

Prepared in cooperation with the
New Jersey Department of Environmental Protection

Occurrence of Radium-224, Radium-226 and Radium-228 in Water from the Vincentown and Wenonah-Mount Laurel Aquifers, the Englishtown Aquifer System, and the Hornerstown and Red Bank Sands, Southwestern and South-Central New Jersey

Scientific Investigations Report 2007-5064

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

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By Vincent T. dePaul and Zoltan Szabo

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U.S. Geological Survey**

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Contents

Abstract.....	1
Introduction.....	2
Purpose and Scope	3
Naturally Occurring Radionuclide Decay Series	3
Description of Study Area	6
Geologic Setting.....	6
Hydrogeologic Setting	8
Vincentown Aquifer.....	11
Hornerstown and Red Bank Sands.....	11
Wenonah-Mount Laurel Aquifer	12
Englishtown Aquifer System.....	12
Land Use.....	12
Previous Investigations of Radionuclide Occurrences in Water and Sediment in Southern and Central New Jersey.....	13
Ground Water	13
Sediment.....	13
Methods.....	14
Design of Sampling Network	14
Sampling Procedures.....	16
Quality-Assurance Program	16
Analytical Methods.....	16
Radium-224 and Radium-226.....	17
Radium-228.....	17
Gross Alpha-Particle and Beta-Particle Activities and Radon-222.....	17
Reporting of Results of Analysis of Radionuclides	17
Ancillary Inorganic and Organic Constituents.....	18
Land-Use Classification.....	18
Statistical Analysis of Radionuclide Occurrence.....	18
Occurrence of Radium-224, Radium-226, Radium-228, and Gross Alpha-Particle Activity in the Ground Water	18
Quality Assurance.....	18
Gross Alpha-Particle Activity	20
Radium-224.....	24
Radium-226 and Radium-228.....	25
Significance of Radium-224 Concentrations for Gross Alpha-Particle Activity.....	25
Ratio of Radium-224 to Gross Alpha-Particle Activity	25
Correlations Among Concentrations of Radium-224, Radium-226, and Radium-228, and Gross Alpha-Particle Activity	26
Factors That Affect Radium-224 Concentrations in the Ground Water	27
Geochemical Factors and Land Use.....	27
Relations Between Radium and pH	27
Relations Between Radium and Nitrate.....	29

Chemical Classification of Ground Waters and Possible Effects on Radium Occurrence	30
Unconfined Parts of the Aquifers.....	31
Confined Parts of the Aquifers	34
Radium Isotopes in, and Land Use Overlying, the Unconfined Parts of the Lesser Aquifers.....	36
Hydrogeological Factors.....	37
Occurrence of Radium Isotopes Among the Aquifers.....	37
Relations of Radium and pH to the Geologic Composition of Aquifer Materials	38
Geographic Distribution of Radium Isotopes within the Lesser Aquifers	39
Regional Significance of Ra-224 Concentrations and Gross Alpha-Particle Activity	40
Comparison of the Occurrence of Ra-224, Ra-226, Ra-228 and Gross Alpha-Particle Activity in the Lesser Aquifers with that in the Kirkwood-Cohansey Aquifer System	40
Comparison of the Occurrence of Ra-224, Ra-226, Ra-228 and Gross Alpha-Particle Activity in the Lesser Aquifers with that in Other Aquifers in the Mid-Atlantic Coastal Plain	41
Summary and Conclusions.....	42
Acknowledgments.....	43
References Cited.....	43
Glossary.....	48
Appendix 1. Construction information for wells sampled for radioactive constituents in water or natural gamma-ray activity in sediment from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and the Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999-2001	52
Appendix 2. Concentrations of radionuclides, major ions, and selected trace elements in equipment blank samples for radionuclide sampling, New Jersey, 1999-2001.....	53
Appendix 3. Concentrations of radionuclides, major ions, selected trace elements in, and physical properties of, water from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and the Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999-2001	57

