Naturally-Occurring Radon-222, Total Uranium, Radium-226, and Radium-228 in Drinking Water Wells in Western and Central North Carolina, 2009-2010

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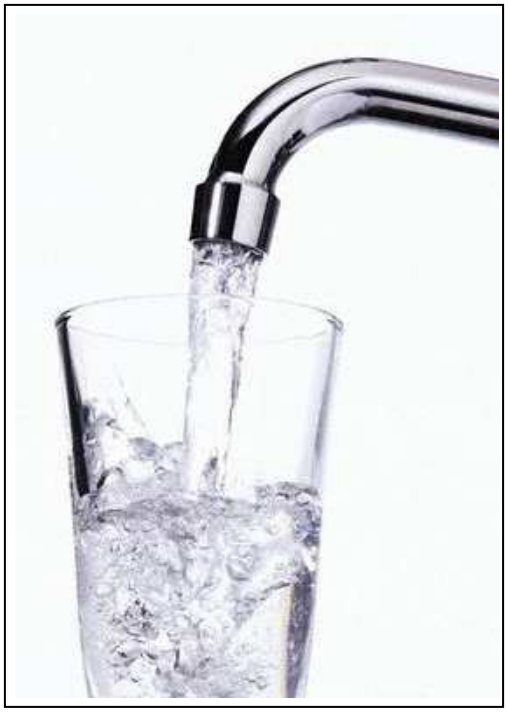

Groundwater Circular 2011-02

Prepared in cooperation with the U.S. Environmental Protection Agency and the N.C. Division of Environmental Health's Radiation Protection Section

North Carolina Department of Environment and Natural Resources
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Suggested Citation: Campbell, T.R., 2011, Naturally-Occurring Radon-222, Total Uranium, Radium-226, and Radium-228 in Drinking Water Wells in Western and Central North Carolina, 2009-2010: North Carolina Division of Water Quality Groundwater Circular 2011-02, 38 p. (available online at http://portal.ncdenr.org/web/wq/aps/gwp/groundwater-study-publications)

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Naturally-Occurring Radon-222, Total Uranium, Radium-226, and Radium-228 in Drinking Water Wells in Western and Central North Carolina, 2009-2010

ABSTRACT

Naturally occurring radon-222 was found at elevated levels (maximum = 21,390 picocuries per liter (pCi/L); median = 1010 pCi/L; n = 115) in groundwater samples collected from supply wells in an 18 county study area in Western and Central North Carolina. Radon is a known human carcinogen and is the second leading cause of lung cancer deaths after smoking. Radon exceeded EPA's proposed maximum contaminant level (MCL) of 300 pCi/L in 91 percent of wells, and exceeded the proposed alternate MCL of 4000 pCi/L in 14 percent of wells. Sampled counties included Yancey, Mitchell, Avery, Watauga, Ashe, Alleghany, Wilkes, Forsyth, Davidson, Catawba, Lincoln, Gaston, Rockingham, Buncombe, Transylvania, Macon, Haywood, and McDowell. The source of the dissolved radon is uranium-rich minerals contained in many rocks across the Piedmont and Mountains of North Carolina.

Dissolved radon concentrations tended to be higher in wells in meta-igneous intrusive rocks (which included metamorphosed granitic rocks, amphibolites, granitic rocks, foliated to massive granitic rocks, and biotite granitic gneisses) (median = 2950 pCi/L) than in meta-sedimentary rocks (median = 1030 pCi/L) and unconforming rocks (median = 600 pCi/L). These findings are consistent with previous studies in the N.C. Piedmont and Mountains (Campbell, 2008; 2006 a; 2006 b).

Thirty-seven wells were sampled for total uranium (U), radium-226 (Ra-226), and radium-228 (Ra-228). Of these, one well (at 30.9 micrograms per liter (ug/L)) exceeded the EPA Maximum Contaminant Level (MCL) of 30 ug/L for total uranium. Total uranium was detected in 41 percent of sampled wells. Three wells contained combined radium-226 and -228 (maximum = 21.5 pCi/L) at levels that exceeded the EPA MCL of 5 pCi/L; two of these were attributed to the common ion effect in wells with unusually high dissolved sodium and chloride. Radium-226 was detected in 49 percent of the sampled wells, and radium-228 was detected in 43 percent of the sampled wells.

Groundwater from the bedrock wells in the study area tended to be slightly acidic to neutral (median pH = 6.8), oxygenated (median dissolved oxygen (DO) = 5.2 milligrams per liter (mg/L)), and minimally conductive (median specific conductance (SC) = 115 microsiemens per centimeter (uS/cm)). Raw oxidation-reduction potential (ORP) values were moderate (median raw oxidation reduction potential (ORP) = 171 mV).

INTRODUCTION

Elevated levels of naturally occurring carcinogenic radionuclides – most notably uranium, radium, and radon-222 (radon) – are known to occur in the groundwater drinking supplies of the Piedmont and Mountains of North Carolina. This is due in large part to the uranium rich rocks that underlie these regions. This is a concern to public health officials because about half of the population relies on groundwater as its principal drinking supply.

To help understand and map the distribution of these contaminants, the North Carolina Division of Water Quality (NC DWQ) is conducting a series of grant-funded studies focused on naturally occurring radionuclides in groundwater. This study helps to fill some of the spatial gaps in existing datasets. The grants have been awarded by the EPA's State Indoor Radon Grant Program and carried out in consultation with the North Carolina Division of Environmental

Health's Radiation Protection Section. Results obtained from these investigations are being used to educate state and local officials, policy makers, and planners about the presence and distribution of naturally occurring radionuclides in groundwater drinking supplies. This work is part of the DWQ's mandate to help ensure that North Carolina's groundwater resources are safe for current and future generations.

Background

Radionuclides are naturally occurring elements that undergo radioactive decay[1]. This decay occurs when an unstable "parent" element releases energy and becomes a new "daughter" element with new properties. Energy released during this decay process occurs as ionizing particles (alpha or beta particles) or rays (gamma rays). The original source of radionuclides in the environment is primarily uranium-238 and thorium-232. Uranium-238 is the original source of radium-226, radon-222, and others, and thorium-232 is the original source of radium-228 and others.

Radionuclides are colorless, odorless, and tasteless. They are ubiquitous in rock, soil, and water. Their concentration and occurrence in ground water are controlled in large part by geochemical conditions and by the degree to which the local geology contains original sources of uranium or thorium. Every radioactive element has a unique half-life which is a measure of the amount of time required for half of the initial amount of the substance to decay. Half-lives vary widely, from over 4 billion years for uranium-238, to 1622 years for radium-226, to 5.8 years for radium-228, to 3.8 days for radon.

Observed concentrations of a parent element are not necessarily correlated with observed concentrations of its daughter elements. This is due to the fact that radioactive elements have different radiochemical properties (solubilities, decay rates, sorption rates, physical states (gas or solid), and geochemical reactivity) and tend to behave differently in the subsurface.

Adverse health effects are associated with long-term exposure of radionuclides, so the EPA has established drinking water standards for U (30 ug/L) and combined Ra-226 and -228 (5 pCi/L) (EPA, 2000). In 1991, the EPA proposed an MCL standard for radon in water of 300 pCi/L (EPA, 1991), and in 1999 proposed an alternate MCL of 4000 pCi/L for water suppliers that have established an indoor radon mitigation program (EPA, 1999 a). As of the date of this report, these proposed levels have not yet been enacted.

The primary health risk associated with drinking elevated levels of uranium over a number of years is potential kidney damage. The risk associated with drinking elevated levels of radium over a number of years is primarily bone, liver, and breast cancer. And the risk associated with exposure to elevated levels of radon over a number of years is lung cancer (inhalation) and, to a much lesser degree, stomach cancer (ingestion). Because radon is a gas, the primary exposure risk is from inhalation - radon-rich water can slightly increase levels of indoor air radon as it volatilizes during routine in-home water usage.

Increased cancer risks associated with radon in water are greater - in some cases by an order of magnitude or more - than a large number of Environmental Protection Agency (EPA) and State (15A NCAC 02L .0200) regulated contaminants at their respective maximum contaminant levels (MCLs), including benzene, trichloroethylene, tetrachloroethylene, ethylene

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[1] Radiation is a measure of the *rate* (or *activity*) of radioactive decay. Activity is expressed as the "curie", a measure of the number of disintegrations per unit time (one curie = 3.7 x 1010 atomic disintegrations per second). Activity in water is expressed in pCi/L, where one pCi/L is equivalent to 2.2 atomic disintegrations per minute per liter of water.

dibromide, vinyl chloride, combined radium, uranium, and others. Generally, the risks associated with radon in water are relatively small when compared to the risks associated with indoor air radon from soil and rock. These risks and their implications for N.C. well owners are discussed in a report published by the N.C. Radon in Water Advisory Committee (2010).

Occurrence of naturally occurring radionuclides in rocks and groundwater in N.C. is common. Eight counties in North Carolina – seven in Western North Carolina – are classified as EPA Zone 1 counties, with predicted average indoor air radon concentrations above the EPA recommended action level of 4 pCi/L (EPA Radon Map, accessed via internet, 8/19/05, http://www.ncradon.org/zone.htm). These include Watauga, Alleghany, Mitchell, Buncombe, Henderson, Transylvania, Cherokee, and Rockingham Counties (fig. 1). Elevated levels of radon are due to the presence of uranium rich minerals in granitic rocks prevalent across the region.

Previous Studies

Studies show that radon concentrations in ground water vary widely across North Carolina, from detection limits to over 45,600 pCi/L (Campbell, 2008; 2006 a; 2006 b; Aldrich and others, 1975; Sasser and Watson, 1978; Loomis and others, 1987; Loomis, 1987a; Horton, 1983; 1985). Radon concentrations in ground water in North Carolina have been among the highest observed in the U.S. (Hess and others, 1985; Horton, 1983; 1985; Aldrich and others, 1975; Mitsch and others, 1984; Strain and others, 1979). A 1993 study reported that of 400 private wells sampled across North Carolina, 67% had radon concentrations above 300 pCi/L, and 11% were above 4,000 pCi/L (University of North Carolina, 1993).

