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Private well groundwater quality in West Virginia, USA–2010

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Abstract

The Centers for Disease Control and Prevention (CDC), in collaboration with the West Virginia Bureau of Public Health (BPH), initiated an investigation to characterize private well water quality in West Virginia. The objective was to better characterize private well water across various aquifer geologies by testing household drinking water samples and comparing them to EPA's National Primary Drinking Water Standards. The BPH selected ten counties representing three regions to capture geologically diverse areas that represent varying aquifer geology. We collected well-water samples from participating households and analyzed all water samples for 20 constituents currently monitored in public drinking-water systems. We calculated geometric means for each constituent and compared metal concentrations to EPA maximum and secondary contaminant levels by the geologic age of the rock surrounding the aquifer where the sample was obtained. All participating households (n = 139) provided a water sample. We detected arsenic at levels higher than the EPA maximum contaminant level in 10 (7.2%) samples. We detected elevated radon-222 in 48 (34.5%) samples. Geologic age of the region was indicative of whether arsenic and radon-222 were present at levels that exceeded current EPA drinking water standards. We found arsenic and radon concentrations were higher in Permian aquifers compared to those of other geologic ages. Homeowners with private wells in areas with Permian aged aquifers could benefit from targeted public health messaging about potentially harmful constituent concentrations in the well water. This may help ensure proper testing and maintenance of private wells and reduce exposure to these constituents.

GRAPHICAL ABSTRACT

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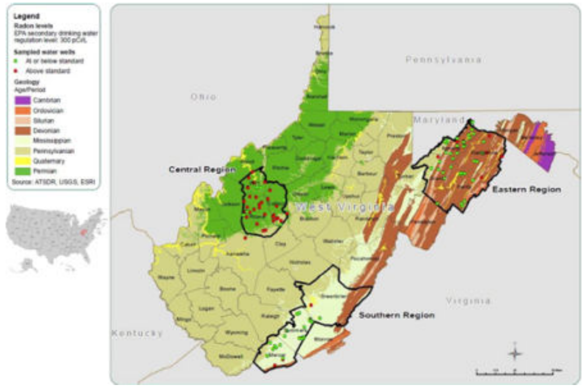
Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the Centers for Disease Control and Prevention or the Agency for Toxic Substances and Disease Registry.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.02.018.



Keywords

Private well water; Contaminant; Arsenic; Radon

1. Background

Approximately 44 million people in the U.S. (about 13% of U.S. households) rely on domestic wells for drinking water (U.S. Geological Survey, 2016a, b). The Environmental Protection Agency (EPA) regulates water from public sources but it does not regulate private wells. Various contaminants, particularly those that occur naturally in groundwater, may be found in private wells. The U.S. Geological Survey's (USGS) National Water-Quality Assessment Program assessed the water quality of 2100 domestic wells within 48 states and reported that more than one in five of the sampled wells contained one or more contaminants at a concentration greater than either EPA's maximum contaminant levels (MCLs) or USGS' health-based screening levels (HBSLs) (DeSimone, 2009). Testing, treatment, and maintenance of these private wells may prevent contamination and thus protect the health of the well users.

The 2010 U.S. Census estimated the rural population of West Virginia at 51.3%, the second highest rural population in the U.S. (U.S. Census Bureau, 2016). An estimated 23% of West Virginians obtain their water from private wells (Atkins, 2007). However, a comprehensive assessment of constituents in drinking water derived from private wells in West Virginia does not exist.

USGS has conducted several studies on basic groundwater quality in West Virginia (Kozar and Brown, 1995; Kozar and Mathes, 2001; Kozar et al., 2001; Larsen and Mann, 2005; Mathes et al., 1998). Most notably, USGS tested groundwater across various rock strata in West Virginia from 1993 to 2008, and testing indicated that the quality of these public drinking water sources before treatment varied highly across various aquifer geologies (Chambers, 2008; Shiber, 2005).

Because of its geology, the majority of West Virginia falls into Radon Zones 1 and 2 as categorized by the EPA, demonstrating moderate to high concerns for radon exposure (Fig. 1) (West Virginia -EPA Map of Radon Zones, 2016). Radon Zones are classified as Zones 1, 2, or 3 with Zone 1 representing counties with predicted average indoor radon screening levels greater than four picocuries per liter (pCi/L), Zone 2 for counties with levels between two and four pCi/L and Zone 3 for counties with levels lower than two pCi/L. The EPA has set the indoor radon screening level of 4 pCi/L as the action level where homeowners are recommended to take corrective measures to reduce exposure to radon gas. Radon-222 is a radioactive gas that can seep from groundwater into plumbing and accumulate in indoor air as it exits the spigot. Though studies indicate only a small proportion (<5%) of the total radon in indoor air is attributable to radon in water, as the water radon level increases, so can the level of indoor air radon (West Virginia -EPA Map of Radon Zones, 2016).