Figures

1.	Diagram showing Uranium-238 and thorium-232 radioactive decay series.....	4
2.	Map showing location of study area and geologic outcrops in the New Jersey Coastal Plain.....	7
3.	Generalized representation of simulated prepumping flow in a hydrogeologic section through the Coastal Plain of southern New Jersey.....	9
4.	Generalized hydrogeologic cross section along strike of the New Jersey Coastal Plain showing natural gamma-ray logs in the late Cretaceous and Paleocene age hydrogeologic units.....	15
5.	Maps showing location of wells sampled for, and distribution of, Ra-224 concentrations and gross alpha-particle activity in water from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999–2001.....	19
6–8.	Graphs showing—	
6.	Gross alpha-particle activity, and concentrations of radium-224 and radium-226 in water samples collected from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999–2001.....	24
7.	Relation of concentrations of radium-224 to gross alpha-particle activity, and to concentrations of radium-226 and radium-228 in water from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999–2001.....	27
8.	Number of water samples in which the concentration of any radium isotope exceeded 2.5 (pCi/L) picocuries per liter as a function of selected ranges of pH in water from the Vincentown and Wenonah-Mount Laurel aquifers, and the Englishtown aquifer system, southwestern and south-central New Jersey, 1999–2001.....	29
9–10.	Boxplots showing—	
9.	Distribution of gross alpha-particle activity and concentrations of radium-224 and the sum of radium-226 plus radium-228 in water grouped by aquifer confinement status, Vincentown and Wenonah-Mount Laurel aquifers, and Englishtown aquifer system, southwestern and south-central New Jersey, 1999–2001.....	31
10.	Distributions of concentrations of selected major ions, trace elements, and physical properties, grouped by confinement status, Vincentown and Wenonah-Mount Laurel aquifers, and Englishtown aquifer system, southwestern and central New Jersey, 1999–2001.....	32
11.	Stiff diagrams representing the composition of water from the confined and unconfined parts of the Vincentown and Wenonah-Mount Laurel aquifers, and Englishtown aquifer system, southwestern and south-central New Jersey, 1999–2001.....	33

12–13. Graphs showing—	
12. Concentration ratios of (a) bicarbonate to chloride, and (b) sodium to chloride, concentrations of (c) calcium, and concentration ratios of (d) chloride to borate as a function of the distance from the outcrop of the base of the Vincentown and Wenonah-Mount Laurel aquifers and the Englishtown aquifer system, southwestern and south-central New Jersey, 1999–2001.....	35
13. Concentrations of bicarbonate as a function of the concentration of (a) chloride and (b) nitrate plus nitrite in the Vincentown and Wenonah-Mount Laurel aquifers and the Englishtown aquifer system, southwestern and south-central New Jersey, 1999–2001, grouped by whether the sample originated from confined or unconfined parts of the aquifer system	36

Tables

1. Time dependence of alpha-particle activity in picocuries per liter in relation to the concentration of radium-224.....	5
2. Geologic and hydrogeologic units of the New Jersey Coastal Plain.	10
3. Number of wells sampled in each aquifer or water-bearing unit in the New Jersey Coastal Plain for determination of radium-224 and other radionuclide concentrations, 1997–2001, and water withdrawals reported in 2000.....	11
4. Statistical summary of concentrations of radionuclides and selected physical properties and chemical constituents in 39 filtered water samples from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999–2001.....	21
5. Spearman rank correlation coefficients for relations of radium-224, radium-226, and radium-228 to selected constituents in water samples from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and Hornerstown and Red Bank Sands (lesser aquifers), southwestern and central New Jersey, 1999–2001, and the Kirkwood-Cohansey aquifer system, southwestern and south-central New Jersey, 1997–1999.....	28
6. Significance levels (p-values) resulting from the Wilcoxon rank sum statistical test to determine whether concentrations of radionuclides and selected ions, and pH differ in water samples on the basis of aquifer, land-use category, and hydrogeologic status in terms of confinement, Vincentown and Wenonah-Mount Laurel aquifers and Englishtown aquifer system, southwestern and south-central New Jersey, 1999–2001.....	30

Conversion Factors, Datums, and Abbreviations

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
AREA		
square kilometer (km ²)	247.1	acre
square meter (m ²)	10.76	square foot (ft ²)
square kilometer (km ²)	0.3861	square mile (mi ²)
Volume		
liter (L)	0.2642	gallon (gal)
cubic meter (m ³)	264.2	gallon (gal)
Flow rate		
cubic meter per second (m ³ /s)	35.31	cubic foot per second (ft ³ /s)
liter per second (L/s)	15.85	gallon per minute (gal/min)
cubic meter per day (m ³ /d)	264.2	gallon per day (gal/d)
cubic meter per second (m ³ /s)	22.83	million gallons per day (Mgal/d)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
Pressure		
kilopascal (kPa)	0.009869	atmosphere, standard (atm)
kilopascal (kPa)	0.01	bar
kilopascal (kPa)	0.1450	pound per square inch (lb/in ²)
Density		
gram per cubic centimeter (g/cm ³)	62.4220	pound per cubic foot (lb/ft ³)
Radioactivity		
becquerel per liter (Bq/L)	27.027	picocurie per liter (pCi/L)
becquerel per liter (Bq/L)	1	Radioactive disintegration per second
Hydraulic conductivity		
meter per day (m/d)	3.281	foot per day (ft/d)
Hydraulic gradient		
meter per kilometer (m/km)	5.27983	foot per mile (ft/mi)
Transmissivity*		
meter squared per day (m ² /d)	10.76	foot squared per day (ft ² /d)

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

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$$

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

$$^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8$$

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

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

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

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft³/d)/ft²]ft. In this report, the mathematically reduced form, foot squared per day (ft²/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$ at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter ($\mu\text{g}/\text{L}$).