Loomis (1987b) found that regional variability in dissolved radon concentrations was mostly consistent with relative abundances of uranium-bearing rocks. An association between rock type and dissolved radon levels also has been observed by other researchers, with granites often containing high levels, up to 100,000 pCi/L (Asikainen and Kahlos, 1979; Brutsaert and others, 1981; Snihs, 1973) and sedimentary rocks often containing much lower levels, often less than 500 pCi/L (Andrews and Wood, 1972; King and others, 1982; and Mitsch and others, 1984). Hess and others (1985) noted that dissolved radon concentrations in surface water typically are very low due to volatilization of radon into the atmosphere, and communities that rely on surface water reservoirs for their drinking water supply typically have little cause for radon concern.

A 2005 study of 103 private wells in Buncombe, Henderson, and Transylvania Counties in Western North Carolina found a median radon of 6,060 pCi/L (maximum = 45,600 pCi/L) (Campbell, 2006 a). In this same study, total uranium exceeded the EPA MCL of 30 ug/L in just over 2 percent of wells (n = 102; maximum = 63 ug/L), and radium-226 was below 1.4 pCi/L in all wells (n = 102). A 2006 study of 80 private wells in Madison, Mitchell, Watauga, Jackson, Buncombe, Henderson, and Transylvania Counties found a median radon level of 1889 pCi/L (maximum = 15,750 pCi/L) (Campbell, 2006 b). This study also showed that all wells were below the MCL for total uranium (n = 78), and all wells were below 2.2 pCi/L for combined radium-226 and -228 (n = 78). And a 2007 study of 87 private wells in Alleghany, Caldwell, Burke, McDowell, Cleveland, Rutherford, Polk, Cherokee, Buncombe, Henderson, and Transylvania Counties found a median radon level of 1,560 pCi/L (maximum = 16,900 pCi/L) (Campbell, 2008). This study showed that 2 percent of wells exceeded the MCL for total uranium (n = 85), and combined radium-226 and -228 was below 3 pCi/L in all wells (n = 85).

Of just over 6000 North Carolina public supply wells sampled for selected radionuclides from 1980 to 2008, about 1 percent contained U above the MCL of 30 ug/L and about 4 percent contained combined radium above the MCL of 5 pCi/L (written communication, E. Chai, N.C. division of Environmental Health, March 27, 2008). Dissolved radon was not sampled. Of

about 6000 wells sampled as part of the National Uranium Resource Evaluation program (NC Hydrogeologic Atlas, Reid, 1993), only a tenth were above the MCL for U.

A large number of counties lack adequate data to evaluate spatial trends in naturally occurring radionuclides. Ongoing studies are helping to fill these data gaps.

Purpose and Scope

The purpose of this report is to document the occurrence and distribution of selected radionuclides in drinking water supply wells in Yancey, Mitchell, Avery, Watauga, Ashe, Alleghany, Wilkes, Macon, Transylvania, Haywood, McDowell, Rockingham, Cleveland, Gaston, Davidson, Lincoln, and Catawba Counties of North Carolina. The study is part of a multi-phased approach to help policy makers and the public to understand the quality of the groundwater supply and the extent to which radionuclides may pose a health risk to the citizens of North Carolina.

Data used to draw conclusions in this report were obtained from raw, untreated, unfiltered groundwater samples collected using a consistent method. Groundwater sample locations were designed to cover broad portions of the study area and geology of interest. No attempt was made to cover all areas or geologies within each county or to produce an unbiased, statistically representative dataset, and results and conclusions are presented accordingly.

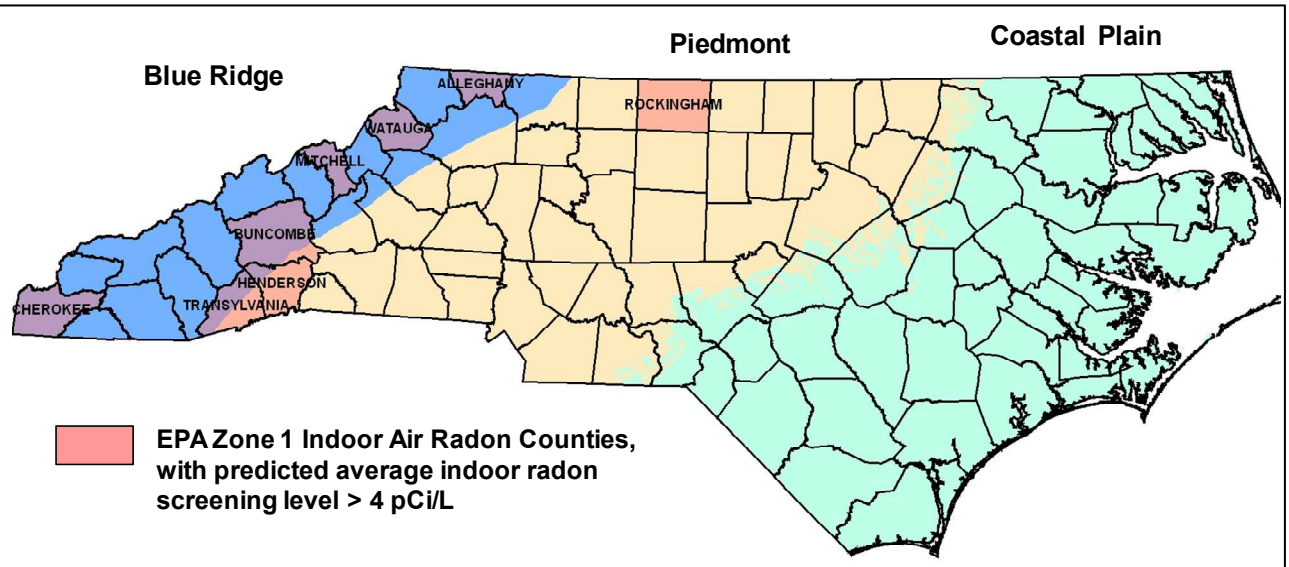

Fig. 1. EPA Zone 1 counties in North Carolina (shaded) with predicted average indoor radon levels of 4 pCi/L or higher, and North Carolina physiographic provinces.

Data Collection and Analytical Methods

A total of 115 ground-water samples were collected between January 2009 and April 2010, from bedrock supply wells (106 private wells and 9 community wells) in Western and Central North Carolina. A typical study area bedrock well was drilled through weathered rock (consisting of saprolite and partially weathered transition zone material), cased several feet into

competent bedrock, and was open hole to depth (fig. 2). Wells were sampled in 18 counties (fig. 3; appendices 1, 2, and 3).

Since each well was sampled on only one occasion, data collected in this study represent a “snap shot” of radionuclide concentrations at a point in time, and do not account for potential temporal variations due to long-term, seasonal, or pumping-related fluctuations. A single sample does not necessarily represent the overall quality of the groundwater resource over a long period of time at that location, but it does provide an indication of the quality of the local groundwater contributing water to the well for the time at which it was sampled.

Groundwater samples were analyzed for U (n = 37), Ra226 (n = 37), Ra228 (n = 37), radon-222 (n = 115), and field parameters including pH, DO, specific conductance, ORP, and temperature. Attempts were made to measure or obtain additional information, including well construction details (casing material, total depth, casing depth, and well yield), latitude and longitude, topographic setting, and surrounding rock type information. Quality control replicate samples were collected and analyzed for about 10 percent of the radon samples. Each well sample was identified by a sequential number between 776 and 890 (fig. 3).

Previous data suggests that a correlation between dissolved radon and indoor air radon at a given location is extremely weak or does not exist (Campbell, 2005 and 2008) due in large part to several factors that affect indoor air radon results. For example, indoor air radon results may be affected by the age and type of home construction, the degree of indoor ventilation and fresh (outdoor) air circulation, the season, timing, and amount of recent rainfall, and other factors. Because these factors were not consistent across homes in the study pool and confounding variables were unavoidable, the measurement of indoor air radon and its comparison to dissolved radon was not undertaken in this investigation.

Rock types generally were identified by statewide (1:500,000 scale, North Carolina Geological Survey, 1985) or local scale geologic maps. Rock types and lithologic characteristics can change over very small distances and with depth, and in some cases the geologic setting of a particular home or well had to be inferred. It is recognized that there were limitations in the use of the 1:500,000 scale geologic map to identify rock types at the local scale due to the complex, heterogeneous distribution of rocks in the region. Nevertheless, for purposes of this report, the designations used in this study were believed to be reasonable characterizations that allowed meaningful evaluations of geologic influence on radionuclide concentrations.

Sample-collection methods

A groundwater sample was collected as an unfiltered, raw water sample from a plumbing fixture as close to the wellhead as possible, usually at the wellhead itself. The sample was collected after the pump had been operating for at least 20 minutes. This helped to ensure that the sampled water was from the formation and not from a stagnant water column from within the well bore. Groundwater was placed in a 4-liter plastic container for the analysis of total uranium, Ra226, and Ra228. The sample date, time, and location were written on the sample container and on the chain of custody form. The sample was shipped to a certified contract laboratory in Oklahoma. Radon samples were collected using a special procedure designed to prevent aeration. Specifically, 60-milliliter glass radon vials were carefully submerged, filled, and sealed inside a 2-liter plastic beaker or similar container that had been filled with well water under laminar flow conditions. The radon samples were delivered or shipped to the laboratory by overnight mail in order to meet a self-imposed 48 hour holding time requirement.

Parameters such as DO, specific conductance, pH, ORP, and temperature, were measured in the field using a calibrated multimeter. A subset of samples - collected by county staff - did not include these field parameter measurements because a field meter was not

available. Information about well construction (depth, casing depth, yield, and others), when available, was noted and recorded in the field. Global Positioning System (GPS) receivers were used to identify the locations of the sampled wells, and the resulting data were entered into Geographic Information System (GIS) data files. In a small number of cases, GPS readings were unavailable, and coordinates were determined on the basis of physical address.

