

Division of Science, Research and Environmental Health

Research Project Summary

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Contribution of Naturally Occurring Radioisotopes to Gross Alpha-Particle Activity in Ground Water in Bedrock Aquifers of Northern New Jersey

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Abstract

A study was conducted to determine the relative contributions of uranium and radium isotopes to overall gross alpha-particle activity in ground water from the Highlands and Piedmont Provinces of New Jersey. The general relationship between the occurrence of these two radionuclides and other water quality parameters in aquifers of these regions was also evaluated. A total of 80 ground water samples were collected from public and private drinking water wells in the Highlands and Piedmont Provinces between 2007 and 2011. Bedrock composition, including mineralogy, lithology, and mineral surface coatings, as well as geochemical conditions including pH and oxidation-reduction potential in the aquifer, directly affect the occurrence and distribution of naturally occurring radionuclides in ground water. Gross alpha-particle activity exceeding the U.S. Environmental Protection Agency and New Jersey Maximum Contaminant Level (MCL) of 15 pCi/L (picocuries per liter) was documented in ground water from widely scattered areas in the bedrock aquifers of northern New Jersey. Most of the measured alpha-particle activity in the waters was attributable to the long-lived isotopes of uranium (U) and, to a lesser extent, radium-226 (Ra-226). Uranium isotope ratios were extremely variable in some areas of the Piedmont, and uranium may account for more of the gross alpha-particle activity in these areas than is evident from a simple uranium mass measurement. Some limited guidance as to the occurrence of uranium and radium for homeowners with private wells is possible on the basis of gross alpha-particle activity, dissolved oxygen, and, to lesser extent, other parameters (pH, bicarbonate alkalinity, filtered iron and/or manganese, and rock type), but none of these “surrogates” are completely definitive. Further investigations to improve understanding of parameters that are predictive of the occurrence of radium and uranium in ground water may be useful to further refine this guidance.

Introduction

Naturally occurring radionuclides occur frequently in principal aquifers of New Jersey, and these aquifers are a vital source of drinking water for the state’s dense population. For these reasons, it is important to understand how to identify the aquifers, or portions of aquifers, most vulnerable to radionuclide contamination. The U.S. Environmental Protection Agency (USEPA) and New Jersey drinking water Maximum Contaminant Level (MCL) for gross alpha, excluding uranium and radon, is 15 pCi/L, and the MCL for combined radium (Ra-226 + Ra-228) is 5 pCi/L. These MCLs are based on cancer risk from exposure to radioactivity. The MCL for uranium (U) (30 µg/L) is based on mass and on the chemical toxicity of this element, rather than radioactivity. Compliance with the MCL for gross alpha-particle activity includes an “adjustment” of the emitted alpha-particle radioactivity to subtract the contribution from uranium radioactivity. The factor used for this adjustment can vary depending on the ratio of the shorter lived U-234 progeny to the longer lived U-238 parent isotope. Radon is eliminated during sample

preparation and therefore, no adjustment for radioactivity from radon is needed.

Elevated gross alpha-particle activity in ground water has been documented in scattered areas in northern New Jersey (New Jersey Department of Environmental Protection (NJDEP), 2004; NJDEP Safe Drinking Water Program, 2008). Because a short lived isotope, Ra-224, and its progeny were found to contribute to gross alpha in some New Jersey ground waters, NJDEP mandates the analysis of gross alpha within 48 hours for samples collected from public water systems statewide (NJ Safe Drinking Water Act, N.J.S.A. 58:12A-1 et seq.) and from private wells in the 12 southern and central counties where testing for gross alpha is required by the Private Well Testing Act (PWTA, N.J.S.A. 58:12A-26 et seq.). However, a separate MCL for Ra-224 has not been set by NJDEP or USEPA.

It is not known whether gross alpha activity is as useful an indicator for the occurrence of specific radionuclides in northern New Jersey as it is in the southern part of the

state. In southern New Jersey, the gross alpha test within 48 hours of sample collection is a specific indicator of Ra-226 and Ra-224 because uranium is not present in this region (Szabo et al., 2005). Comparable information on the interpretation of gross alpha results from northern New Jersey is needed, since alpha-particle activity is attributable to a mixture of long-lived uranium isotopes and the long-lived progeny, Ra-226, as well as short-lived Ra-224. The gross alpha-particle activity analysis is subject to complicated errors and biases that are, at least partly, sample composition dependent (Arndt, 2010) and further evaluation is needed in any region where complex mixtures of radionuclides are expected.