Water-Quality Abbreviations

μm	micrometer
$\mu\text{g}/\text{L}$	micrograms per liter (parts per billion)
mg/L	milligrams per liter (parts per billion)
$\mu\text{g}/\text{kg}$	micrograms per kilogram
g/cm^3	grams per cubic centimeter
pCi/L	picocurie per liter
pCi/g	picocurie per liter
M	molar
Mmol	millimolar
Ac	actinium
Cs	cesium
Pb	lead
Ra	radium
Rn	radon
Th	thorium
U	uranium
LRL	laboratory reporting limit
PE, 2s	precision estimate, 2-sigma
SSMDC	sample specific minimum detectable concentration
<	less than
>	greater than

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By Vincent T. dePaul and Zoltan Szabo

Abstract

This investigation is the first regionally focused study of the presence of natural radioactivity in water from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and the Hornerstown and Red Bank Sands. Geologic materials composing the Vincentown and Wenonah-Mount Laurel aquifers and the Hornerstown and Red Bank Sands previously have been reported to contain radioactive (uranium-enriched) phosphatic strata, which is common in deposits from some moderate-depth coastal marine environments. The decay of uranium and thorium gives rise to natural radioactivity and numerous radioactive progeny, including isotopes of radium. Naturally occurring radioactive isotopes, especially those of radium, are of concern because radium is a known human carcinogen and ingestion (especially in water used for drinking) can present appreciable health risks.

A regional network in southwestern and south-central New Jersey of 39 wells completed in the Vincentown and Wenonah-Mount Laurel aquifers, the Englishtown aquifer system, and the Hornerstown and Red Bank Sands was sampled for determination of gross alpha-particle activity; concentrations of radium radionuclides, major ions, and selected trace elements; and physical properties. Concentrations of radium-224, radium-226, and radium-228 were determined for water from 28 of the 39 wells, whereas gross alpha-particle activity was determined for all 39. The alpha spectroscopic technique was used to determine concentrations of radium-224, which ranged from less than 0.5 to 2.7 pCi/L with a median concentration of less than 0.5 pCi/L, and of radium-226, which ranged from less than 0.5 to 3.2 pCi/L with a median concentration of less than 0.5 pCi/L. The beta-counting technique was used to determine concentrations of radium-228. The concentration of radium-228 ranged from less than 0.5 to 4.3 pCi/L with a median of less than 0.5. Radium-228, when quantifiable, had the greatest concentration of the three radium radioisotopes

in 9 of the 12 samples (75 percent). The concentration of radium-224 exceeded that of radium-226 in five of the six (83 percent) samples when both were quantifiable. The radium concentration distribution differed by aquifer, with the highest Ra-228 concentrations present in the Englishtown aquifer system and the highest Ra-226 concentrations present in the Wenonah-Mount Laurel aquifer. Radium-224 generally contributed a considerable amount of gross alpha-particle activity to water produced from all the sampled aquifers, but was not the dominant radionuclide as it is in water from the Kirkwood-Cohansey aquifer system, nor were concentrations greater than 1 pCi/L of radium-224 widespread.

Gross alpha-particle activity was found to exceed the U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL) of 15 pCi/L in one sample (16 pCi/L) from the Vincentown aquifer. A greater part of the gross alpha-particle activity in water from the Wenonah-Mount Laurel aquifer resulted from the decay of Ra-226 than did the gross alpha-particle activity in the other sampled aquifers; this relation is consistent with the concentration distribution of the Ra-226 itself.

Concentrations of radium-224 correlate strongly with those of both radium-226 and radium-228 (Spearman correlation coefficients, r , +0.86 and +0.66, respectively). The greatest concentrations of radium-224, radium-226, and radium-228 were present in the most acidic ground water. All radium-224, radium-226, and radium-228 concentrations greater than 2.5 pCi/L were present in ground-water samples with a pH less than 5.0. The presence of combined radium-226 and radium-228 concentrations greater than 5 pCi/L in samples from the Vincentown and Wenonah-Mount Laurel aquifers and the Englishtown aquifer system was not nearly as common as in samples from the Kirkwood-Cohansey aquifer system, likely because of the slightly higher pH of water from these aquifers relative to that of Kirkwood-Cohansey aquifer system. Only about 25 percent of the sampled wells in the unconfined parts

2 Occurrence of Radium in Water, Southwestern and South-Central New Jersey

of the aquifers studied contained water with pH less than 5.0, whereas about 75 percent of the wells sampled in the Kirkwood-Cohansey aquifer system contained water with pH less than 5.0.