One of the strongest determinants of groundwater quality is the geology where the groundwater resides (Chambers, 2008). For example, higher arsenic concentrations have been found to be closely associated with sandstone mudstone geologic formations found in certain geologic ages (Abbott, 2002; Schlottmann, 2016). Each geologic age has particular geologic content and rock strata which affect the quality of the groundwater residing there. West Virginia lies predominantly across five geologic strata which range in age from 251 and 444 million years old. The central region of West Virginia and most of the western region is mostly sedimentary rock formed between 318 and 251 million years ago during the Pennsylvanian and Permian ages. Southern West Virginia comprises sedimentary rock formed between 318 and 359 million years ago, predominantly during the Mississippian age. Eastern West Virginia comprises shale, siltstone, and sandstone formed between 359 and 444 million years ago during the Devonian and Silurian periods (Chambers, 2008). Aquifers in the Appalachian Plateaus Province where West Virginia is situated are divided into Mississippian, Permian, and Pennsylvanian aquifers (USGS, 2017).

The Centers for Disease Control and Prevention (CDC), in collaboration with the West Virginia Bureau of Public Health (BPH), initiated an investigation to characterize private well water quality based on the age of the local geology. The objective of this study was to characterize the ground water serving private wells by testing household drinking-water samples and comparing them to EPA's primary and secondary MCLs (Environmental Protection Agency, 2015a, b, c). The study can provide information to state and local public health and local communities about constituent concentrations for planning, testing, and mitigation.

2. Methods

2.1. Study area

The BPH selected regions and counties in a way to best represent the geologic differences across the state. They selected 10 of 55 counties from three regions: the central region (Calhoun, Roane, and Wirt counties), the southern region (Greenbrier, Mercer, and Summers counties), and the eastern region (Grant, Hampshire, Hardy, and Mineral counties) (Fig. 1).

2.2. Well selection

West Virginia county health departments maintain a registry of all private drinking water wells. The county health departments participating in the study provided the BPH with a list of residences that utilized private wells as a source of drinking water.

With the help of county health departments, BPH staff mailed a recruitment letter and return card to residents with private wells, briefly explaining the study. Interested residents were asked to return the card to BPH in order to obtain more information about the study from BPH and to give consent for BPH to collect a water sample. Twenty-dollar gift cards were given to residents for their participation.

2.3. Sample collection and basic measures

We collected basic information from well permit data provided by the county health department about properties of the wells, such as age, depth, and type of casing. We took water samples between August 23 and September 3, 2010, from outside faucets when available (otherwise from indoor faucets). We allowed the water to run for 3 min at full flow to clear the line, and then reduced the flow to a slow, steady, stream (Environmental Protection Agency, 2005). We filled a bucket with water and measured basic water-quality parameters (i.e., temperature, pH, turbidity, conductivity, dissolved oxygen, and salinity) on-site using a Horiba U-50 Multi-parameter Water Quality Checker (Kyoto, Japan, 2009). We mapped Global Positioning System (GPS) coordinates to West Virginia geologic maps created by USGS to determine the geologic age of the aquifer from which the water sample was collected (West Virginia Geological and Economic Survey, 2014; Chambers, 2008).

We chilled water samples in ice packs and sent the samples to the Colorado Department of Public Health and Environment's (CDPHE) Laboratory Services Division within 24 h of collection; they analyzed the samples for the 20 constituents currently monitored in public drinking-water systems and frequently detected in private well water. These constituents included Aluminum, Antimony, Arsenic, bacteria (*E. coli* and total coliform), Barium, Beryllium, Cadmium, Chromium, Copper, Cyanide, Fluoride, Iron, Lead, Manganese, Mercury, Nitrogen, Nitrate/Nitrite, Radon-222, Selenium, Silver, and Zinc. EPA has different categories of drinking-water standards. Maximum contaminant levels (MCLs) are legally enforceable standards set by the EPA for certain constituents for drinking water in public water systems, and are based on the concentrations that may lead to adverse health effects. Secondary maximum contaminant levels (SMCLs) are EPA-recommended concentration levels for certain constituents that do not cause health problems but can lead to unpleasant effects (e.g., unpleasant taste or odor). Proposed maximum contaminant levels (PMCLs) are EPA-proposed contaminant levels for certain constituents (e.g., radon) that are not enforceable but are used as guidelines for community water systems to limit contaminant exposure (Environmental Protection Agency, 2015a, b, c).