Laboratory analytical methods

Radon in water was analyzed using the E-Perm ion electret chamber de-emanation procedure (Kotrappa and Jester, 1993). In this method, radon in water off- gases inside a sealed oversized mason-type glass jar, and an electret ion chamber measures the voltage drop as the radon de-emanates. The voltage drop is then used in a calculation to determine the amount of radon in water. Quality control samples were analyzed for radon using a procedure based on Standard Method 7500-Rn (EPA, 1999b). In this method, radon is partitioned selectively into a mineral-oil scintillation cocktail immiscible with the water sample. The sample is dark-adapted, equilibrated, and then counted in a liquid scintillation counter using a region or window of the energy spectrum optimal for the specific alpha particles emitted from radon. Radium-226 was analyzed using a modification of method SM7500 Ra (EPA, 1995). The method uses alpha spectroscopy methodology. Radium-228 was analyzed using a modification of method EPA 904/9320 (EPA, 1986). Total uranium was analyzed using method KPA ASTM 5174M (ASTM, 1994). The sample was digested with nitric acid and peroxide and measured by the laser-based kinetic phosphorescence analyzer (KPA).

Acknowledgments

The author would like to thank Dr. Felix Fong and the staff at the North Carolina Radiation Protection Section for their support and assistance during this investigation. The author would also like to thank Mike Cash (Catawba County Environmental Health Department), Andy Blethen (Appalachian District Environmental Health Department), Allen Hughes (Toe River Health District), Steve Nixon (Wilkes County Health Department), Vincent Dodge (Davidson County Health Department), and Jonathon Harris (Lincoln County Health Department) and staff for their assistance in data collection. Special thanks also are offered to the well owners in Western and Central North Carolina who participated in this study. This investigation was made possible by a grant from the EPA and administered by the North Carolina Radiation Protection Section.

STUDY AREA SETTING

The study area comprises 18 counties within Western (Blue Ridge) and Central (Piedmont) North Carolina, including Yancey, Mitchell, Avery, Watauga, Ashe, Alleghany, Wilkes, Forsyth, Davidson, Catawba, Lincoln, Gaston, Rockingham, Buncombe, Transylvania, Macon, Haywood, and McDowell (fig. 3). The topography of the Blue Ridge province was formed by uplift, erosion, and rock resistance, and is characterized by steep, rugged, incised, mountainous terrain, intermontane basins, and valleys. The topography of the Piedmont was formed through the same earth processes and is characterized by gently rolling, rounded hills, long low ridges, and shallow valleys. Rock formation characteristics are similar in both provinces.

Precipitation in the study area generally ranges from about 45 to 60 inches per year. Groundwater is particularly important to this region, and about half of the residents rely on it as their principal drinking supply (U.S. Geological Survey, N.C. Water Use, 2005, website http://nc.water.usgs.gov/wateruse/data/Data_Tables_2000.html, accessed November 3, 2008). Yields from private wells typically range from about 1 to 50 gallons per minute (gpm), with averages of about 10 to 15 gpm (Daniel and Dahlen, 2002).

Bedrock geology in the study area is complex and consists of Paleozoic to Proterozoic aged inter-layered, folded, and faulted meta-igneous and meta-sedimentary rocks. These rocks outcrop throughout the region or, when not present at land surface, they occur beneath a variably thick layer (typically about 20 to 80 ft) of soil and weathered or partially weathered saprolite. The Brevard Fault Zone separates the Blue Ridge geologic belt to the west from the Inner Piedmont Belt to the east and trends to the northeast through the study area.

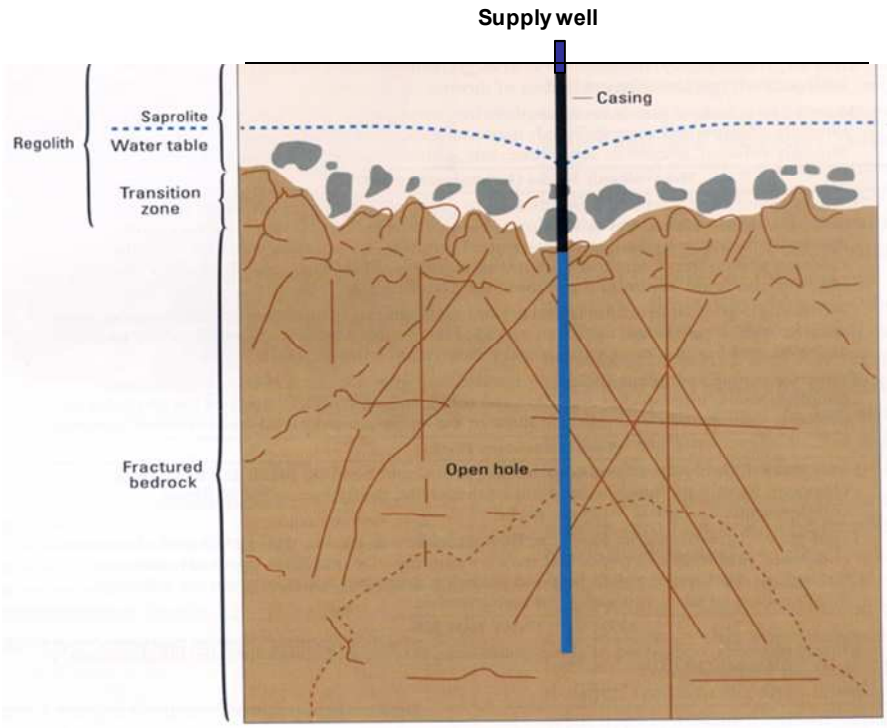

Fig. 2. Schematic showing construction of typical drinking water well in study area.

In the broadest sense, rocks in the study area can be grouped into meta-igneous intrusive rocks, meta-sedimentary rocks, and unconforming rocks (rocks that represent a break in the normal geologic age sequence and that share characteristics of both meta-igneous and meta-sedimentary rocks). Another class, meta-igneous extrusive (meta-volcanic) rocks, was uncommon in the sampled areas.

These broad rock classes may be further divided into individual formal and informal rock units. For example, meta-igneous intrusive rock formations in the study area (represented by 20 wells) included metamorphosed granitic rocks, amphibolites, granitic rocks, foliated to massive granitic rocks, and biotite granitic gneisses. Meta-sedimentary rock formations in the study area (represented by 80 wells) included migmatitic biotite hornblende gneiss, gneiss,

Blacksburg Formation, muscovite biotite gneiss, Battleground Formation, rocks of the Brevard Fault Zone, biotite gneiss and schist, biotite gneiss, and mica schist. Unconforming rock formations in the study area (represented by 15 wells) included biotite granite gneiss and granodiorite gneiss.

The numbers of wells sampled in each county are shown in the chart in figure 4. The rock type/formation of each well location was identified by on-site observation or by statewide (1:500,000 scale; North Carolina Geological Survey, 1985) or local scale geologic maps. The percentage of wells sampled in a given rock type was not intended to correspond to the percentage of area represented by that rock type within the study area.

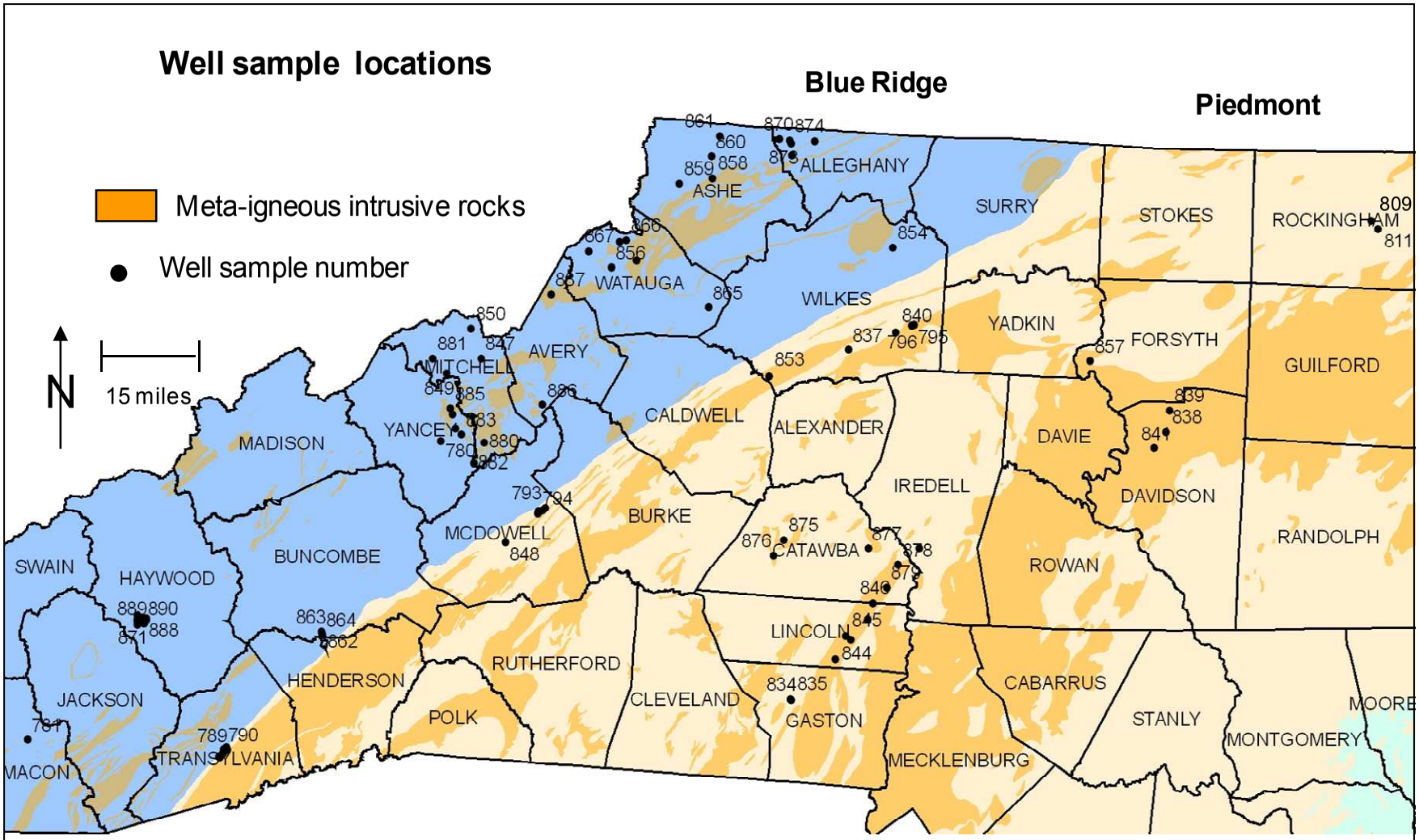

Fig. 3. Wells sampled during study, superimposed on map of meta-igneous intrusive rocks, Western and Central North Carolina, 2009-2010.