Introduction

Exposure to naturally occurring radioactivity in varying degrees occurs universally because radionuclides are ubiquitous trace elements in rocks, soils, and waters. Most naturally occurring radionuclides are formed through the decay of uranium-238 and thorium-232. Uranium-235 is a third naturally occurring, long-lived radionuclide; however, its abundance is less than one percent of that of uranium-238. Both uranium and thorium decay slowly to produce other intermediate radioactive elements, such as radium, which in turn undergo still further radioactive decay. These radioactive progenies exhibit different chemical properties, have shorter half-lives, and emit various types of radiation at different rates and energies than do the parent isotopes (Durrance, 1986; Zapecza and Szabo, 1988). Radioactive decay is the emission of particles and energy from the nucleus of an atom (a radionuclide) with an unstable configuration within the nucleus. The emitted particles are classified as either alpha particles (a nucleus of a helium-4 atom) or beta particles (an electron), each with a characteristic level of kinetic energy specific to the nuclide. Energy also is emitted in the form of gamma rays, again with intensity specific to the nuclide. The radiation that is emitted can strip electrons from atoms with which it collides, causing the atom it contacts to become ionized. Cellular tissue can be damaged by exposure to ionizing radiation; this tissue damage can increase the risk of incurring cancer. The ionizing radiation emitted by radium is alpha and beta radiation. Alpha particles move slowly and cannot penetrate skin. Beta particles can penetrate skin but only through the surficial layer. If radium (Ra) is ingested, however, especially dissolved in water, then the emitted alpha- and beta-particle radiation can come into contact with, ionize, and damage internal cell tissue. Radium in drinking water is known to increase cancer risk, primarily bone and sinus cancers (Mays and others, 1985). The risk incurred from the alpha particle emissions depends on the way the body metabolizes the radionuclide ingested (Durrance, 1986, p. 90).

The U.S. Environmental Protection Agency (USEPA) has established a Maximum Contaminant Level (MCL) for Ra in public drinking-water supplies because of health risks associated with the ingestion of Ra. The MCL is 5 pCi/L for combined radium, which is defined as the sum of radium-228 (Ra-228) and radium-226 (Ra-226). The USEPA MCL for gross alpha-particle activity is 15 pCi/L. These MCLs are established on the estimated probability of a 1 in 20,000 risk of incurring a fatal cancer when 2 L (liters) of water containing the contaminant are consumed per day for 70 years. The MCLs had interim status since 1976 and were finalized in

2000 (U.S. Environmental Protection Agency, 1976; U.S. Environmental Protection Agency 2000b). Currently (2006) there is no MCL for Ra-224. The presence of Ra-224 may pose additional quantifiable health risk not currently represented by the USEPA MCL of 5 pCi/L for combined Ra in drinking water. A range of concentration values has been suggested informally for an MCL or action level (AL) for the concentration of Ra-224; but no MCL or AL has been formally proposed in the absence of additional regional data regarding the occurrence of this radionuclide (U. S. Environmental Protection Agency, 2000a). One of the major reasons for the identification of the occurrence and distribution of naturally occurring Ra-224 (or other commonly occurring radionuclides) is that the amount of the radionuclide present represents the real physical phenomenon of radiation to which individuals may be exposed; from this information, the computation of the risk from the radiation can be undertaken on the basis of a risk model such as that used by USEPA (U.S. Environmental Protection Agency, 1999).

Until recent work by Parsa (1998) and Szabo and others (1998; 2005) documenting the abundant presence of Ra-224 in ground water, only long-lived Ra-226 and 228Ra had been documented as present in substantial concentrations in ground water. Because insufficient information on the occurrence of Ra-224 and Ra-228 in drinking-water resources were available (Hess and others, 1985), routine monitoring programs focused on the detection of Ra-226, and a holding time for the gross alpha-particle activity test was not required because of the long half life of Ra-226. As a result of the work of Parsa (1998) and Szabo and others (1998) that shows the presence of Ra-224 and Ra-228 in the acidic water of the Kirkwood-Cohansey aquifer system in southern and east-central New Jersey (Szabo and others, 2005), where elevated radioactivity had not been confirmed before 1998, the State of New Jersey, since September 2002, has required adherence to the 48-hour holding time for gross alpha-particle activity analysis for compliance monitoring (New Jersey Administrative Code, 2002a). The 48-hour gross alpha-particle activity is timely and sensitive enough to detect alpha-particle emissions from Ra-224, not just Ra-226. The New Jersey Department of Environmental Protection (NJDEP) recommends that concerned homeowners have private self-supply well water tested for gross alpha-particle activity (New Jersey Department of Environmental Protection, 1997) and requires such testing at the time of real-estate transaction (New Jersey Administrative Code, 2002a).