Due to the large geological, geochemical, and hydrological variability in the northern part of the state (Drake et al., 2000; Serfes, 2004), this region includes numerous distinct environmental settings in which the occurrence of radionuclides must be specifically evaluated. An understanding of the occurrence and the primary geochemical variables that may be indicative of preferential occurrence of specific radionuclides may be useful in targeting future monitoring efforts toward sites where occurrence is most likely. Additionally, drinking water treatment removal options are widely different for uranium and radium. Thus, when high gross alpha-particle activity is present, it is critical to determine the proportion of the alpha-particle activity from uranium and from radium so that the best treatment option for risk reduction can be selected.

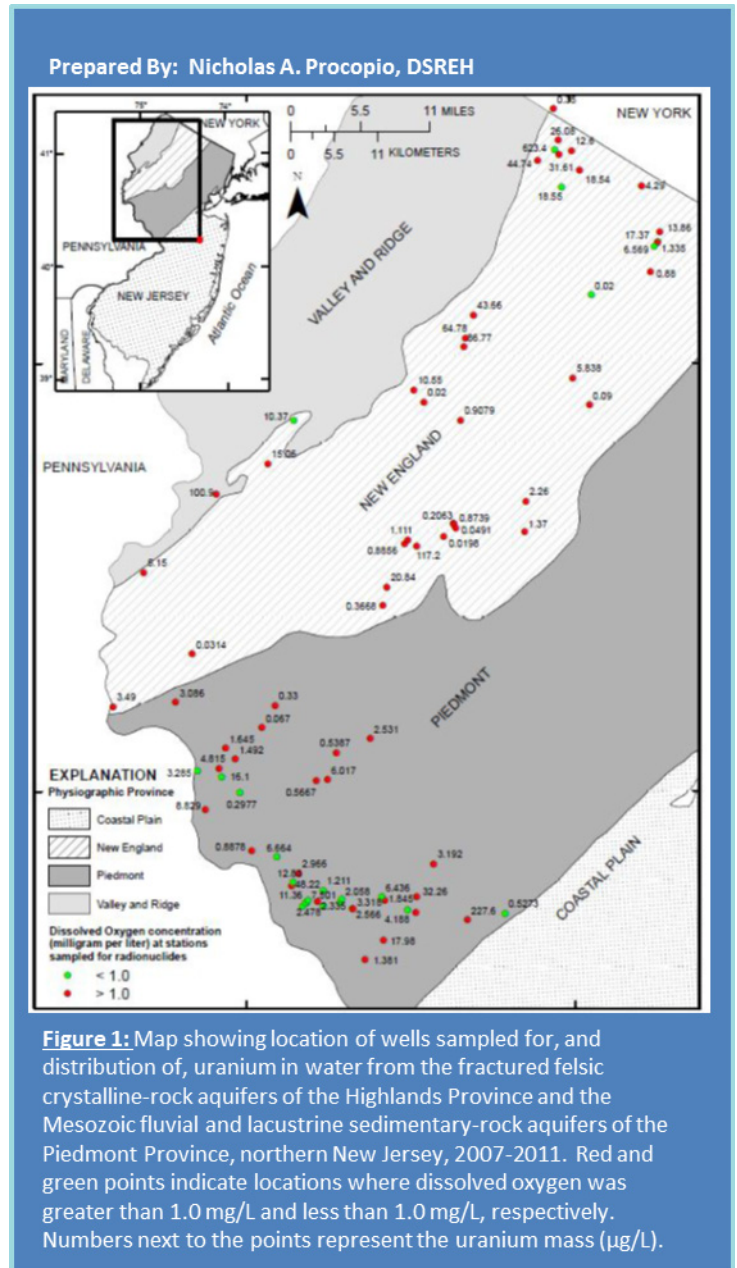
The purpose of this study was to analyze ground water samples in the Highlands and Piedmont Provinces of New Jersey for gross alpha-particle activity, isotopes of uranium and radium, and other water-quality parameters to ascertain the relative contributions of different isotopes to the overall alpha particle activity. The general relationship between these two radionuclides and concomitant water chemistry in crystalline-rock aquifers of the Highlands Province and the sedimentary rocks of the Piedmont Province of New Jersey was also evaluated.