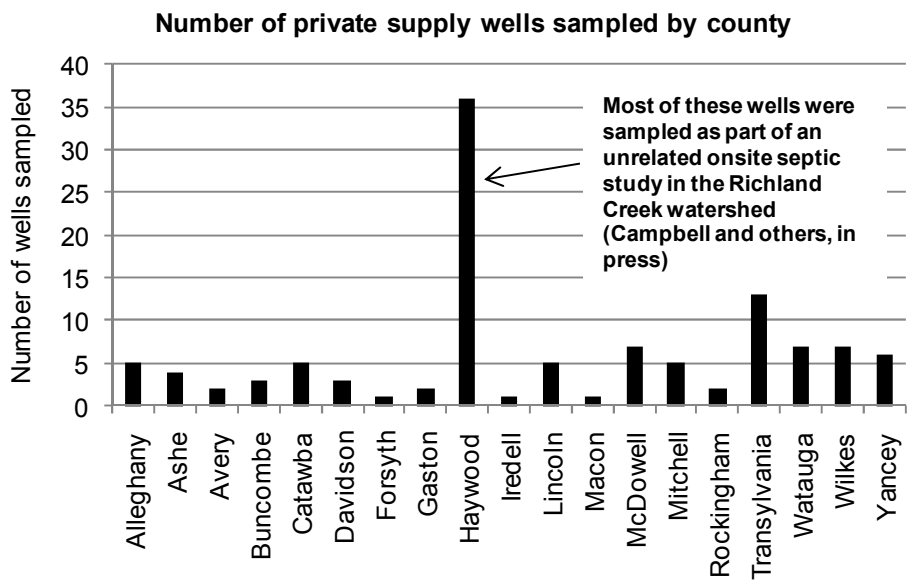

Fig. 4. Number of supply wells sampled, by county, 2009-2010.

Geochemical results obtained during the study are summarized in Table 1. The table also provides information on casing depth, a surrogate used in this study to estimate the regolith thickness, and well depth. Taken as a whole, sampled groundwater tended to be slightly acidic to neutral (median pH = 6.8), oxygenated (median DO = 5.2 mg/L), and minimally conductive (median SC = 115 uS/cm). Raw ORP values were moderate (median raw ORP = 171 mV)[2].

Because of moderately high DO levels, moderate ORP levels, and low dissolved iron and manganese, most groundwater in the study area generally was considered to be oxidizing. However, a more thorough analysis (including, for example, dissolved hydrogen and the speciation of iron, nitrogen, manganese, sulfur, and carbon) would be needed to determine definitively the oxidation-reduction state of the groundwater system. Further, it is recognized that conditions can change with time and location and are dependent upon many variables not measured in this study. It should be noted that in some cases otherwise *an*oxic groundwater (formation water) may become oxygenated inside the well bore due to water level fluctuations caused by intermittent pumping, chlorination, and (or) a “cascade effect” that can occur when water enters the bore hole from a fracture located above the water level in the well. Reducing or moderately reducing conditions were observed in 12 sample locations (well numbers 791, 792, 794, 800, 801, 805, 820, 832, 833, 834, 836, and 851), where DO values ranged from 0.3 to 1.1 mg/L, raw ORP values ranged from -32 to -248, and SC values ranged from 114 to 5440 uS/cm (generally well above the normal range for the study area as a whole).

[2] Five wells in the data set were associated with high levels of dissolved sodium chloride of unknown source (written communication, B. Laverty, N.C. Division of Water Quality, May 14, 2009), and SC values for these wells ranged from 784 to 5440 uS/cm.

Table 1. Descriptive statistics for field parameters and well characteristics measured in study wells, 2009-2010.

Parameter	No. of samples	Maximum value	Minimum value	Median value
pH	64	8.9	4.5	6.8
Specific conductivity, in uS/cm	68	5440*	31	115
Temperature, in degrees Celsius	67	17.2	8.6	14.3
Dissolved oxygen, in mg/L	66	10.3	0.2	5.2
Raw oxidation reduction potential, in mV	51	392	-248	171
Casing depth, in feet	16	152	21	74
Well depth, in feet	27	765	100	293
Well yield, in gpm	20	100	2	7

uS/cm, microSiemens per centimeter
mg/L, milligrams per liter
ug/L, micrograms per liter
gpm, gallons per minute
* associated with well having high sodium chloride concentrations of unknown source

OCCURRENCE AND DISTRIBUTION OF SELECTED RADIONUCLIDES IN DRINKING WATER WELLS

Samples of raw, untreated groundwater were collected at 115 bedrock wells in the study area comprising parts of Yancey, Mitchell, Avery, Watauga, Ashe, Alleghany, Wilkes, Forsyth, Davidson, Catawba, Lincoln, Gaston, Rockingham, Buncombe, Transylvania, Macon, Haywood, and McDowell counties, North Carolina (fig. 3). All of the wells were sampled for radon, and 37 of the wells were sampled for total uranium, Ra-226, and Ra-228.

ESRI geographic information system software was used to map selected values of radon, uranium, and radium isotopes and to evaluate geologic and other spatial influences on the observed data. The data were plotted on a geologic map of North Carolina (N.C. Geological Survey, 1985) and assessed for distributions and trends. Elevated radon was observed in many wells, and uranium and radium isotopes were elevated in a relatively small percentage of wells. Analytical results are provided in the following section and in tabular form in Appendices 1, 2 and 3. Table 2 shows summary statistics (maximum, minimum, and median), number of samples exceeding the EPA standards, and number of samples exceeding the laboratory's method detection limit for radon-222, U, Ra-226, and Ra-228.

Radon concentrations (n = 115) ranged from less than 50 to 21,390 pCi/L, with a median value of 1010 pCi/L (table 2). Of the 115 sampled wells, 91 percent exceeded the proposed EPA MCL of 300 pCi/L, and 14 percent exceeded the EPA proposed alternate MCL of 4000 pCi/L. Figure 5 shows study wells with radon concentrations above EPA proposed standards, superimposed on a map of meta-igneous intrusive rocks. These are rocks that have been commonly associated with elevated levels of dissolved radon in other areas (Campbell, 2008; 2006 a; 2006 b). Radon concentration

ranges, grouped by rock type/formation, are shown in figure 6. The most common concentration range was 1000 to 5000 pCi/L.

Wells drilled in meta-igneous intrusive rocks tended to have higher dissolved radon (n = 20, median = 2950 pCi/L) than wells drilled in meta-sedimentary rocks (n = 80, median = 1030 pCi/L) and unconforming rocks (n = 15, median = 600 pCi/L) (tables 3 and 4). Wells characterized by oxidizing conditions were higher in dissolved radon (median = 1120 pCi/L) than wells characterized by reducing conditions (median = 690 pCi/L).

Total uranium concentrations for the 37 sampled wells ranged from below the analytical detection limit of 1 ug/L to a maximum of 30.9 ug/L, with a median value of less than 1 ug/L (table 2). The EPA MCL for total uranium is 30 ug/L. Figure 7 shows study wells with total uranium above the EPA standard, superimposed on a map of meta-igneous intrusive rocks. Because of the limited number of wells containing elevated uranium, associations between dissolved uranium and rock type were unclear.

Radium-226 concentrations (n = 37) ranged from less than the analytical detection limit (about 0.5 pCi/L) to a maximum of 9.3 pCi/L, with a median value of less than 1 pCi/L (table 2). Radium-228 concentrations (n = 37) ranged from less than the analytical detection limit (about 0.5 pCi/L) to a maximum of 13.1 pCi/L, with a median value of less than 1 pCi/L. Combined radium (Ra226 and 228) ranged from less than the analytical detection limit of about 1 pCi/L to a maximum of 21.5 pCi/L (median = 1.1 pCi/L).

Three wells exceeded the EPA MCL of 5 pCi/L for combined radium (fig. 8). Of these, two were also high in sodium chloride concentrations of unknown origin (SC of 3620 and 5000 uS/cm). It is highly likely that the “common ion effect” was a major contributor to the elevated dissolved radium values at these wells. Where high concentrations of dissolved ions exist, the common ion effect can result in preferential sorption of the ions (sodium and chloride ions, in this case) and a concurrent release of previously sorbed radium ions into solution (Focazio, 2001; Szabo, 1986). Figure 8 shows study wells with combined radium above the EPA standard, superimposed on a map of meta-igneous intrusive rocks. Because of the limited number of wells containing elevated radium, associations between dissolved radium and rock type were unclear.

Table 2. Summary statistics, exceedence rates, laboratory detection limits, and detection limit exceedances for radon, uranium, Ra-226, and Ra-228, 2009-2010.