A major concern is that in previous (before 1998) routine monitoring programs, the presence of Ra-224, Ra-228, and gross alpha-particle activity may have gone undetected because the focus of the monitoring programs was to detect the presence of Ra-226 (Hess and others, 1985); ingestion of drinking water that contains these radionuclides at the MCLs may have posed a health risk to consumers. It was assumed that with the 48-hour measurement technique, gross alpha-particle activity in excess of the 15-pCi/L MCL will be detected in other aquifers of southern New Jersey. Sand aquifers in

the Coastal Plain other than the Kirkwood-Cohansey aquifer system likely are acidic in some areas and thus present the greatest possibility among other aquifers in New Jersey that elevated (at or near the MCLs) concentrations of radium isotopes and gross alpha-particle activity are present. Detailed investigation was required to determine whether these radioisotopes were present in the other Coastal Plain aquifers. If so, the distribution of the radioisotope(s) in the water of the aquifers could be defined so that those water resource managers, distributors, and consumers that are most likely to be affected can be alerted through NJDEP public health outreach efforts (New Jersey Department of Environmental Protection, 1997; Cohn and others, 2003).

Water samples collected from municipal distribution points may not be representative of the small individual aquifers that may contribute only a small amount of the water to the system. Because of the small areal extent of these sand units from which water is withdrawn for municipal drinking-water supply, multiple wells completed in multiple aquifers are used to provide the water supply, and randomly collected samples from entry points into the distribution system (POEs) represent mixtures of waters from many sources. The presence of elevated concentrations of naturally occurring radionuclides in water from these specific aquifers may not have been detected in routine drinking-water quality monitoring programs that sample distribution points or even POEs that deliver water from multiple sources.

Researchers are seeking to gain a more complete understanding of the nature of the radioactivity in water from aquifer systems in the New Jersey Coastal Plain. Most study efforts to date have focused on water from the acidic sand and gravel Kirkwood-Cohansey aquifer system. As of 1999, a regional investigation of the presence of natural radioactivity in the thin, pre-Miocene lesser sand aquifers of southwestern and south-central New Jersey had not been conducted. Concern has increased with the recent reporting that the geologic materials comprising the Vincentown and Wenonah-Mount Laurel aquifers, and Englishtown aquifer system, contain uranium-enriched phosphatic strata (Sugarman, 1999). These quartzose aquifers, where the gross alpha-particle activity in ground water has not previously (prior to 1997) exceeded the MCL, are nevertheless considered vulnerable because of the known zones of uranium enrichment and because of the acidic waters they contain. Much of the drinking water obtained from these lesser aquifers is from private self-supply wells that likely are not tested for the occurrence of these radionuclides. Water from these lesser aquifers has not been tested extensively for the presence of Ra because of low gross alpha-particle activity in a few samples collected before 1997. Because the outcrops of the Vincentown and Wenonah-Mount Laurel aquifers, and Englishtown aquifer system are overlain primarily by rural residential land, the risk from radionuclide occurrence in ground water, despite the monitoring requirements of the Private Well Testing Act (New Jersey Administrative Code, 2002a), is likely to remain undetected for some time to come as a result of the potentially low frequency of

real-estate transfers and infrequent ground-water sampling in the area. Determining the presence of naturally occurring radioactivity (gross alpha-particle activity), especially the concentration distribution of the isotopes of radium (radium-224, radium-226, and radium-228) in these aquifers is thus of considerable interest to water scientists and water-resource managers in order to determine whether radioactivity is great enough to pose a health risk from the ingestion of drinking water. To address these concerns, this study, one in a series of studies undertaken to understand the radioactivity in water in New Jersey Coastal Plain aquifers, was conducted by the U.S. Geological Survey (USGS), in cooperation with the NJDEP, to evaluate the presence of radium in the lesser aquifers of the New Jersey Coastal Plain.

Purpose and Scope

This report describes the occurrence of gross alpha-particle radioactivity and that of the short-lived isotope of radium, Ra-224 in water in the lesser aquifers in southwestern and south-central New Jersey and compare its distribution to that of the radium isotopes Ra-226 and Ra-228. From 1999 to 2001, water samples were collected from 39 wells. The wells are distributed almost equally among the Vincentown and Wenonah-Mount Laurel aquifers, and the Englishtown aquifer system; one and two samples were collected from the Hornerstown and Red Bank Sands, respectively. Radionuclide concentrations and those of ancillary constituents are detailed in tables. Geological, hydrological, geochemical, and land-use factors that could affect the occurrence of these radionuclides in the water are statistically evaluated. The relations between the occurrence of the radium radionuclides and the concentrations of nitrate in, and the pH of water from, the Vincentown and Wenonah-Mount Laurel aquifers and the Englishtown aquifer system are determined. Lastly, radionuclide distribution in the subregional aquifers is compared to that in the Kirkwood-Cohansey aquifer system.