Methods

A broad variety of wells serving small water supplies, including small community or non-transient non-community water suppliers and private domestic self-supply wells, were targeted for sampling. The wells selected were known to have high levels of gross alpha particle activity or were near wells that had previously been shown to have elevated levels of radiologicals. A total of 40 wells were targeted for sampling in the Highlands from 2007 to 2011, and another 40 wells were targeted in the Piedmont from 2009 to 2011 (Fig. 1).

Wells were selected for sampling with intent of providing a rough geographic distribution across the Highlands Province, so that a typical pattern of radionuclide occurrence could be partly defined both geographically and geologically. Sampling was focused on only three major rock types in the Highlands: granites, metamorphic rocks, and carbonate rocks. Sampling in the Piedmont Province was focused in the south central part of the

province where the black shale, representing organic-carbon-rich former lake bed deposits, and red shale, representing former sabkha and mudflat deposits, are located. Much of the northern and eastern part of the Piedmont in New Jersey is composed of either conglomeratic deposits or basalts, neither of which is known to contain radionuclides in substantive levels.



Samples were collected and analyzed for short-term gross alpha-particle activity, uranium isotopes (U-234, -235, and -238), radium isotopes (Ra-224, -226, and -228), arsenic species, iron, manganese, and anions in order to characterize the geochemical nature of the ground water. Parameters and analytical methods are listed in Table 1. Concentrations of sulfate, iron, manganese, nitrate, arsenic, dissolved oxygen, bicarbonate, and pH were used as possible indicators of oxidation-reduction potential and alkalinity (Hem, 1985; McMahon and Chapelle, 2008).

Table 1. Analytical technique and method reporting level of chemical analyses performed.		
Constituent	Method Reporting Level	Method
Gross alpha, short term (48-hr) [with another sample bottle held for 30+ day analysis]	3 pCi/L	Ba-sulfate co-precipitation & Low-background proportional count
Ra-226	0.3 pCi/L	Ba-sulfate co-precipitation & Gamma Spectroscopy
Ra-228	0.5 pCi/L	
Ra-224	0.5 pCi/L	
Uranium	0.3 µg/L	ICP-Mass Spectrometry
Manganese	0.2 µg/L	
Iron	10 µg/L	ICP - optical spectroscopy
Arsenic	0.1-0.3 µg/L	ICP-collision Mass Spectrometry
Sulfate	0.3 mg/L	Ion Chromatography
Nutrients, chloride	<0.1 mg/L	Colorimetry
Uranium isotopes	0.1 pCi/L	ICP-Mass Spectrometry
Arsenic species (optional)	0.1-0.3 µg/L	Field extraction; ICP-Mass Spectrometry
FIELD MEASUREMENTS		
Temperature	0.1 °C	Field Meter
PH	0.1 units	
Dissolved oxygen	0.1 mg/L	
Eh	MV, +20	
Conductance	5 µS/cm	
Turbidity	0.1 NTU	
Alkalinity	0.1 mg/L	
Rn-222	120 pCi/L	Titration
		Alpha Spectrometry

Water sampling was conducted using appropriate (USGS) “trace-element-clean” ground-water sampling techniques (U.S. Geological Survey, 2004). Measurements of numerous characteristics including pH, Eh, and turbidity were conducted in the field during sampling. A flow-through chamber was used for monitoring field parameters except turbidity (U.S. Geological Survey, 2004). Prior to sampling for radionuclides, one to three casing volumes were purged, and all of the monitored field parameters including turbidity were monitored until they stabilized. At this time, final measurements were recorded and water sampling commenced.

