378	0.039
connsus1	NEC	U	^{232}Thorium (gamma-ray)	29	0.370	0.048
connsus1	NEC	U	Calcium (water)	30	0.364	0.048
connsus1	NEC	U	Specific conductance, field (water)	30	0.361	0.050
connsus1	NEC	U	Depth to top of screen interval	30	-0.349	0.058
connsus1	NEC	U	Total dissolved solids (water)	30	0.342	0.064
connsus1	NEC	U	Phosphorus (water)	30	-0.257	0.171
linjsus1	NEC	U	Acid neutralizing capacity (water)	28	0.701	0.000
linjsus1	NEC	U	Calcium (NURE)	16	0.609	0.012
linjsus1	NEC	U	Molybdenum (water)	29	0.601	0.001
linjsus1	NEC	U	Calcium (water)	29	0.565	0.001
linjsus1	NEC	U	Field pH (water)	29	0.561	0.002
linjsus1	NEC	U	^{222}Radon (water)	26	0.535	0.005
linjsus1	NEC	U	Boron (water)	29	0.505	–
linjsus1	NEC	U	Specific conductance, field (water)	29	0.472	0.010
linjsus1	NEC	U	Total dissolved solids (water)	29	0.446	0.015
linjsus1	NEC	U	Dissolved oxygen (water)	27	-0.436	0.023
linjsus1	NEC	U	Iron (water)	29	-0.398	0.032

Appendix 5. Significant rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and other ancillary data with uranium concentrations in selected NAWQA well networks in the Columbia Plateau glacial, West-Central glacial, and New York and New England crystalline aquifer groups, in the northern United States, 1993–2003.—Continued

NAWQA well network (See appendix 1 for definition)	Aquifer group code	Radionuclide	Variable name	Number of samples	Spearman's coefficient (rho)	*P*-value
linjsus1	NEC	U	Potassium (NURE)	29	-0.390	0.037
linjsus1	NEC	U	Fluoride (water)	29	0.378	0.043
linjsus1	NEC	U	Phosphorus (water)	29	0.357	0.057
linjsus1	NEC	U	Barium (water)	29	-0.349	0.064
linjsus1	NEC	U	Magnesium (water)	29	0.346	0.066
linjsus1	NEC	U	Manganese (water)	29	-0.337	0.074
linjsus1	NEC	U	Nickel (water)	29	-0.303	0.110
linjsus1	NEC	U	Depth to top of screen interval	29	0.295	0.120
linjsus1	NEC	U	^{40}Potassium (gamma-ray)	29	-0.269	0.158
necbsus1	NEC	U	Gross alpha particle activity (water)	27	0.520	0.005
necbsus1	NEC	U	Calcium (NURE)	19	0.441	0.059
necbsus1	NEC	U	Depth to water table	28	-0.437	0.020
necbsus1	NEC	U	Strontium (water)	28	0.408	0.031
necbsus1	NEC	U	Selenium (NURE)	15	-0.382	0.160
necbsus1	NEC	U	Deutritium (water)	28	-0.364	0.057
necbsus1	NEC	U	Antimony (water)	27	0.350	0.073
necbsus1	NEC	U	Molybdenum (NURE)	28	0.350	0.068
necbsus1	NEC	U	^{18}Oxygen (water)	28	-0.325	0.092
necbsus1	NEC	U	^{222}Radon (water)	26	0.308	0.126
necbsus1	NEC	U	Sodium (water)	28	0.252	0.195
necbsus2	NEC	U	Gross alpha particle activity (water)	28	0.875	<0.0001
necbsus2	NEC	U	^{222}Radon (water)	28	0.620	0.000
necbsus2	NEC	U	Boron (water)	18	-0.528	–
necbsus2	NEC	U	Gross beta particle activity (water)	29	0.525	0.003
necbsus2	NEC	U	Arsenic (water)	29	0.465	0.011
necbsus2	NEC	U	Dissolved oxygen (water)	30	0.414	0.023
necbsus2	NEC	U	Uranium (NURE)	30	0.397	0.030
necbsus2	NEC	U	Manganese (water)	30	-0.376	0.041
necbsus2	NEC	U	Iron (water)	30	-0.347	0.060
necbsus2	NEC	U	Lead (water)	30	0.330	0.075
necbsus2	NEC	U	Barium (water)	30	-0.304	0.102
necbsus2	NEC	U	^{226}Radium (water)	29	0.295	0.120
necbsus2	NEC	U	Copper (water)	30	0.284	0.128
necbsus2	NEC	U	Lithium (water)	30	0.279	0.136
necbsus2	NEC	U	^{224}Radium (water)	27	-0.268	0.177

Reference

Phillips, J.D., Duval, J.S., and Ambroziak, R.A., 1993, National Geophysical Data Grids: Gamma-Ray, Gravity, Magnetic, and Topographic Data for the Conterminous United States: U.S. Geological Survey Digital Data Series DDS-9, accessed online May 2005 at *ftp://ftpext.usgs.gov/pub/cr/co/denver/musette/pub/GEOPHYSICAL_DATA/cdrom_DDS-9/*

Appendix 6. Significant rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and other ancillary data with ^{222}radon concentrations in the NAWQA well networks in the New York and New England crystalline aquifer group, in the northern United States, 1993–2003.