2.4. Lab analysis

CDPHE used the following methods to monitor the constituents indicated: EPA 200.8 (antimony, arsenic, beryllium, cadmium, lead, selenium, silver); EPA 200.7 (aluminum, barium, calcium, chromium, copper, iron, manganese, nickel, zinc); EPA 353.2 (nitrate, nitrite); QC-10204001X (cyanide); ASTM-5072-92 (radon-222); SM9223 3.2.c (*E. coli*, coliform); EPA 300.0 (fluoride); and EPA 245.1 (mercury) (Environmental Protection Agency, 2015a, b, c; ASTM International, n.d.; National Environmental Methods Index, n.d.).

2.5. Data analysis

We entered data into Microsoft Excel spreadsheets from the original laboratory reports and into an EpiInfo™ 7 database. We performed descriptive data analyses using SAS version 9.2 (SAS Institute, Cary NC).

We performed descriptive statistical analysis for each basic water quality characteristic by region. We determined concentrations and compared them with drinking water standards for constituent using EPA MCLs, SMCLs, or PMCLs, as appropriate. EPA has proposed two drinking-water contaminant levels for radon-222; for this study, we used the lower PMCL of 300 picocuries per liter (pCi/L).

We also stratified the exceedances by geologic age (i.e., Silurian, Devonian, Mississippian, Pennsylvanian, and Permian geologic ages) for comparison. We calculated percentages of total samples that exceeded EPA maximum contaminant levels (MCLs), secondary contaminant levels (SMCLs), and proposed contaminant levels (PMCLs) for each group.

We used maximum likelihood estimation with a gamma distribution to calculate geometric means for each constituent by geologic age. This method accounts for the left censoring that results when some constituent concentrations are below the limit of detection (LOD). We applied the step-down Bonferroni-Holm correction where pairwise testing was performed, resulting in tests that are more powerful than the Bonferroni correction while still controlling the familywise error rate. We considered p-values <0.05 to be statistically significant. We generated maps using ArcGIS version 10 (ESRI, Redlands CA) for radon-222 for spatial analysis (Fig. 2).

3. Results

One hundred and thirty-nine residents throughout 10 rural counties from the three regions returned cards inviting them to be a part of our study. We sampled from 8 to 28 wells in each of the 10 counties for a total of 139 water samples. Of these, 40 (28.8%) were in the central region, 52 (37.4%) in the eastern region, and 47 (33.8%) in the southern region. By geologic age, we tested 39 (28.1%) samples from the Devonian age, 32 (23.0%) from the Permian age, 27 (19.4%) from the Mississippian age, 14 (10.1%) from the Pennsylvanian age, and 5 (3.0%) from the Silurian age. GPS coordinates were not provided for 22 (15.8%) samples because a signal was not available. Among wells with recorded drilling year (n = 97, 69.8%), the oldest well was drilled in 1973 and the newest well was drilled in 2010; Thirty six (37.1%) of the wells tested in this study were drilled in 2009. Among wells with recorded depths (n = 90, 64.7%), the range was 40–800 ft.

We show basic water-quality measures by region in Table 1. The average temperature across all regions was 18.4 °C and the average pH was 7.4 (5.6–10.3) for all samples. The average pH was 7.2 (range 6.6–8.6) in the eastern region, 8.0 (range 6.9–10.0) in the central region, and 8.0 (range 5.6–10.3) in the southern region. The turbidity range in all water samples was 0.0–201.0 nephelometric turbidity units (NTU) (mean = 7.2); conductivity range was 0.04–5.1 microsiemens per centimeter (μS/cm) (mean = 0.5); dissolved oxygen range was 3.8–31.7 mg/L (mean = 16.0 mg/L); and salinity range was 0.0–3.7 g/L (mean= 0.3 g/L).

3.1. Constituent concentrations

No samples exceeded the MCL for antimony, barium, beryllium, cadmium, chromium, copper, cyanide, mercury, nitrogen, and selenium (Table 2). Ten (7.2%) samples exceeded the MCL for total arsenic, three (2.2%) exceeded for fluoride, and one (0.7%) exceeded for lead.

No samples exceeded the SMCL for silver and zinc. Three (2.2%) samples exceeded the SMCL for aluminum, 43 (30.9%) exceeded for iron, and 68 (48.9%) exceeded for manganese.

For Proposed Drinking Water Regulations, 48 (34.5%) samples exceeded the PMCL for radon. Table 2 shows all concentration levels with geometric mean and 95% confidence intervals of the previously noted constituents.