Correlations among radium radionuclides and other constituents were calculated using the Spearman correlation coefficient, a measure of the degree to which the two data sets increase or decrease together. Group-comparison tests such as the Wilcoxon and Kruskal-Wallis tests were used to determine whether radium isotope concentration distributions from two or more groups of wells were significantly different (Helsel and Hirsch, 1992). The Tukey-Kramer test was used on the ranks of the data to identify which group means were significantly different relative to other groups (Helsel and Hirsch, 1992).

To determine compliance with the gross alpha-particle activity MCL, total uranium activity was subtracted from the measured gross alpha activity to obtain “adjusted” gross alpha activity (USEPA, 2000). The USEPA allows for the conversion from uranium mass to uranium alpha activity directly using a single factor of 0.672 pCi/µg of measured uranium mass reported in µg/L concentration

units. The use of this single factor, known as the “natural” uranium conversion factor (CF_n), assumes that the uranium in solution is, in fact, “natural uranium” and that the shorter lived U-234 progeny of the longer lived U-238 parent isotope are in secular equilibrium (i.e. the radioactivity of these two isotopes is in a 1:1 activity ratio). If the U-234:U-238 activity ratio has been measured, then the conversion factor (CF) can be calculated from the actual ratio rather than assuming a 1:1 ratio and assigning the constant. The CF is defined in terms of the measured U234:U238 isotope activity ratio as:

$$CF = 0.336 \left(1 + \frac{U-234 \text{ activity}}{U-238 \text{ activity}} \right)$$

where CF is the conversion factor, and the uranium isotope activity ratio is defined the ratio of the activities of U-234 to U-238). A resulting uranium alpha-particle activity can then be recalculated as: CF(uranium mass).

The difference between gross alpha-particle activity and total uranium activity was computed by two separate techniques. First, the total uranium (mass) was converted to a calculated alpha radioactivity based on the assumed uranium isotope activity ratio of 1:1. Second, the total uranium (mass) was converted to a calculated alpha radioactivity based on the measured uranium isotope mass ratio (U-234/U-238) as determined by ICP-MS. The actual uranium isotope activity ratio and the actual alpha radioactivity emitted by the uranium isotopes were determined from the measured uranium-isotope mass ratio.

Results

Highlands

Water from 14 of the 40 wells in the Highlands Province exceeded the gross alpha standard of 15 pCi/L before adjustment by subtraction of radioactivity from uranium, and the activity in 10 of these samples was greater than or equal to 20 pCi/L prior to adjustment. The median gross alpha-particle activity prior to adjustment was 8.1 pCi/L, and the maximum value was 232 pCi/L.

Uranium appears to be the predominant source of gross alpha-particle activity in water sampled in the Highlands. Water from 8 of the 40 wells exceeded the uranium MCL of 30 µg/L, with 5 samples exceeding 60 µg/L, and 3 samples exceeding 100 µg/L. The median uranium concentration was 5.8 µg/L, and the maximum value was 623 µg/L. The uranium isotope activity ratio was measured in 33 Highlands samples, and U-234 was present at higher concentrations than U-238 in all but 2 of these 33 samples. The excess U-234 isotope can cause an increase in gross alpha-particle activity above that expected from “natural” uranium for which the activity ratio is assumed to be 1:1. In these 33 samples, U-234:U-238 isotopic activity ratios ranged from 0.94 to 2.95, with a median of 1.36. In 82 percent of these samples, the uranium isotope activity ratio was greater than 1.2, the global median groundwater uranium isotope activity ratio reported by Osmond and Cowart (1968), and the ratio was greater than 2 in 18 percent of samples. When the measured isotopic activity ratios of the uranium isotopes were considered, gross alpha-particle activity was completely accounted for by the uranium activity except at a few sites where alpha-particle emitting isotopes of radium were also present and thus the adjusted gross alpha-particle activity did not exceed the MCL. In fact, only 3 samples had remaining net gross alpha activity greater than five pCi/L when “excess U-234” was accounted for.

At least one isotope of radium was detectable in 17 of 40 wells. Ra-226 was most frequently detected. Samples collected in areas underlain by uranium-rich felsic granites, granite gneisses, and marbles in the Highlands generally had concentrations of radium-226 that were substantially higher than the associated concentrations of radium-228.