Radionuclide	No. of samples	Maximum value	Minimum value	Median value	USEPA Standard	% exceeding standard	Working detection limit	% exceeding detection limit
Radon, pCi/L	115	21390	50	1010	300[a]/4000[b]	91/14	50 pCi/L	100
Uranium, ug/L	37	30.9	<1	<1	30	3	1 ug/L	41
Radium-226, pCi/L	37	9.3[d]	<0.5	<1	5[c]	8	0.5 ug/L	49
Radium-228, pCi/L	36	13.1[e]	<0.5	<1	5[c]	8	0.5 ug/L	44

[a] proposed

[b] proposed alternate

[c] combined, Ra-228 + Ra-226

[d] associated with well that contains high salt content (SC = 3620 uS/cm), a geochemical condition that can contribute to elevated dissolved radium

[e] associated with well that contains high salt content (SC = 5000 uS/cm), a geochemical condition that can contribute to elevated dissolved radium

pCi/L, picocuries per liter

ug/L, micrograms per liter

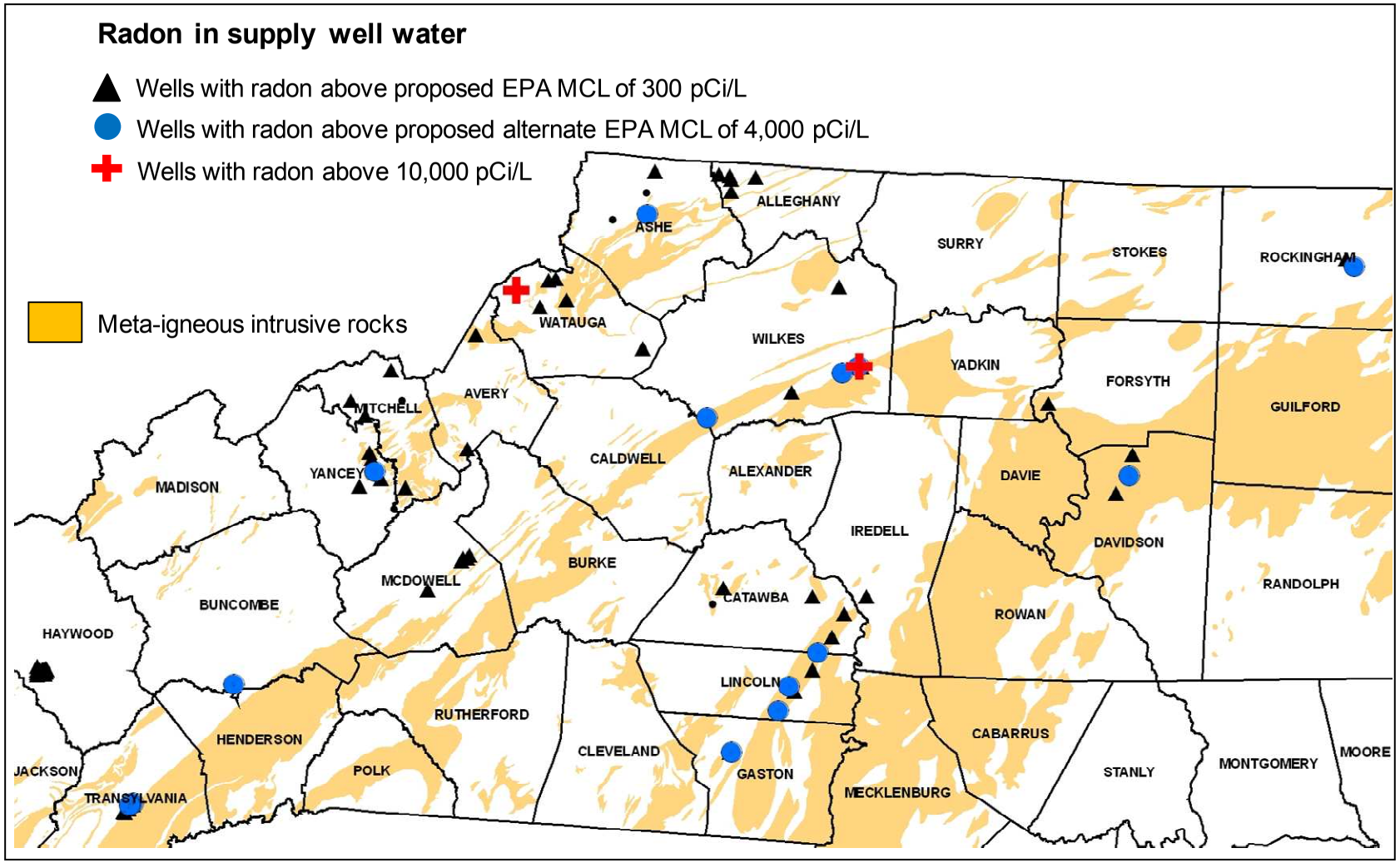

Fig. 5. Dissolved radon-222 concentrations in sampled supply wells, superimposed on map of meta-igneous intrusive rocks, 2009-2010.

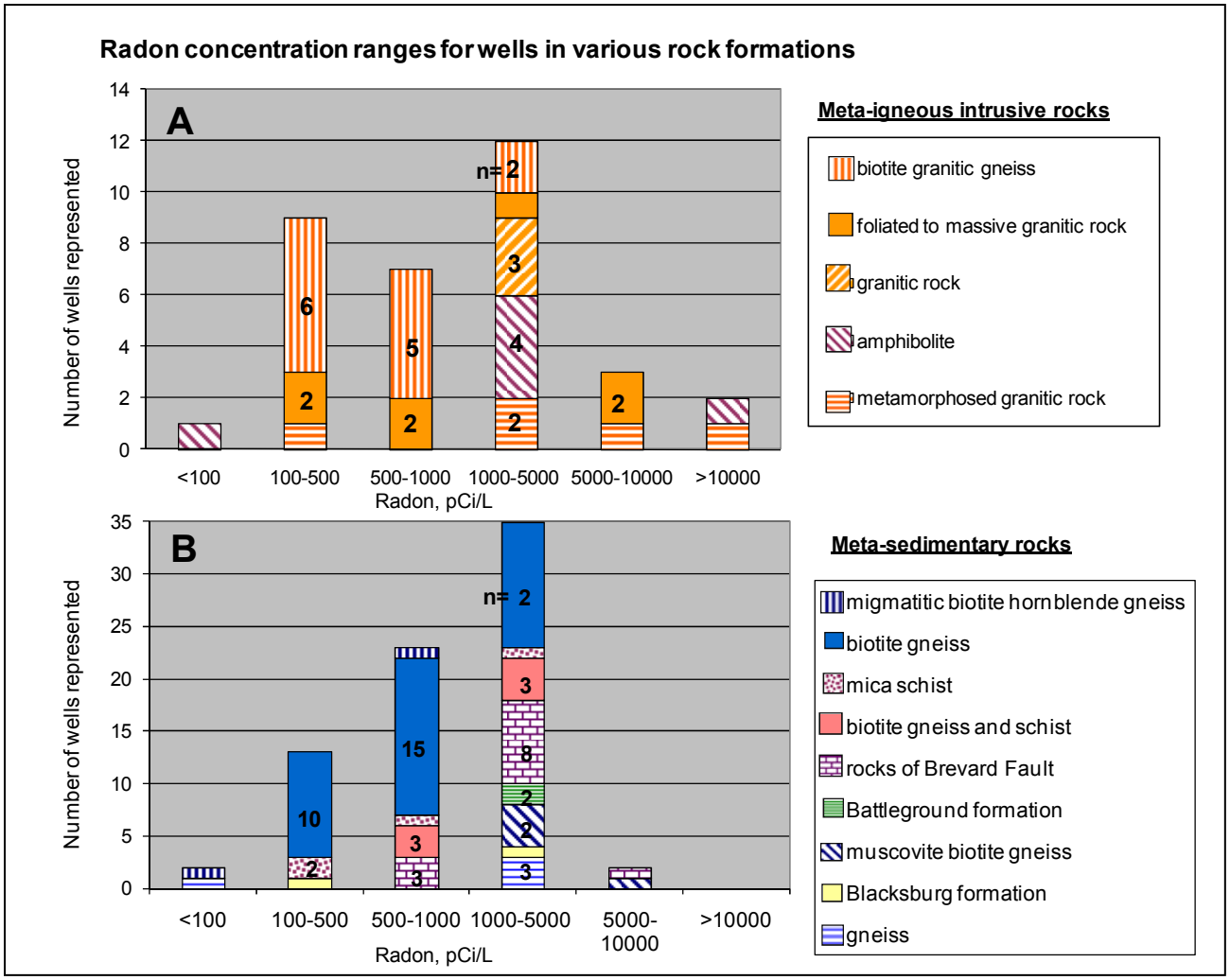

Fig. 6. Dissolved radon-222 concentration ranges for wells in (A) meta-igneous intrusive rock formations and (B) meta-sedimentary rock formations, 2009-2010.

Table 3. Summary statistics for radionuclides in wells grouped according to rock class (meta-igneous intrusive, meta-sedimentary, or unconforming rocks), 2009-2010.

	RADON, pCi/L			URANIUM, ug/L			RADIUM-226, pCi/L			RADIUM-228, pCi/L		
Rock class	n	median	max	n	median	max	n	median	max	n	median	max
Meta-igneous intrusive rocks	20	2,950	10,190	15	<1	5.6	15	<1	2.0	15	<1	5.2
Meta-sedimentary rocks	80	1,030	7,900	15	<1	16.6	15	<1	9.3*	14	<1	13.1*
Unconforming rocks	15	600	21,390	7	1.4	30.9	7	<1	<1	7	<1	2

pCi/L, picocuries per liter
ug/L, micrograms per liter
* associated with wells high in dissolved sodium chloride of unknown origin; radium de-sorbed from formation rocks in the presence of very high dissolved solids

Table 4. Summary statistics for dissolved radon-222 concentrations in wells grouped according to rock class (meta-igneous, meta-sedimentary, or unconforming rocks) and geochemical conditions observed in the well water (oxidizing or reducing), 2009-2010.