Each of the 139 samples collected were tested for *E. coli* and coliform; 47 (33.8%) of these samples tested positive for coliform. Seven (5.0%) of the samples contained both *E. coli* and coliform, which indicates poor microbial drinking water quality. *E. coli* and coliform were not isolated to a specific region but found throughout all counties sampled.

Of 139 samples, 117 (84.2%) were geographically located using GPS coordinates and mapped to determine the geologic ages of the rock surrounding the aquifer. Of these, 32 (27.4%) were mapped to the Permian age, 14 (12.0%) were mapped to the Pennsylvanian age, 27 (23.1%) were mapped to the Mississippian age, 39 (33.3%) were mapped to the Devonian age, and five (4.3%) were mapped to the Silurian age. Of 36 SMCL exceedances for iron, 13 (36.1%) of the samples were from the Devonian age, and 10 (27.8%) were from the Permian age. Of 60 SMCL exceedances for manganese, 27 (45%) were from the Devonian age, and 14 (23.3%) were from the Permian age. Of 10 MCL exceedances for arsenic, 9 (81.8%) were from the Permian age. Of 47 PMCL exceedances for radon-222, 27 (57.4%) were from the Permian age. Fig. 1 shows the spatial distribution of radon exceedances.

Constituent concentrations did not differ significantly by geologic age for iron and manganese (Table 3). The geometric mean for arsenic in the Permian age was higher than other geologic ages and arsenic concentrations of the Permian age differed significantly from all other geologic ages in pairwise comparisons (Table 3). Radon concentrations of the Permian age were significantly higher than the Silurian age (p value < 0.001), Devonian age (p value < 0.001), and Mississippian age (p value < 0.001), but not for the Pennsylvanian age (p value = 0.246).

4. Discussion

Previous studies of West Virginia groundwater demonstrated that most groundwater samples throughout the region did not exceed current MCLs (Kozar and Brown, 1995; Kozar and Mathes, 2001; Kozar et al., 2001; Larsen and Mann, 2005;Mathes et al., 1998). This study reiterates those findings; only 3 of the 13 constituents tested had at least one sample that exceeded their respective MCL. The most notable were the ten samples that exceeded the arsenic MCL (0.01 mg/L); the maximum arsenic concentration in a sample was more than three times the MCL. Even though these concentrations are lower than any levels that may cause acute arsenic toxicity, many studies have suggested that prolonged use of water with arsenic concentrations higher than the MCL may cause chronic adverse health effects, including cardiovascular disease, diabetes mellitus, and lung, bladder, liver, renal, and skin cancer (Meliker, 2007; Kurttio, 1999).

The arsenic concentrations of samples differed greatly by the age of the surrounding geology; most of the exceedances were from samples located in bedrock aquifers from the Permian age, which comprise primarily sandstone. Studies have shown that arsenic occurs naturally in certain deposits from the Permian age due to many factors, including the oxidized nature of the aquifer and the distribution of finer-grained rock formations such as sandstone and mudstone in the aquifer (Abbott, 2002). Studies in Oklahoma have also reported dissolved arsenic concentrations higher than the MCLs in aquifers from the Permian age (Schlottmann, 2016; Abbott, 2002).

We found that iron and manganese were the only two SMCL constituents where samples had high concentrations that exceeded SMCLs. While SMCLs are not enforceable and adverse health effects are unlikely at the concentrations found in our study, water with high concentrations of iron or manganese may be aesthetically unpleasant and affect the perceived quality of drinking water. Moreover, iron and manganese may increase the corrosiveness of the water, which can stain household fixtures and reduce water flow in distribution pipes (Environmental Protection Agency, 2015a, b, c). Samples with results for iron and manganese that exceeded the SMCL were reported in all regions and geological ages in this study. The geometric mean concentrations for iron were higher in bedrock aquifers from the Devonian age, a finding supported by previous studies in West Virginia (Kozar and Mathes, 2001; Kozar et al., 2001; Chambers, 2008).