The concentrations of additional ancillary constituents were critical in characterizing the potable water quality of the aquifers, as well as in defining the geochemical environment. When dissolved oxygen in the sample water was at or near saturation (greater than 8 mg/L), uranium isotopes accounted for nearly all of the gross alpha-particle activity; and Ra-226 was detected only once. For those sites where water was not near saturation with dissolved oxygen, Ra-226 was detected more frequently. Samples from 2 wells exceeded the NJ arsenic MCL of 5 µg/l (NJDEP, 2002), samples from 7 wells exceeded the 50 µg/L secondary standard for manganese. Samples from 3 wells exceeded the secondary standard of 300 µg/L for iron, although 2 of these 3 samples were turbid (greater than 5 NTUs (Nephelometric Turbidity Units)) indicating

that some iron may have passed through the filters in colloidal form. Ammonia was detected in 7 wells.

Piedmont

Water-quality data collected from the 40 wells sampled in the Piedmont Province indicate that the occurrence of radionuclides, especially the occurrence of Ra-226, is an important issue for ground water in this province as well. Water from 13 of the wells exceeded the 15 pCi/L before adjustment for uranium, and 10 of the samples exceeded or equaled an activity of 20 pCi/L. The median gross alpha-particle activity was 5.6 pCi/L, and the maximum value was 225 pCi/L.

Water samples from 3 of the 40 wells exceeded the uranium MCL of 30 µg/L, with 1 sample exceeding 100 µg/L. The median uranium concentration was 3.0 µg/L, and the 3rd quartile value was 6.9 µg/L, about 1 µg/L greater than the median found in the Highlands Province. The uranium isotope activity ratio (U-234:U-238) was determined in 30 samples. The activity of the U-234 isotope was higher than for the U-238 isotope in all but one sample. The U-234:U-238 ratio exceeded 1.2 in 93% of the samples, was greater than 2 in 60% of samples, and was greater than 3.42 in 25% of samples. The ratios ranged from 0.94 to 8.45 with a median ratio of 2.19. The quantification of “excess” U-234 isotope concentration more accurately characterized the source of the gross alpha-particle activities than using the default 1:1 ratio. In about 7.5% of the samples, adjustment based on the sample-specific uranium isotope ratio instead of the default assumption for the ratio affected compliance with the gross alpha-particle MCL. In these cases, the samples could have been assumed to be out-of-compliance for gross alpha using the default ratio when in fact the use of the actual isotope ratios would have suggested compliance with the gross alpha standard.

Concentrations of combined Ra (Ra-226+Ra-228) in samples of water from 8 of the 40 wells exceeded the 5 pCi/L MCL, and the concentration of Ra-226 alone was greater than 5 pCi/L in 7 of these 8 samples. At least one isotope of radium was detectable in all but one of the 40 wells; the most frequently detected isotope was Ra-226. In samples from areas underlain by organic carbon-rich siltstone and mudstone in the Early Mesozoic basin aquifers, concentrations of Ra-226 were generally higher than the associated concentrations of Ra-228. In 7 of the 8 samples in which the concentration of Ra-226 was greater than the 5 pCi/L MCL, dissolved oxygen concentration was less than 0.5 mg/L. Ra-224 made considerable contributions to gross alpha-particle activity measured 48 hours after sample collection at the few sites where it was present in concentrations greater than 3 pCi/L. The gross alpha-particle activity in the Piedmont was thus rarely accounted for by only the uranium activity.

The concentrations of additional ancillary constituents were critical in characterizing the potable quality of water from the aquifers, as well as in defining the geochemical environment. Samples from 15 of the wells exceeded the NJ arsenic MCL of 5 µg/L (NJDEP, 2002) (maximum, 24.7

µg/L), and 5 wells exceeded the USEPA arsenic MCL of 10 µg/L. Twelve samples exceeded the secondary standard for manganese of 50 µg/L, and 4 exceeded the secondary standard for iron of 300 µg/L. Low concentrations of dissolved oxygen (anoxic conditions) were almost as likely to occur as more oxic conditions. Ammonia was detected (greater than or equal to 0.02 mg/L) in 14 of the 40 Piedmont samples, in contrast with the more oxic waters of the Highlands where concentrations of ammonia were less frequently detected.