Naturally Occurring Radionuclide Decay Series

Most naturally occurring radionuclides are formed through the decay of uranium-238 (U-238) and thorium-232 (Th-232). Uranium-235 (U-235) is a third naturally occurring long-lived radionuclide, but its abundance is less than one percent that of U-238. Both U-238 and Th-232 decay slowly (half-lives, 4.5 and 10.1 billion years, respectively) and produce other intermediate radioactive elements, such as radium, which in turn undergo further radioactive decay. The various isotopes of naturally occurring radium are radium-223 (Ra-223), radium-224 (Ra-224), radium-226 (Ra-226) and radium-228 (Ra-228). Ra-224, the fifth radionuclide in the Th-232 decay series (fig. 1), is derived from the decay of thorium-228 (Th-228) and has the shortest half-life (3.64 days) compared to that of Ra-223 (11.43 days), Ra-228 (5.75 years), and Ra-226 (1,602 years). The half-life of a radionuclide is

4 Occurrence of Radium in Water, Southwestern and South-Central New Jersey

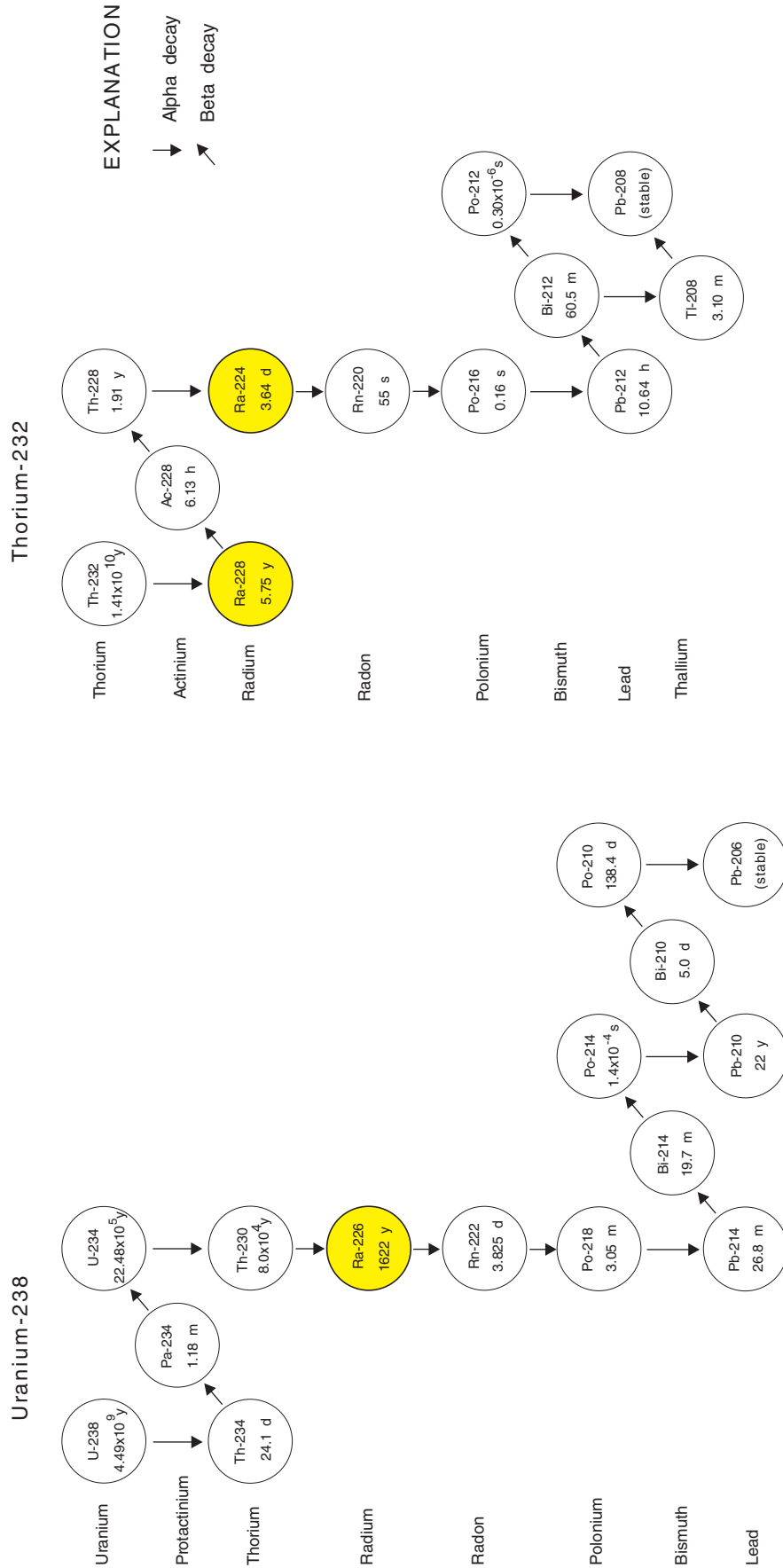


Figure 1. Uranium-238 and thorium-232 radioactive decay series. (Radionuclides of interest in this study are shaded; times shown are half-lives: y, years; d, days; h, hours; m, minutes; s, seconds; modified from Hall and others, 1985).