We found levels of radon above the PMCL in a large percentage (34.5%) of the water samples we tested, with most of the exceedances occurring in aquifers from Permian-aged rock. Our findings are consistent with other studies suggesting higher groundwater levels of radon exist in the northwestern West Virginia (Chambers, 2008). Private well owners should be aware that groundwater radon concentrations may exceed the PMCL, particularly in aquifers from Permian-aged geologies. Private well owners should also be aware that the majority of West Virginia falls within EPA Radon Zones 1 and 2, which indicate a moderate to high radon potential in the indoor air. Though studies indicate only a small proportion (<5%) of the total radon in indoor air is attributable to radon in water, as the water radon level increases, so can the level of indoor air radon (West Virginia -EPA Map of Radon Zones, 2016). Lung cancer is associated with inhalational radon exposure and is considered the second leading cause of lung cancer after cigarette smoking (Environmental Protection Agency, 2013; National Research Council, 1999). Well owners, particularly those who obtain their water from Permian-aged aquifers or in Radon Zones 1 and 2, may be advised to routinely test their homes for radon to ensure that the indoor air levels are not of any health concern.

Our study had several limitations. West Virginia county health departments for the counties included in this study conducted the recruitment process so we could not determine the overall response rate for the study. Respondents may have had significantly different well characteristics and constituent levels than persons who did not reply to the recruitment card. Future studies using a random selection process from well permits may produce results that are more generalizable.

While we outlined water collection protocols prior to sample collection, there may have been uncontrollable deviations in the sample collection process that produced aberrant results. For example, testing for dissolved oxygen in an open bucket and in higher elevation could produce higher dissolved oxygen levels thus skewing the mean and range above expected levels.

We did not determine the frequency of water use, drinking water treatment, or alternative water sources in this study so we could not assess whether the constituent concentrations might lead to significant exposure. For future studies, researchers could assess water use and knowledge, attitudes, and practices of private-well owners at the time of testing to assess the extent of exposure to potential constituents found in the water samples.

While geologic age can be useful for characterizing differences in water quality and has been shown to be a predictor of potentially high constituent concentrations in private well water, it is important to note that the geochemistry of the aquifer and groundwater are the main drivers of constituent concentrations relating to geologic age. Geologic age has been shown to be a useful surrogate for the actual features of the system that ultimately determines private well water quality. Moreover, constituent concentrations may be associated with factors besides geologic age of the rock surrounding aquifer. Other variables not measured in this analysis, such as proximity to other sources of contamination (e.g., coal power plants and mining facilities) were not accounted for in this analysis.

When an individual sample exceeded the allowable levels for total arsenic or radon, or indicated the presence of *E. coli* or coliform, BPH provided an information fact sheet in the results packet to the household. The fact sheets aimed to help reduce risks from contaminated water by explaining how to identify potential sources of contamination, have tap water tested, and reduce contamination in drinking water. When arsenic concentrations exceeded the MCL, the fact sheet explained the potential sources of arsenic in private well water, the adverse health effects of ingesting arsenic, and ways to remove arsenic from drinking water. When radon exceeded the PMCL, the fact sheet explained radon sources, the possible health effects of radon in groundwater, and ways to avoid groundwater radon from being released in the air (e.g., by installing an aerator for indoor faucets or granular activated carbon filters). BPH also provided a free radon air sampling kit to the individuals for future testing by BPH. When *E. coli* or coliform were present in the sample, the fact sheet explained symptoms related to *E. coli* or coliform exposure and ways to ensure that drinking water was safe before ingesting it. BPH included in the packets a total of 11 fact sheets for arsenic, 48 fact sheets for radon-222, and 39 fact sheets for *E. coli* or coliform. Public health messaging following testing of private wells may be a cost-efficient method to inform private-well owners of ways to mitigate potential contamination of their wells. State and local public health authorities may consider standardized public health messaging for preemptive notification to private well owners who drill in aquifers that have potentially harmful constituent concentrations.

5. Conclusions

We found arsenic and radon concentrations were higher in water samples collected in areas mapped to Permian-aged aquifers compared to those sampled from aquifers mapped to other geologic ages. Homeowners with private wells in areas with Permian aged aquifers could benefit from targeted public health messaging about potentially harmful contaminant concentrations in the well water. This may help ensure proper testing and maintenance of private wells to ensure water quality.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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HIGHLIGHTS

- Characterize well water across aquifer geologies by testing drinking water in 10 WV counties
- We found arsenic and radon concentrations higher in Permian aquifers compared to other geologic ages.
- Private wells in Permian aged aquifers could benefit from targeted public health messaging.