Conclusions

Elevated gross alpha-particle activity at levels greater than the U.S. Environmental Protection Agency and New Jersey Maximum Contaminant Level of 15 pCi/L, was detected in drinking water wells in widely scattered areas in the crystalline-rock (granite, gneiss, marble) Highlands Province and in black mudstone (Mesozoic Basin) in the Piedmont Province of northern New Jersey. Most of this alpha-particle activity in the waters in the Highlands and Piedmont Provinces, respectively, was attributable to the long-lived isotopes of uranium, and to a lesser extent, Ra-226 and Ra-224, which is derived indirectly from Ra-228.

Conventional measurements of the general amount of radioactivity in the water, such as measurements of gross alpha-particle activity, did not prove to be reliable for identifying specifically when concentrations exceeded the combined radium MCL or the uranium MCL. Elevated gross alpha-particle activity indicates the presence of one or both of these two alpha-particle-emitting radioactive constituents in relatively high concentrations, but gross alpha-particle activity measurement alone does not indicate which of these nuclides is predominant and contributes more to the radioactivity of the water sample.

A general pattern of radionuclide occurrence with respect to uranium and radium can be partly defined based on geology and geochemistry of these regions. A general pattern of occurrence of considerably greater uranium isotope activity ratios was defined for the Piedmont Province. Among the most noticeable differences between the two regions was the considerably higher dissolved oxygen concentration in the Highlands, which had a median value almost 5-fold higher than in the Piedmont. Additionally, nearly half (43.5%) of the samples collected from the Piedmont had dissolved oxygen concentrations less than or equal to 1 mg/L, classified as “anoxic” for purposes of this study, whereas only 16 percent of the samples from the Highlands fit this description.

Sample geochemistry (oxic or anoxic conditions) and bedrock geology (crystalline or sedimentary) could be helpful in estimating the likelihood of which radionuclide is predominant. In addition to the gross alpha-particle activity level, the inexpensive uranium mass analysis along with dissolved oxygen concentration, iron and manganese concentration, and pH might serve as suitable initial water-quality indicators at most sites in the region; however, none of the “surrogates” are 100% definitive.

Anion-exchange systems did remove uranium and gross alpha-particle activity when uranium was the predominant source of the radiation. Cation-exchange (water softener) systems did not remove uranium, nor did they reduce gross alpha-particle activity, when uranium was the predominant source of the radiation, although water softeners were effective in reducing radium concentrations. Because remediation options differ widely for uranium and radium, it is critical to determine the predominant source of the alpha activity in northern New Jersey where high gross alpha-particle activity is present.

Summary conclusions for this study include:

- ◆ Uranium occurrence predominates where waters have high dissolved oxygen concentrations. Ra-226 occurrence predominates where waters have low dissolved oxygen concentrations.
- ◆ Uranium activity accounts for all of the gross alpha-particle activity in the most oxic waters. Uranium isotope ratios are extremely variable in some areas of the Piedmont, and uranium may account for more of the gross alpha-particle activity in these areas than is evident from the simple uranium mass measurement.
- ◆ Uranium and arsenic were frequently higher in alkaline waters with pH greater than 7.4 than in less alkaline waters. These conditions were more common in metamorphic than granitic rock in the Highlands, and in mudstone than sandstone in the Piedmont.
- ◆ Ra-226 occurrence predominates where waters have dissolved oxygen concentrations of < 1 mg/L, filtered manganese and iron concentrations of 50 µg/L, and detectable ammonia.
- ◆ On rare occasions, all of the constituents occurred together, possibly because of mixing of waters from different fracture zones.
- ◆ On rare occasions, “excess” U-234 isotope concentrations were detected. This phenomenon increases the measured gross alpha-particle activity without increasing the observed uranium concentration. This situation may be confusing to homeowners and even knowledgeable treatment system operators.
- ◆ For computing the “uranium-adjusted” gross alpha-particle activity, the “natural-U” isotope ratio of 1:1 is most conservative, in that it most likely underestimates the mass-to-alpha-activity conversion factor, making it more likely that the “adjusted” gross alpha-particle activity is not in compliance with the MCL (giving a “false positive” result). This can be misleading when isotope ratios are highly variable.
- ◆ Anion exchange systems successfully removed uranium while cation exchange systems (water softeners) successfully removed radium. Homeowners need to be aware of this critical difference when selecting a treatment option.