defined as the time it takes for one half of the original amount of the radionuclide to decay. Radium-223, Ra-224, and Ra-226 decay by emitting an alpha particle, whereas Ra-228 emits a beta particle in decay to actinium-228 (Ac-228) (fig. 1). Radium-224 decays directly to radon-220 (Rn-220), which has a half-life of less than 1 minute, and eventually to stable lead-208 (Pb-208) through other intermediate products; of these products, only lead-212 (Pb-212) has a half-life (10.64 hours) that is longer than one hour (fig. 1). Radium-226 decays to radon-222 (Rn-222), which has a half-life of 3.88 days. Because of the long half-life relative to Rn-220, Rn-222 typically is naturally abundant in ground water, soil gas, and in places in indoor air and thus presents exposure risk to humans, whereas Rn-220 is abundant less frequently than Rn-222 and typically in somewhat unusual circumstances. Radium-223 is derived from decay of uranium-235 (U-235) and is likely to be less abundant than the other naturally occurring radium radionuclides.

Naturally occurring Ra-224, Ra-226, and Ra-228 can enter ground water from aquifer solids by radioactive decay of the parent thorium isotope (Th-228, Th-230, and Th-232, respectively) coupled with alpha recoil, by chemical processes such as the dissolution of aquifer materials or desorption from rock or sediment surfaces, or by radioactive decay of the parent isotope in solution (unlikely except in extremely acidic or alkaline waters because Th, in general, is insoluble (Langmuir and Herman, 1980)). The occurrence, distribution, and concentration of the parent Th-232 and Th-228 radionuclides are, therefore, major controls on the occurrence of Ra-228 and Ra-224. The uranium isotope precursors of Th-230 often control the distribution of Ra-226.

Alpha recoil is a process whereby kinetic energy is imparted to the product nuclide during alpha decay, damaging the crystal lattice surrounding the atom and allowing the atom to break free from the solid structure. Through recoil in the opposite direction from the emitted alpha particle, the product

radionuclide eventually may be preferentially dissolved at the locus of crystal lattice damage (a process termed “track etching” by Fleischer (1980)) or, depending upon the proximity of the parent radionuclide to the mineral-grain boundary, may be emitted directly into water-filled pore space. Once in the aqueous environment, the short half-life (3.64 days), the sorptive properties of the aquifer material, and the overall geochemical setting govern the concentration of Ra-224.

Radium in drinking water is known to increase cancer risk, primarily bone and sinus cancers (Mays and others, 1985). Human bone tissue accumulates radium much like calcium and strontium rather than allowing it to be removed from the body. The bones then are exposed to tissue-damaging alpha or beta radiation. Tissue damage from continuous exposure may cause malignancies. Risk is increased with increased exposure. Mays and others (1985) estimated the cancer risk from Ra-224 to be less than that of Ra-226 because the short half-life limits the radiation dose to the body. Because of the short half-life of Ra-224, however, much of the Ra-224 decays on bone surfaces, where it may have enhanced effectiveness; this concern was mentioned but not evaluated by Mays and others (1985). Recent reevaluation by the USEPA indicates that the lifetime cancer risk from the ingestion of Ra-224 is less than that for ingestion of an equal amount of Ra-226 or Ra-228 (U. S. Environmental Protection Agency, 1999) but is greater than that suggested in the aforementioned study by Mays and others (1985).

Despite the fact that there currently is no MCL for radium-224, its presence is nonetheless of concern. Theoretical calculations by Parsa (1998) indicate that Ra-224, if present, contributes a considerable amount of gross alpha-particle activity to a water sample from the aquifer for about 7 days after sample collection. In fact, the theoretical calculations of Parsa (1998) indicate that for each pCi/L of Ra-224 present in the sample almost 3 pCi/L of gross alpha-particle activity will be present in the sample 48 hours after collection (table 1).

Table 1. Time dependence of alpha-particle activity in picocuries per liter in relation to the concentration of radium-224.

[Modified from Parsa, 1998; pCi/L, picocuries per liter]

Radium-224 (pCi/L)	Time after sample collection (hours)												
	2	4	8	16	24	36	48	72	96	144	192	384	576
	Gross alpha particle activity (pCi/L)												
1	2.99	3.05	3.14	3.2	3.16	2.99	2.77	2.32	1.93	1.32	0.9	0.19	0.04
2	5.98	6.1	6.28	6.4	6.32	5.98	5.54	4.64	3.86	2.64	1.8	0.38	0.08
3	8.97	9.15	9.42	9.6	9.48	8.97	8.31	6.96	5.79	3.96	2.7	0.57	0.12
4	11.96	12.2	12.56	12.8	12.64	11.96	11.08	9.28	7.72	5.28	3.6	0.76	0.16
5	14.95	15.25	15.7	16	15.8	14.95	13.85	11.6	9.65	6.6	4.5	0.95	0.2
6	17.94	18.3	18.84	19.2	18.96	17.94	16.62	13.92	11.58	7.92	5.4	1.14	0.24
10	29.9	30.5	31.4	32	31.6	29.9	27.7	23.2	19.3	13.2	9	1.9	0.4
20	59.8	61	62.8	64	63.2	59.8	55.4	46.4	38.6	26.4	18	3.8	0.8
100	299	305	314	320	316	299	277	232	193	132	90	19	4
375	1121.25	1143.75	1177.5	1200	1185	1121.25	1038.75	870	723.75	495	337.5	71.25	15