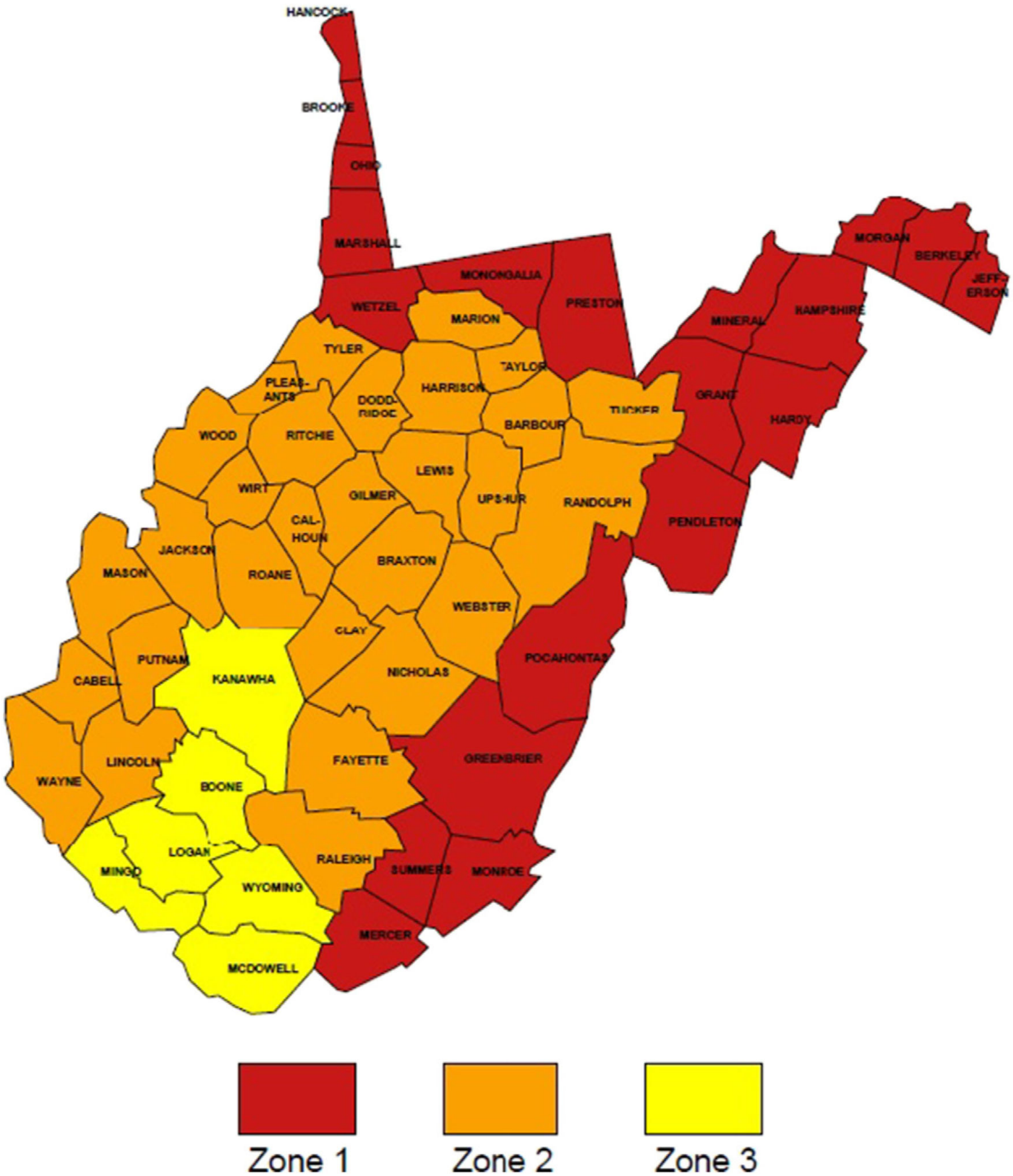

Fig. 1.
Map of West Virginia Radon Zones.