Rock class	n	Median radon	Maximum radon	Minimum radon
meta-igneous intrusive rocks	20	2,950	10,190	220
meta-sedimentary rocks	80	1,030	7,900	50
unconforming	15	600	21,390	140
Geochemical conditions*				
oxidizing	103	1,120	21,390	50
reducing	12	690	1,310	120

* Inferred based on values of dissolved oxygen, raw oxidation reduction potential, and specific conductance

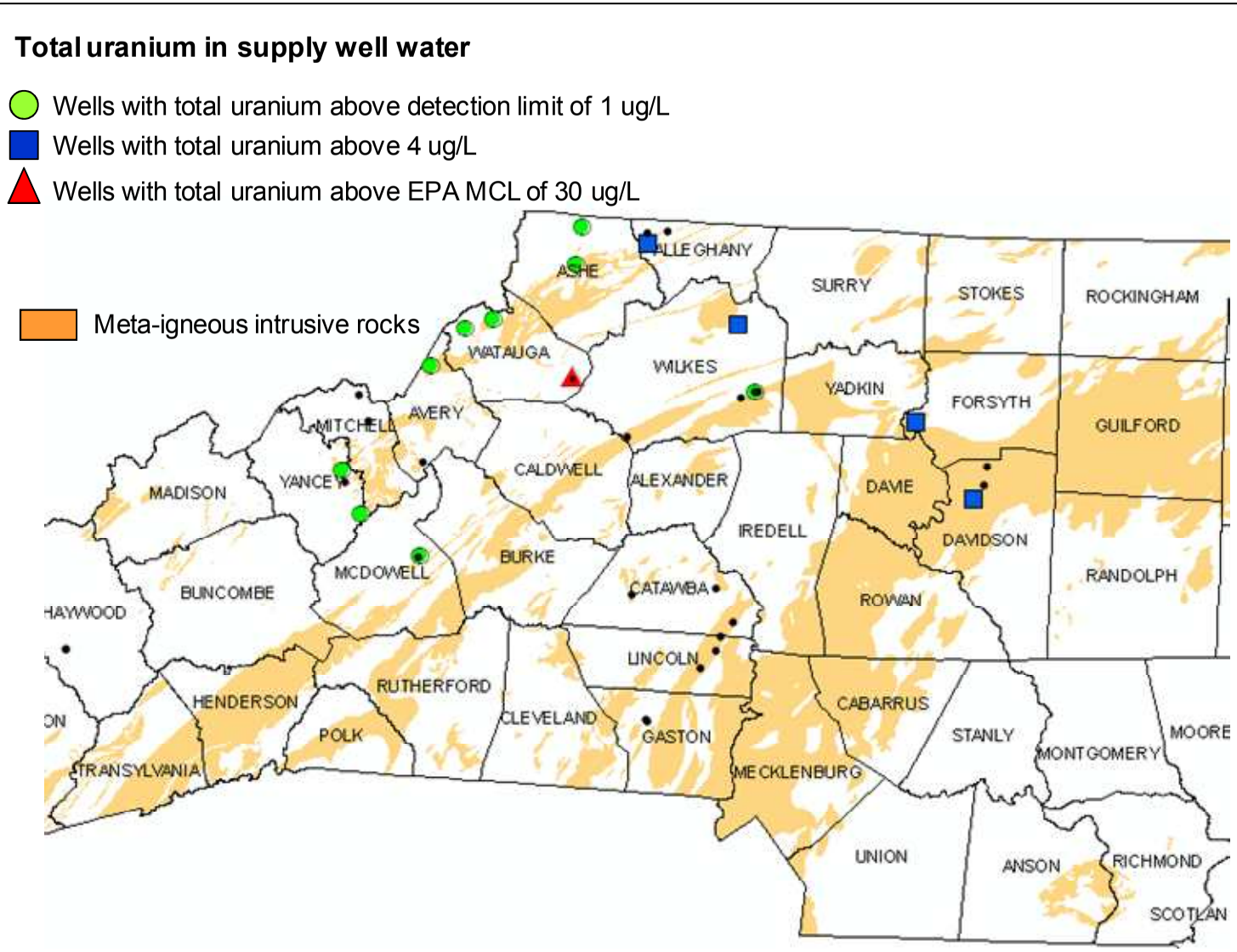

Fig. 7. Total uranium concentrations in sampled supply wells, superimposed on map of meta-igneous intrusive rocks, 2009-2010.

Combined Radium-226 and Radium-228 in supply well water

Wells with combined radium-226 and -228 above detection limit of 1 pCi/L

Wells with combined radium-226 and -228 above EPA MCL of 5 pCi/L

Meta-igneous intrusive rocks

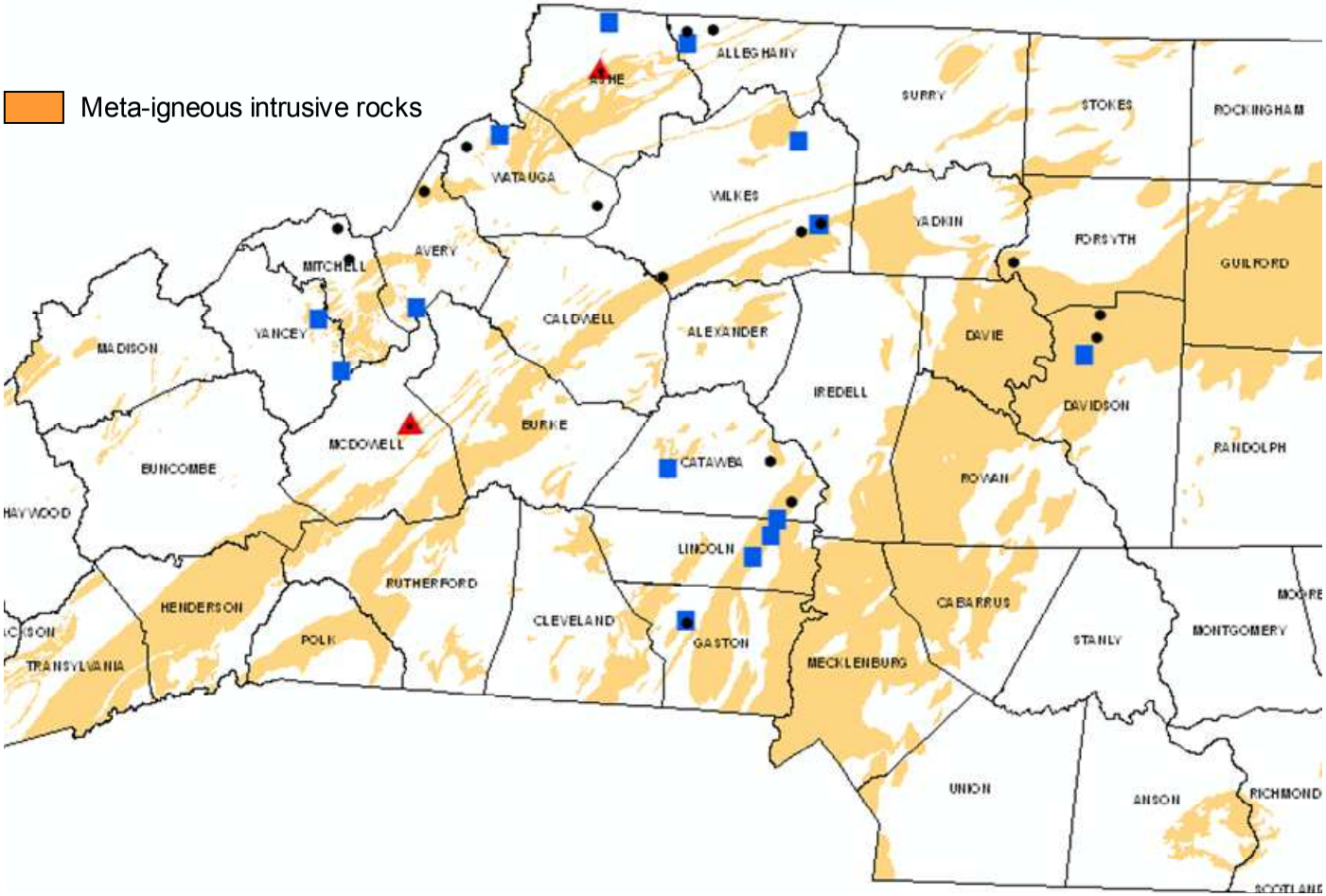

Fig. 8. Combined radium-226 and -228 concentrations in sampled supply wells, superimposed on map of meta-igneous intrusive rocks, 2009-2010.

SUMMARY

Elevated levels of naturally occurring radionuclides are known to occur in groundwater and indoor air (radon) in the Blue Ridge and Piedmont Provinces of Western North Carolina. This occurrence is due to the presence of uranium rich rocks – including granites and granitic gneisses - across much of the region. Radionuclides are human carcinogens and have been linked to bone, kidney, and lung cancers, among others. About half of the citizens of Western North Carolina rely on public and private groundwater wells for their principal drinking water supply. Indoor air in parts of North Carolina is susceptible to elevated levels of radon, and eight counties are classified as EPA Zone 1 counties, with predicted indoor radon concentrations above the action level of 4 pCi/L (EPA Radon Map, accessed via internet, 8/19/05, http://www.ncradon.org/zone.htm).

A number of the 106 private and 9 community drinking water wells sampled within Yancey, Mitchell, Avery, Watauga, Ashe, Alleghany, Wilkes, Forsyth, Davidson, Catawba, Lincoln, Gaston, Rockingham, Buncombe, Transylvania, Macon, Haywood, and McDowell counties were found to contain elevated levels of radon (50 to 21,390 pCi/L; median = 1010 pCi/L). Radon exceeded EPA's proposed MCL of 300 pCi/L in 91 percent of the wells and exceeded the proposed alternate MCL of 4000 pCi/L in 14 percent of the wells.

Dissolved radon concentrations tended to be higher in wells in meta-igneous intrusive rocks (which included metamorphosed granitic rocks, amphibolites, granitic rocks, foliated to massive granitic rocks, and biotite granitic gneisses) (median = 2950 pCi/L) than in meta-sedimentary rocks (median = 1030 pCi/L) and unconforming rocks (median = 600 pCi/L). Wells characterized by oxidizing conditions were higher in dissolved radon (median = 1120 pCi/L) than wells characterized by reducing conditions (median = 690 pCi/L). These findings generally are consistent with previous studies in the North Carolina Piedmont and Mountains (Campbell, 2008; 2006 a; 2006 b).

Total uranium concentrations ranged from less than 1 to 30.9 ug/L (median = less than 1 ug/L) and exceeded the EPA MCL of 30 ug/L in one sampled well. Combined radium (radium-226 and -228) exceeded the EPA MCL of 5 pCi/L in 3 of the sampled wells, two of which were attributed to the common ion effect in wells that contained unusually high dissolved sodium and chloride. At least some concentration of radium-226 was detected in 49 percent of the sampled wells, and at least some concentration of radium-228 was detected in 43 percent of the sampled wells. Because of the limited number of wells containing elevated uranium and radium, associations between these radionuclides and rock type were unclear.

Subsequent radionuclide investigation will focus on areas of the state with data gaps. Subsequent investigation will also evaluate potential changes in dissolved radon concentrations over time, differences in radon levels between wells in close proximity, and differences in radon levels between community wells and private wells in similar geologies.