For each well network, the order of the correlation variable is listed by the highest correlation (either negative or positive) value to the lowest correlation value. Spearman's coefficients (rho) are significant when the *P*-values are less than or equal to 0.05; a negative rho value indicates an inverse relation. The following variables consist of geochemical data for the United States based primarily on streambed sediments and analyzed for using a consistent set of methods as part of the USGS National Geochemical Survey (U.S. Geological Survey Open-File Report 2004–1001). Most of the original samples were collected as part of the U.S. Geological Survey's National Uranium Resource Evaluation (NURE) Program from 1975 to 1983 and re-analyzed (data were accessed online May 2005, at *http://tin.er.usgs.gov/geochem/doc/home.htm*).

The variables are expressed in parts per million, unless stated otherwise:

Calcium (NURE)	in percent weight
Molybdenum (NURE)	
Selenium (NURE)	
Sodium (NURE)	in percent weight
Lithium (NURE)	
Lead (NURE)	
Potassium (NURE)	
Iron (NURE)	
Uranium (NURE)	
<	less than
^{222}Rn	radon
deg. C	degrees Celsius
precip90	mean annual precipitation, for 1961 through 1990 (Source of data is at Oregon State University in Corvallis, OR, accessed online December 2006, at *http://www.ocs.oregonstate.edu/prism/index.phtml*)
^{18}Oxygen	a stable isotope, reported as the ratio per mill (‰, or per thousand) of $^{18}O/^{16}O$ ($\delta^{18}O$)
Deuterium	a stable isotope, reported as the ratio per mill (‰, or per thousand) of $^{2}H/^{1}H$ (δD)
^{40}Potassium	aerial gamma-ray survey across the conterminous United States that measured the gamma-ray flux produced by the radioactive decay of the naturally-occurring element ^{40}Potassium in the top few centimeters of rock and soil, expressed in units of percent potassium (Phillips and others, 1993)
^{232}Thorium	aerial gamma-ray survey across the conterminous United States that measure the gamma-ray flux produced by the radioactive decay of the naturally-occurring element ^{232}Thorium in the top few centimeters of rock and soil, expressed as parts per million equivalent thorium (eTh) (Phillips and others, 1993).

Appendix 6. Significant rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and other ancillary data with ^{222}radon concentrations in the NAWQA well networks in the New York and New England crystalline aquifer group, in the northern United States, 1993–2003.—Continued

NAWQA well network (See appendix 1 for definition)	Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
connsus1	^{222}Rn	Selenium (NURE)	6	0.943	0.005
connsus1	^{222}Rn	Uranium (water)	30	0.621	0.000
connsus1	^{222}Rn	Lithium (NURE)	30	-0.293	0.116
connsus1	^{222}Rn	Bromide (water)	30	-0.271	0.148
connsus1	^{222}Rn	Depth to top of open interval	30	-0.262	0.162
connsus1	^{222}Rn	Sulfate (water)	30	-0.256	0.173
linjsus1	^{222}Rn	Calcium (NURE)	13	0.674	0.012
linjsus1	^{222}Rn	Uranium (water)	26	0.535	0.005
linjsus1	^{222}Rn	Barium (water)	26	-0.518	0.007
linjsus1	^{222}Rn	Depth to top of open interval	26	0.461	0.018
linjsus1	^{222}Rn	Lead (NURE)	26	-0.460	0.018
linjsus1	^{222}Rn	Field pH (water)	26	0.452	0.021
linjsus1	^{222}Rn	Silica (water)	26	-0.426	0.030
linjsus1	^{222}Rn	Fluoride (water)	26	0.389	0.049
linjsus1	^{222}Rn	Phosphorus (water)	26	0.375	0.059
linjsus1	^{222}Rn	Molybdenum (water)	26	0.354	0.076
linjsus1	^{222}Rn	Potassium (water)	26	-0.353	0.077
linjsus1	^{222}Rn	Manganese (water)	26	-0.343	0.086
linjsus1	^{222}Rn	Uranium (NURE)	26	0.331	0.099
linjsus1	^{222}Rn	Sulfate (water)	26	-0.327	0.103
linjsus1	^{222}Rn	Dissolved oxygen (water)	24	-0.305	0.147
linjsus1	^{222}Rn	Sodium (NURE)	26	0.302	0.133
linjsus1	^{222}Rn	Iron (NURE)	26	0.300	0.137
linjsus1	^{222}Rn	Iron (water)	26	-0.289	0.153
linjsus1	^{222}Rn	Depth to water table	26	-0.282	0.162
necbsus1	^{222}Rn	Dissolved organic carbon (water)	22	-0.476	0.025
necbsus1	^{222}Rn	Water temperature, in deg. C	26	0.400	0.043
necbsus1	^{222}Rn	Gross alpha particle activity (water)	26	0.397	0.045
necbsus1	^{222}Rn	Sulfate (water)	26	-0.355	0.075
necbsus1	^{222}Rn	Iron (NURE)	26	-0.325	0.105
necbsus1	^{222}Rn	Uranium (water)	26	0.308	0.126
necbsus1	^{222}Rn	Lead (water)	26	0.301	0.135
necbsus1	^{222}Rn	Calcium (NURE)	17	0.290	0.260
necbsus1	^{222}Rn	Barium (water)	26	-0.272	0.179
necbsus1	^{222}Rn	Acid neutralizing capacity (water)	26	-0.268	0.185
necbsus1	^{222}Rn	Dissolved oxygen (water)	26	0.256	0.207
necbsus1	^{222}Rn	precip90	26	0.255	0.208
necbsus1	^{222}Rn	Uranium (NURE)	26	0.252	0.214
necbsus1	^{222}Rn	^{232}Thorium (gamma-ray)	25	0.251	0.227
necbsus1	^{222}Rn	Lead (NURE)	26	-0.251	0.217