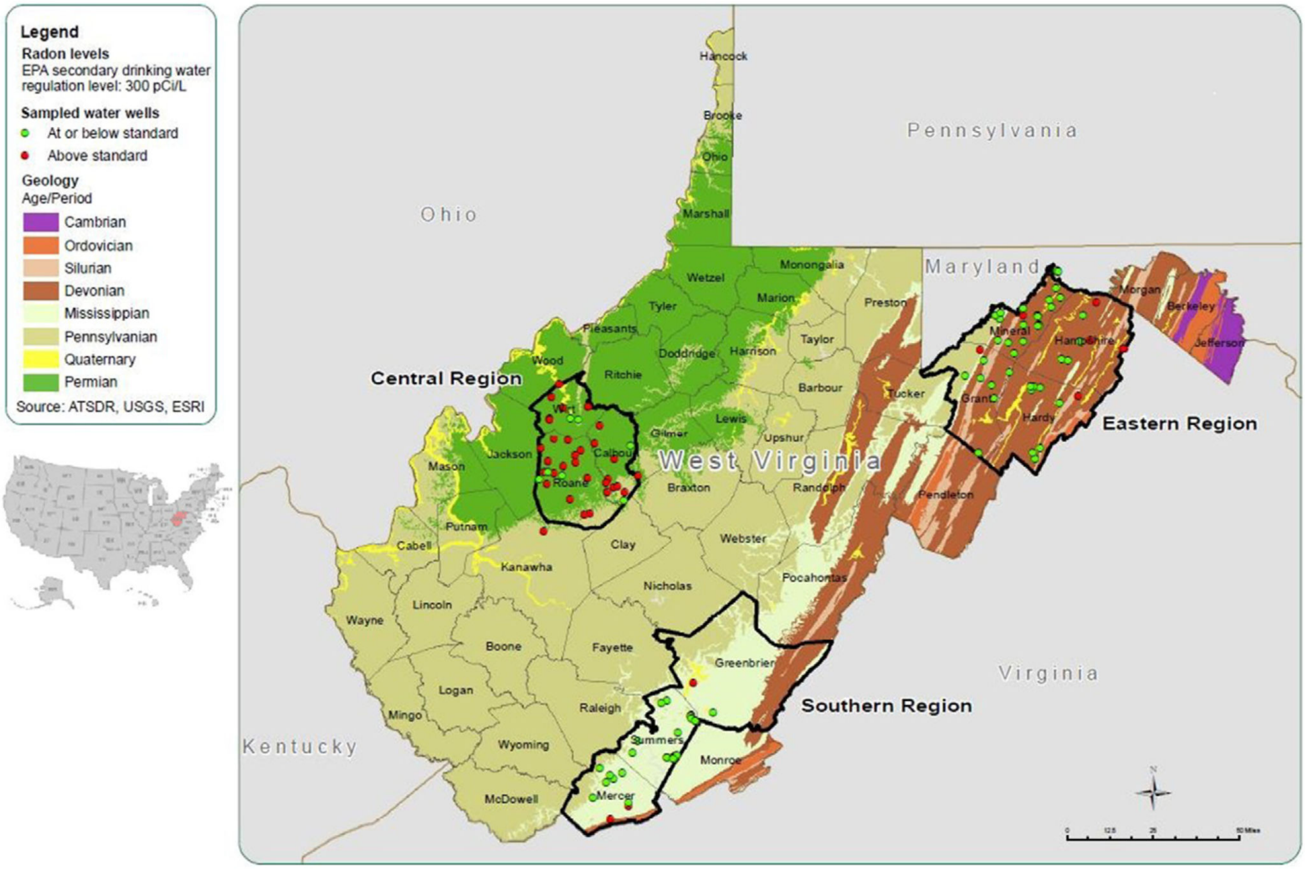

Fig. 2.

Distribution of groundwater samples analyzed for radon-222 with highlighted regions, 2010 (n = 117).

Table 1

Basic private well water quality measures by region—West Virginia, 2010 (n = 139).

Measure	Eastern region Mean (range)	Central region Mean (range)	Southern region Mean (range)	All Mean (range)
Temperature (°C)	18.8 (14.7–25.8)	18.7 (14.6–26.3)	17.8 (13.3–23.6)	18.4 (13.3–26.3)
pH	7.2 (6.6–8.6)	8.0 (6.9–10.0)	8.0 (5.6–10.3)	7.4 (5.6–10.3)
Turbidity (NTU)	2.3 (0–25.3)	12.8 (0–89.1)	6.7 (0–201.0)	7.2 (0–201.0)
Conductivity (μS/cm)	0.4 (0.04–0.8)	0.6 (0.2–1.6)	0.6 (0.1–5.1)	0.5 (0.04–5.1)
Dissolved oxygen (mg/L)	9.2 (3.8–15.8)	18.8 (8.4–20.0)	19.4 (7.3–31.7)	16.0 (3.8–31.7)
Salinity (g/L)	0.2 (0.0–0.5)	0.4 (0.1–1.0)	0.4 (0.06–3.7)	0.3 (0.0–3.7)

NTU = Nephelometric Turbidity Units.

μS/cm = microsiemens per centimeter.

Table 2

National primary drinking water contaminants: level of detection (LOD), percent of well water samples exceeding the LOD, geometric mean of samples and associated 95% confidence interval—West Virginia, 2010 (n = 139).