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APPENDIX 1. Raw data collected during study of 115 private drinking water wells in Yancey, Mitchell, Avery, Watauga, Ashe, Alleghany, Wilkes, Forsyth, Davidson, Catawba, Lincoln, Gaston, Rockingham, Buncombe, Transylvania, Macon, Haywood, and McDowell counties, North Carolina, 2009-2010. [ft = feet; blank = no data; pCi/L = picocuries per liter; ug/L = micrograms per liter; Temp = temperature; C = degrees Celsius; SC = specific conductance; DO = dissolved oxygen; ORP = oxidation reduction potential; BDL = below detection limit; gpm = gallons per minute; uS/cm = microsiemens per centimeter; mg/L = milligrams per liter; mV = millivolts.]

Appendix 1. Continued.

* Community Supply Well

well number	county	rock class	rock formation	province	hydro setting
776	Transylvania	metamorphic	rocks of Brevard Fault	Mountain	recharge
777	Transylvania	intrusive	Henderson gneiss	Mountain	midslope
778	Transylvania	metamorphic	rocks of Brevard Fault	Mountain	recharge
779	Transylvania	metamorphic	rocks of Brevard Fault	Mountain	midslope
780	Yancey	metamorphic	metagraywacke	Mountain	
781	Macon	metamorphic	biotite gneiss	Mountain	midslope
782	Transylvania	metamorphic	rocks of Brevard Fault	Mountain	midslope
783	Transylvania	metamorphic	rocks of Brevard Fault	Mountain	midslope
784	Transylvania	metamorphic	rocks of Brevard Fault	Mountain	midslope
785	Transylvania	metamorphic	rocks of Brevard Fault	Mountain	midslope
786	Transylvania	metamorphic	rocks of Brevard Fault	Mountain	midslope
787	Transylvania	metamorphic	rocks of Brevard Fault	Mountain	midslope
788	Transylvania	metamorphic	rocks of Brevard Fault	Mountain	discharge
789	Transylvania	metamorphic	rocks of Brevard Fault	Mountain	discharge
790	Transylvania	metamorphic	rocks of Brevard Fault	Mountain	midslope
791	McDowell	metamorphic	biotite gneiss and schist	Piedmont	midslope
792	McDowell	metamorphic	mica schist	Piedmont	midslope
793	McDowell	metamorphic	mica schist	Piedmont	midslope
794	McDowell	metamorphic	mica schist	Piedmont	midslope
795	Wilkes	intrusive	metamorphosed granitic rock	Piedmont	midslope
796	Wilkes	intrusive	metamorphosed granitic rock	Piedmont	midslope
797	Watauga	metamorphic	amphibolite	Mountain	
798	Watauga	metamorphic	amphibolite	Mountain	
799	Haywood	metamorphic	biotite gneiss	Mountain	recharge
800	Haywood	metamorphic	biotite gneiss	Mountain	discharge
801	Haywood	metamorphic	biotite gneiss	Mountain	midslope
802	Haywood	metamorphic	biotite gneiss	Mountain	midslope
803	Haywood	metamorphic	biotite gneiss	Mountain	midslope
804	Haywood	metamorphic	biotite gneiss	Mountain	midslope
805	Haywood	metamorphic	biotite gneiss	Mountain	midslope
806	Haywood	metamorphic	biotite gneiss	Mountain	midslope
807	Haywood	metamorphic	biotite gneiss	Mountain	midslope
808	Haywood	metamorphic	biotite gneiss	Mountain	midslope
809	Rockingham	metamorphic	biotite gneiss and schist	Piedmont	discharge
810	Wilkes	intrusive	metamorphosed granitic rock	Piedmont	midslope
811	Rockingham	metamorphic	felsic mica gneiss	Piedmont	midslope
812	Haywood	metamorphic	biotite gneiss	Mountain	midslope
813	Haywood	metamorphic	biotite gneiss	Mountain	midslope
814	Haywood	metamorphic	biotite gneiss	Mountain	recharge
815	Haywood	metamorphic	biotite gneiss	Mountain	midslope
816	Haywood	metamorphic	biotite gneiss	Mountain	midslope
817	Haywood	metamorphic	biotite gneiss	Mountain	midslope
818	Haywood	metamorphic	biotite gneiss	Mountain	midslope
819	Haywood	metamorphic	biotite gneiss	Mountain	recharge
820	Haywood	metamorphic	biotite gneiss	Mountain	recharge
821	Haywood	metamorphic	biotite gneiss	Mountain	discharge
822	Haywood	metamorphic	biotite gneiss	Mountain	
823	Haywood	metamorphic	biotite gneiss	Mountain	

Appendix 1. Continued.

* Community Supply Well

well number	county	rock class	rock formation	province	hydro setting
824	Haywood	metamorphic	biotite gneiss	Mountain	
825	Haywood	metamorphic	biotite gneiss	Mountain	
826	Haywood	metamorphic	biotite gneiss	Mountain	
827	Haywood	metamorphic	biotite gneiss	Mountain	
828	Haywood	metamorphic	biotite gneiss	Mountain	
829	Haywood	metamorphic	biotite gneiss	Mountain	
830	Haywood	metamorphic	biotite gneiss	Mountain	
831	Haywood	metamorphic	biotite gneiss	Mountain	
832	McDowell	metamorphic	biotite gneiss and schist	Piedmont	midslope
833	McDowell	metamorphic	mica schist	Piedmont	midslope
834	Gaston	metamorphic	Blacksburg formation	Piedmont	
835	Gaston	metamorphic	Blacksburg formation	Piedmont	
836	Iredell	metamorphic	Battleground formation	Piedmont	
837	Wilkes	metamorphic	biotite gneiss and schist	Piedmont	
838	Davidson	intrusive	granitic rock	Piedmont	
839	Davidson	intrusive	granitic rock	Piedmont	
840	Wilkes	intrusive	biotite gneiss and schist	Piedmont	
841	Davidson	intrusive	granitic rock	Piedmont	
842	Lincoln	intrusive	foliated to massive granitic rock	Piedmont	
843	Lincoln	intrusive	foliated to massive granitic rock	Piedmont	
844	Lincoln	intrusive	foliated to massive granitic rock	Piedmont	
845	Lincoln	intrusive	foliated to massive granitic rock	Piedmont	
* 846	Lincoln	intrusive	foliated to massive granitic rock	Piedmont	
847	Mitchell	metamorphic	Migmatitic biotite hornblende gneiss	Mountain	
848	McDowell	metamorphic	biotite gneiss and schist	Piedmont	discharge
849	Mitchell	metamorphic	Migmatitic biotite hornblende gneiss	Mountain	
850	Mitchell	unconformity	Biotite granitic gneiss	Mountain	
851	Haywood	metamorphic	biotite gneiss	Mountain	midslope
852	Haywood	metamorphic	biotite gneiss	Mountain	discharge
853	Wilkes	intrusive	migmatitic granitic gneiss	Piedmont	
854	Wilkes	metamorphic	gneiss	Piedmont	
* 855	Watauga	unconformity	biotite granitic gneiss	Mountain	
* 856	Watauga	unconformity	biotite granitic gneiss	Mountain	
857	Forsyth	metamorphic	biotite gneiss and schist	Piedmont	midslope
858	Ashe	intrusive	amphibolite	Mountain	
* 859	Ashe	unconformity	biotite granitic gneiss	Mountain	
860	Ashe	unconformity	biotite granitic gneiss	Mountain	
* 861	Ashe	unconformity	biotite granitic gneiss	Mountain	
862	Buncombe	metamorphic	muscovite biotite gneiss	Mountain	
863	Buncombe	metamorphic	muscovite biotite gneiss	Mountain	
864	Buncombe	metamorphic	muscovite biotite gneiss	Mountain	midslope
865	Watauga	unconformity	biotite granitic gneiss	Mountain	
* 866	Watauga	unconformity	biotite granitic gneiss	Mountain	
867	Watauga	unconformity	granodiorite gneiss	Mountain	
868	Alleghany	metamorphic	muscovite biotite gneiss	Mountain	
869	Yancey	metamorphic	gneiss	Mountain	
* 870	Alleghany	unconformity	biotite granitic gneiss	Mountain	
871	Haywood	metamorphic	biotite gneiss	Mountain	discharge

Appendix 1. Continued.

* Community Supply Well

well number	county	rock class	rock formation	province	hydro setting
* 872	Alleghany	metamorphic	muscovite biotite gneiss	Mountain	
873	Alleghany	unconformity	biotite granitic gneiss	Mountain	
* 874	Alleghany	unconformity	biotite granitic gneiss	Mountain	
875	Catawba	intrusive	amphibolite and biotite gneiss	Piedmont	
876	Catawba	intrusive	metamorphosed granitic rock	Piedmont	
877	Catawba	metamorphic	Battleground formation	Piedmont	
878	Catawba	intrusive	foliated to massive granitic rock	Piedmont	
879	Catawba	intrusive	foliated to massive granitic rock	Piedmont	
880	Mitchell	metamorphic	Amphibolite	Mountain	
881	Mitchell	unconformity	biotite granitic gneiss	Mountain	
882	Yancey	metamorphic	gneiss	Mountain	
883	Yancey	metamorphic	gneiss	Mountain	
884	Yancey	metamorphic	Amphibolite	Mountain	
885	Yancey	unconformity	quartz diorite to granodiorite	Mountain	
886	Avery	unconformity	Biotite granitic gneiss	Mountain	midslope
887	Avery	intrusive	metamorphosed granitic rock	Mountain	midslope
888	Haywood	metamorphic	biotite gneiss	Mountain	discharge
889	Haywood	metamorphic	biotite gneiss	Mountain	midslope
890	Haywood	metamorphic	biotite gneiss	Mountain	midslope

APPENDIX 2. Raw data collected during study of 115 private drinking water wells in Yancey, Mitchell, Avery, Watauga, Ashe, Alleghany, Wilkes, Forsyth, Davidson, Catawba, Lincoln, Gaston, Rockingham, Buncombe, Transylvania, Macon, Haywood, and McDowell counties, North Carolina, 2009-2010. [Ra = Radium; ft = feet; blank = no data; pCi/L = picocuries per liter; ug/L = micrograms per liter; Temp = temperature; C = degrees Celsius; SC = specific conductance; DO = dissolved oxygen; ORP = oxidation reduction potential; BDL = below detection limit; gpm = gallons per minute; uS/cm = microsiemens per centimeter; mg/L = milligrams per liter; mV = millivolts.]

Appendix 2. Continued.