References

- Ames, L.L., McGarrah, J.E., Walker, B.A., and Salter, F., 1983, Uranium and radium sorption on amorphous ferric oxyhydroxide: *Chemical Geology*, v. 40, p. 135-148.
- Arndt, M.F. 2010. Evaluation of gross alpha and uranium measurements for MCL compliance. Water Research Foundation, Denver, CO.
- Drake, A.A., Jr., Volkert, R.A., Monteverde, D.H., Herman, G.C., Houghton, H.F., Parker, R.A., and Dalton, R.F., 1996, Bedrock map of northern New Jersey: U.S. Geological Survey Miscellaneous Investigations Series Map I-2540-A, 2 pl.
- Helsel, D.R. and Hirsch, R.M., 1992, Statistical methods in water resources: New York, Elsevier, 522 p.
- Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water -Supply Paper 2254, 263 p.
- Landa, E.R., Phillips, E.J.P., and Lovely, D.R., 1991, Release of ²²⁶Ra from uranium mill tailings by microbial Fe(III) reduction: *Applied Geochemistry*, v. 6, p. 647-652.
- Langmuir, D., and Riese, A.C., 1985, The thermodynamic properties of radium: *Geochimica Cosmochimica Acta*, v. 49, p. 1593-1601.
- Mays, C.W., Rowland, R.E. and Stehney, A.F. 1985, Cancer risk from the lifetime intake of Ra and U isotopes: *Health Physics*, v. 48, p. 635-647.
- McMahon, P.B., and Chapelle, F.H., 2008, Redox processes and water quality of selected principal aquifer systems: *Ground Water*, v.46, p. 259-271.
- Moore, W.S., 1976, Sampling ²²⁸Ra in the deep ocean: *Deep Sea Research*, v. 23, p. 647-651.
- New Jersey Department Environmental Protection, 2002, Safe Drinking Water Act rules; Arsenic drinking water standard; Proposed amendment NJAC 7:10-5.2: *New Jersey Register*, v. 34, p. 402-407.
- New Jersey Department Environmental Protection, 2004, A North Jersey homeowner's guide to radioactivity in drinking water: Uranium: Trenton, NJ, New Jersey Department Environmental Protection, 4 p. [At URL <http://www.nj.gov/dep/rpp/download/urwater.pdf>]
- New Jersey Department Environmental Protection (Bureau Safe Drinking Water and Division Science Research Technology), 2008, New Jersey Private Well Testing Act; Program, well test results for September 2002 to April 2007: Trenton, NJ, 75 p. [At URL http://www.nj.gov/dep/pwta/pwta_report_final.pdf]
- Serfes, M.E., 2004, Ground-water quality in the bedrock aquifers of the Highlands and Valley and Ridge Provinces of New Jersey: New Jersey Geological Survey Geological Survey Report GSR 39, 28 p.
- Szabo, Zoltan, dePaul, V.T., Kraemer, T.F., Parsa, Bahman, 2005, Occurrence of radium-224 and comparison to that of radium-226 and radium-228 in water from the unconfined Kirkwood-Cohansey Aquifer System, Southern New Jersey: U.S. Geological Survey Scientific Investigations Report 2004-5224, 92 p. [<http://pubs.er.usgs.gov/pubs/sir/sir20045224>]
- Szabo, Zoltan, dePaul, V.T., Fischer, J.M., Kraemer, T.F., and Jacobsen, Eric, 2012, Occurrence and geochemistry of Radium in aquifers used for drinking water in the United States: *Applied Geochemistry*, v. 27, p. 729-752. [doi:10.1016/j.apgeochem.2011.11.002]
- U.S. Environmental Protection Agency, 2000, National Primary Drinking Water Regulations; Radionuclides; Notice of data availability; Proposed rule: Washington, D.C., Office of Water, U.S. Environmental Protection Agency Report EPA-815-2-00-003.
- U.S. Geological Survey, 2004, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9. [<http://pubs.water.usgs.gov/twri9A>]

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