Appendix 6. Significant rho and probability values from Spearman correlations of selected trace elements, major ions, and physical properties in ground water, National Uranium Resource Evaluation program streambed sediment, terrestrial gamma-ray emissions, and other ancillary data with ^{222}radon concentrations in the NAWQA well networks in the New York and New England crystalline aquifer group, in the northern United States, 1993–2003.—Continued

NAWQA well network (See appendix 1 for definition)	Radionuclide	Correlation variable	Number of samples	Spearman's coefficient (rho)	*P*-value
necbsus2	^{222}Rn	Uranium (water)	28	0.620	0.000
necbsus2	^{222}Rn	Gross alpha particle activity (water)	27	0.608	0.001
necbsus2	^{222}Rn	Acid neutralizing capacity (water)	28	-0.580	0.001
necbsus2	^{222}Rn	Gross beta particle activity (water)	28	0.576	0.001
necbsus2	^{222}Rn	Bicarbonate (water)	28	-0.570	0.002
necbsus2	^{222}Rn	Lead (water)	28	0.521	0.004
necbsus2	^{222}Rn	Dissolved oxygen (water)	28	0.503	0.006
necbsus2	^{222}Rn	Boron (water)	16	-0.487	–
necbsus2	^{222}Rn	Copper (water)	28	0.469	0.012
necbsus2	^{222}Rn	Strontium (water)	28	-0.442	0.019
necbsus2	^{222}Rn	Barium (water)	28	-0.405	0.032
necbsus2	^{222}Rn	Depth to bottom of open interval	28	-0.384	0.044
necbsus2	^{222}Rn	Well depth	28	-0.384	0.044
necbsus2	^{222}Rn	Field pH (water)	28	-0.383	0.044
necbsus2	^{222}Rn	Potassium (NURE)	27	0.360	0.065
necbsus2	^{222}Rn	Total dissolved solids (water)	28	-0.359	0.060
necbsus2	^{222}Rn	Specific conductance, field (water)	28	-0.349	0.068
necbsus2	^{222}Rn	Zinc (water)	28	0.347	0.071
necbsus2	^{222}Rn	^{226}Radium (water)	28	0.340	0.077
necbsus2	^{222}Rn	precip90	28	0.336	0.080
necbsus2	^{222}Rn	Depth to water table	28	0.322	0.095
necbsus2	^{222}Rn	Cobalt (water)	28	0.322	0.095
necbsus2	^{222}Rn	^{18}Oxygen (water)	28	0.319	0.098
necbsus2	^{222}Rn	^{40}Potassium (gamma-ray)	28	0.308	0.111
necbsus2	^{222}Rn	Beryllium (water)	28	0.307	0.112
necbsus2	^{222}Rn	Antimony (water)	28	-0.298	0.124
necbsus2	^{222}Rn	Aluminum (water)	28	0.292	0.132
necbsus2	^{222}Rn	Time of recharge (age date)	26	0.288	0.153
necbsus2	^{222}Rn	Thallium (water)	11	-0.272	0.419
necbsus2	^{222}Rn	Iron (NURE)	28	-0.256	0.188
necbsus2	^{222}Rn	Deuterium (water)	28	0.255	0.191
necbsus2	^{222}Rn	Ortho-phosphate (water)	28	0.252	0.195

Reference

Phillips, J.D., Duval, J.S., and Ambroziak, R.A., 1993, National Geophysical Data Grids: Gamma-ray, gravity, magnetic, and topographic data for the conterminous United States: U.S. Geological Survey Digital Data Series DDS-9, accessed online May 2005, at *ftp://ftpext.usgs.gov/pub/cr/co/denver/musette/pub/GEOPHYSICAL_DATA/cdrom_DDS-9/*

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For more information concerning the research in this report, contact:
Keith W. Robinson, Director
U.S. Geological Survey
New Hampshire-Vermont Water Science Center
361 Commerce Way
Pembroke, NH 03275

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