* Community Supply Well

well number	geochemistry	radon	total uranium	Ra226	Ra228	combined Ra226 + Ra228	pH	SC
		pCi/L	ug/L	pCi/L	pCi/L	pCi/L		uS/cm
776	oxidizing	570					5.5	136
777	oxidizing	1450					5.4	75
778	oxidizing	1170					6.4	78
779	oxidizing	1840					5.8	31
780	oxidizing	2060						
781	oxidizing	300					7.2	220
782	oxidizing	4820					6.8	100
783	oxidizing	1780					7.2	120
784	oxidizing	2050					7.4	180
785	oxidizing	2190					7.1	61
786	oxidizing	860					4.5	106
787	oxidizing	1270					5	140
788	oxidizing	7900					5.9	39
789	oxidizing	2920					5.9	41
790	oxidizing	960						
791	reducing	670						784
792	reducing	770						1265
793	oxidizing	340						57
794	reducing	290						5440
795	oxidizing	3520	0.5	0.3	0.7	1.0	5.96	88
796	oxidizing	8430	0.5	0.7	0.6	1.4	5.2	160
797	oxidizing	1120					8.1	99
798	oxidizing	90					6.6	52
799	oxidizing	680					7.3	158
800	reducing	710					7.5	156
801	reducing	1210	0.5	0.8	2.9	3.7	6.9	182
802	oxidizing	1600					6.6	85
803	oxidizing	1010					6.3	126
804	oxidizing	530					7.1	162
805	reducing	890	0.5	0.3	0.8	1.1	7.8	194
806	oxidizing	350					6.9	108
807	oxidizing	920					6.9	94
808	oxidizing	480					7.2	145
809	oxidizing	3340					7.8	251
810	oxidizing	10190	3.4	0.9	2.8	3.7	6.6	222
811	oxidizing	4220					6	180
812	oxidizing	780					6.5	86
813	oxidizing	140					6.3	99
814	oxidizing	500					6.8	125
815	oxidizing	2150					6.7	115
816	oxidizing	450					6	120
817	oxidizing	560					5.7	56
818	oxidizing	330					6.8	118
819	oxidizing	530					7.3	121
820	reducing	120					8.9	114
821	oxidizing	1340					6.9	89
822	oxidizing	1880					7.9	171
823	oxidizing	540					7.9	137

Appendix 2. Continued.

* Community Supply Well

well number	geochemistry	radon	total uranium	Ra226	Ra228	combined Ra226 + Ra228	pH	SC
		pCi/L	ug/L	pCi/L	pCi/L	pCi/L		uS/cm
824	oxidizing	840					7.3	159
825	oxidizing	1410					6.5	74
826	oxidizing	1900					6.4	67
827	oxidizing	1140					5.1	156
828	oxidizing	940						34
829	oxidizing	1940					6.8	92
830	oxidizing	510					5.7	84
831	oxidizing	460					6.2	92
832	reducing	520	1.2	8.4	13.1	21.5	7.7	3620
833	reducing	1310	0.5	9.3	7.5	16.8	8.5	5000
834	reducing	460	0.5	0.9	0.3	1.3	7.6	166
835	oxidizing	4750	0.5	0.3	0.1	0.4	6.7	83
836	reducing	1040					7.4	177
837	oxidizing	610						
838	oxidizing	4400	0.5	0.6	0.2	0.8		
839	oxidizing	1420	0.5	0.3	0.4	0.6		
840	oxidizing	4210	0.5	0.4	0.4	0.8		
841	oxidizing	1050	5.6	0.3	0.8	1.1		
842	oxidizing	830	1.0	0.5	0.5	1.0		
843	oxidizing	480	0.5	0.5	1.5	2.0		
844	oxidizing	8800						
845	oxidizing	5590						
* 846	oxidizing	4180	0.5	1.9	0.6	2.5		
847	oxidizing	50	0.5	0.3	0.3	0.6		
848	oxidizing	1750					7.3	55
849	oxidizing	590						
850	oxidizing	440	0.5	0.4	0.2	0.6		
851	reducing	470					7.7	119
852	oxidizing	710					5.7	107
853	oxidizing	9270	0.5	0.2	0.2	0.4		
854	oxidizing	2750	5.2	1.0	0.2	1.2		
* 855	oxidizing	3320	3.5	0.4	0.7	1.1		
* 856	oxidizing	420						
857	oxidizing	3400	16.6	0.2	0.6	0.8	5.8	204
858	oxidizing	4860	2.0	2.0	5.2	7.2		
* 859	oxidizing	230						
860	oxidizing	140						
* 861	oxidizing	1040	1.4	0.9	1.8	2.7		
862	oxidizing	5890						
863	oxidizing	1960						
864	oxidizing	3550					6.2	95
865	oxidizing	740	30.9	0.4	0.5	0.8		
* 866	oxidizing	600						
867	oxidizing	21390	3.9	0.7	0.3	1.0		
868	oxidizing	1460	0.5	0.5	0.2	0.7		
869	oxidizing	4170	0.5	0.3				
* 870	oxidizing	720						
871	oxidizing	1600					6.8	61

Appendix 2. Continued.

* Community Supply Well

well number	geochemistry	radon	total uranium	Ra226	Ra228	combined Ra226 + Ra228	pH	SC
		pCi/L	ug/L	pCi/L	pCi/L	pCi/L		uS/cm
* 872	oxidizing	2430	7.1	1.7	0.5	2.2		
873	oxidizing	830	0.5	0.6	0.2	0.8		
* 874	oxidizing	740						
875	oxidizing	470						
876	oxidizing	220	0.5	0.6	1.0	1.6		
877	oxidizing	3160	0.5	0.6	0.2	0.8		
878	oxidizing	940						
879	oxidizing	470	0.5	0.1	0.2	0.3		
880	oxidizing	3830						
881	oxidizing	350					7.2	
882	oxidizing	60	1.2	1.3	0.2	1.5		
883	oxidizing	3410						
884	oxidizing	3240	1.3	0.9	0.4	1.3		
885	oxidizing	550						
886	oxidizing	470	0.5	0.4	2.0	2.4		
887	oxidizing	2370	2.5	0.3	0.4	0.7		
888	oxidizing	1170					5.9	81
889	oxidizing	990					6.3	58
890	oxidizing	840					6.8	68

APPENDIX 3. Raw data collected during study of 115 private drinking water wells in Yancey, Mitchell, Avery, Watauga, Ashe, Alleghany, Wilkes, Forsyth, Davidson, Catawba, Lincoln, Gaston, Rockingham, Buncombe, Transylvania, Macon, Haywood, and McDowell counties, North Carolina, 2009-2010. [Ra = Radium; ft = feet; blank = no data; pCi/L = picocuries per liter; ug/L = micrograms per liter; Temp = temperature; C = degrees Celsius; SC = specific conductance; DO = dissolved oxygen; ORP = oxidation reduction potential; BDL = below detection limit; gpm = gallons per minute; uS/cm = microsiemens per centimeter; mg/L = milligrams per liter; mV = millivolts.]

Appendix 3. Continued.

* Community Supply Well

well number	temp	DO	ORP	well depth	casing depth	well yield
	C	mg/L	mV	ft	ft	gpm
776	14.5	6.6				
777	13.7	7.5				
778	13.9	3.7				
779	14	8.3				
780						
781	14	2.2	-23	425	68	2.5
782	14.5	6.3	156			
783	15.6	4.6	147			
784	14.3	0.6	150			
785	15	6.1	156			
786	14.4	1.3	350			
787	12.8	1.2	320			
788	13.7	9.1	257			
789	11.8	7.5	225			
790						
791	15.7	0.3		505		
792	15.1	0.3		285		
793	15.4	5.1				
794	16.6	0.3		505		
795	15.2	6.7				
796	15.9	5.2				
797	10.9	2				
798	13.2	8.7				
799	13.9	0.5	92	150		60
800	14.2	0.9	-111			
801	14.8	0.8	-60			
802	15.8	7.5	93	113		
803	14.3	7.2	392	225	80	
804	15.2	3.3	-36	240		2.5
805	14.7	0.9	-108			
806	15.3	6.8	225			
807	14.5	7.4	208		98	100
808	14.8	5.2	169			
809	16.4	0.2				
810	16.8	5.5				
811	16.1	6.5				
812	14.2	7.2	229			
813	17.2	5.3	219	157		3
814	14.5	5.4	155			
815	14.3	6.7	171			
816	14.7	6.9	180	50?		20
817	12.4	10.3	223			
818	14.3	4.4	182	160		21
819	13.9	5.3	140	400		
820	14	1.1	-245			
821	15.3	4.2	249			8
822	13.7	0.6	186			
823	13.1	1.2	-45			

Appendix 3. Continued.

* Community Supply Well

well number	temp	DO	ORP	well depth	casing depth	well yield
	C	mg/L	mV	ft	ft	gpm
824	13.6	2.7	164			
825	13.2	6.3	226			
826	13.3	7.1	209			
827	12.3	0.5	264			
828						
829	12.6	0.6	191			
830	9.1	>5	278			
831	8.9	6.8	284			
832	17.2	0.8	-87	765	125	20
833	16	0.3	-147	600	110	15
834	16.6	0.9	-41	300	152	25
835	16.4	6.6	-11			
836	15.3	0.5	-32			
837						
838				100	80	
839						
840						
841				410	85	
842						
843						
844						
845						
* 846						
847				185	21	10
848	15.3	7	160			
849				104	34	4
850				240	105	4
851	12.7	0.5	-248			
852	13	4.5	181			
853						
854						
* 855						
* 856						
857	14.1					
858						
* 859						
860						
* 861						
862						
863						
864	8.6	4.9	308			
865						
* 866						
867						
868						
869						
* 870						
871	10.9	6.8	210			

Appendix 3. Continued.

* Community Supply Well

well number	temp	DO	ORP	well depth	casing depth	well yield
	C	mg/L	mV	ft	ft	gpm
* 872						
873						
* 874						
875						
876						
877						
878						
879						
880				225	35	6
881				365		6
882				605	32	2
883				465	40	2
884						
885						
886				340	45	30
887				500	23	3
888	14.1	7.1	204	125		
889	13.2	8.2	191			
890	13.5	6.6	166			