Contaminant	LOD	% > LOD	Geometric mean (95% confidence interval)	MCL		SMCL		PMCL	
				MCL value	Samples exceeding MCL (%)	SMCL value	Samples exceeding SMCL (%)	PMCL value	Samples exceeding PMCL (%)
Antimony	0.001	7.9%	<LOD	0.006	0 (0)	–	–	–	–
Arsenic	0.001	44.6%	<LOD (<LOD, 0.0013)	0.010	10 (7.2)	–	–	–	–
Barium	0.005	94.2%	0.114 (0.093, 0.138)	2.0	0 (0)	–	–	–	–
Beryllium	0.001	0.0%	<LOD	0.004	0 (0)	–	–	–	–
Cadmium	0.0006	0.0%	<LOD	0.005	0 (0)	–	–	–	–
Chromium	0.02	0.0%	<LOD	0.1	0 (0)	–	–	–	–
Copper	0.005	41.7%	<LOD (<LOD, 0.0053)	1.3	0 (0)	–	–	–	–
Cyanide	0.01	0.0%	<LOD	0.2	0 (0)	–	–	–	–
Fluoride	0.02	99.3%	0.190 (0.162, 0.224)	4.0	3 (2.2)	–	–	–	–
Lead	0.001	30.9%	<LOD	0.015	1 (0.7)	–	–	–	–
Mercury	0.0001	0.0%	<LOD	0.002	0 (0)	–	–	–	–
Nitrogen, nitrate/nitrite	0.03	19.4%	0.038 (<LOD, 0.055)	10.0	0 (0)	–	–	–	–
Selenium	0.001	0.7%	<LOD	0.05	0 (0)	–	–	–	–
Aluminum	0.05	8.6%	<LOD	–	–	0.2	3 (2.2)	–	–
Iron	0.01	86.3%	0.113 (0.080, 0.161)	–	–	0.3	43 (30.9)	–	–
Manganese	0.002	81.3%	0.026 (0.017, 0.039)	–	–	0.05	68 (48.9)	–	–
Silver	0.001	0.7%	<LOD	–	–	0.10	0 (0)	–	–
Zinc	0.01	54.0%	0.012 (<LOD, 0.017)	–	–	5.0	0 (0)	–	–
Radon-222	54	43.9%	<LOD (<LOD, 87.3)	–	–	–	–	300	48 (34.5)

LOD = Limit of detection.
MCL = Maximum contaminant level.
SMCL = Secondary maximum contaminant level.
PMCL = Proposed maximum contaminant level.

Table 3

Private well-water samples exceeding national drinking water standards and maximum likelihood estimation by Geologic Age —West Virginia, 2010 (n = 117).

Contaminant (MCL/SMCL/PMCL)	Geologic age	Number of exceedances (% of exceedances)	Geometric mean (95% confidence interval)	p value[a]
Iron (0.3 mg/L)	Permian	10 (27.8)	0.085 (0.037, 0.197)	REF
	Pennsylvanian	6 (16.7)	0.194 (0.078, 0.484)	0.612
	Mississippian	5 (13.9)	0.056 (0.028, 0.109)	0.896
	Devonian	13 (36.1)	0.152 (0.084, 0.276)	0.870
	Silurian	2 (5.6)	0.110 (0.019, 0.63)	0.896
Manganese (0.05 mg/L)	Permian	14 (23.3)	0.015 (0.004, 0.051)	REF
	Pennsylvanian	10 (16.7)	0.037 (0.015, 0.093)	0.741
	Mississippian	7 (11.7)	0.013 (0.006, 0.029)	1.000
	Devonian	27 (45.0)	0.070 (0.034, 0.146)	0.092
	Silurian	0	0.012 (0.003, 0.047)	1.000
Arsenic (0.010 mg/L)	Permian	9 (81.8)	0.006 (0.004, 0.011)	REF
	Pennsylvanian	1 (9.1)	0.002 (0.001, 0.004)	0.02
	Mississippian	7 (11.7)	<LOD (<LOD, 0.001)	<0.001
	Devonian	0	<LOD	<0.001
	Silurian	0	<LOD (<LOD, 0.613)	0.02
Radon-222 (300 pCi/L)	Permian	27 (57.4)	917 (506, 1661)	REF
	Pennsylvanian	8 (17.0)	462 (233, 914)	0.246
	Mississippian	7 (11.7)	<LOD (<LOD, 87.8)	<0.001
	Devonian	6 (12.8)	<LOD	<0.001
	Silurian	0	<LOD (<LOD, 1377)	<0.001

MCL = Maximum contaminant level.
SMCL = Secondary maximum contaminant level.
PMCL = Proposed maximum contaminant level.
LOD = Limit of detection.
pCi/L = Picocuries per liter.
REF = Referent.

[a] p-Values for pairwise comparisons were adjusted using the step-down Bonferroni-Holm correction.