6 Occurrence of Radium in Water, Southwestern and South-Central New Jersey

Thus, Parsa (1998) established that determination of the concentration of Ra-224, if present, and measurement of gross alpha-particle activity within 48 hours after sample collection is needed to determine the true amount of alpha-particle activity the consumer is exposed to by the ingestion of drinking water; ingestion in almost all cases occurs in the first few days after withdrawal of water from the aquifer. A concentration of 5 to 5.5 pCi/L is considered appreciable for Ra-224 because these levels result in a gross alpha-particle activity of about the 15 pCi/L (the MCL) 36 to 48 hours, respectively, after sample collection when ingrowth of Ra-224 progeny radionuclides is considered, even with the unlikely assumption that no other alpha-particle emitting radionuclide is present in the water. A concentration of 3.4 to 3.7 pCi/L is considered appreciable for Ra-224 because these levels result in a gross alpha-particle activity of 10 pCi/L 36 to 48 hours after sample collection when ingrowth of Ra-224 progeny radionuclides is considered. In this latter case, it is possible that the summed alpha-particle activity from Ra-226 present in concentrations of 4.9 pCi/L (or some similar appreciable value slightly less than 5 pCi/L, the combined radium MCL) and from Ra-224 present in concentrations of about 3.41 pCi/L or greater could exceed the 15 pCi/L MCL for gross alpha-particle activity.

Description of Study Area

The study area in southwestern and south-central New Jersey, illustrated in figure 2, represents the eastern half of the "Inner Coastal Plain" as originally defined by Muessig and others (1992). The Inner Coastal Plain can be divided into two groups of contiguous areas on the basis of underlying geologic materials. A thin (about 10-mi wide) band extending southwest to northeast (from Delaware Bay, paralleling the Delaware River to Trenton, then paralleling the Fall Line to Raritan Bay) that encompasses the entire outcrop area of mostly clayey and glauconitic sediment of late Cretaceous to Oligocene age (Owens and others, 1998) forms the eastern half of the Inner Coastal Plain and forms the study area. The study area includes all or parts of seven counties in which the geologic formations composing the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and Hornerstown and Red Bank Sands crop out: Monmouth, Ocean, Mercer, Burlington, Camden, Gloucester, and Salem (fig. 2). Upper Cretaceous sandy sediments that crop out along the Delaware River and the Fall Line to the west of the glauconitic sediments represent the sandiest and oldest (middle to late Cretaceous) part of the Inner Coastal Plain. The outcrop of the middle to late Cretaceous age Potomac, Raritan, and Magothy sands together form the unconfined part of the Potomac-Raritan-Magothy aquifer system, the most heavily used aquifer system in southern New Jersey (Nawyn, 1997); this aquifer system is not part of the study. Directly to the east of the outcrop area of the upper Cretaceous to Oligocene glauconitic sediments that forms the study area lies the outcrop area of the Miocene Kirkwood Formation and the Miocene Cohansey

Sand that form the Kirkwood-Cohansey aquifer system, which covers most of the southern New Jersey Coastal Plain and underlies more than 3,000 mi². Radionuclide occurrence in the water of the Kirkwood-Cohansey aquifer system has been extensively studied (Kozinski and others, 1995; Szabo and dePaul, 1998; Szabo and others, 2005).

Geologic Setting

The New Jersey Coastal Plain is a seaward-dipping wedge of unconsolidated sediments of Cretaceous to Tertiary age (fig. 2) with a Quaternary veneer of sediments occurring locally (Olsson and others, 1988). The Coastal Plain sediments thicken to the southeast from a featheredge at the Fall Line to more than 6,500 ft in southern Cape May County (Zapeczka, 1989). Upper Cretaceous and lower Tertiary unconsolidated sediments overlie the bedrock basement and crop out in southwestern and south-central New Jersey. The sediments were deposited in various shelf, marginal marine, nearshore or coastal beach, and deltaic environments, the extent of which fluctuated in response to the relative rise and fall in the mean sea level. The sand units form the aquifers. The presence of abundant fresh water from aquifers has enabled the efficient use of land by a large human population

The sand units that form the aquifers generally consist of the upper parts of upward coarsening depositional sequences (Sugarman and Miller, 1997) and were deposited in inner shelf, nearshore, coastal, and deltaic areas during slow fall (retreat) in mean sea level (regression). Silty, clayey, and glauconitic units form confining units; these were deposited along the middle to outer shelf environment during a rise in mean sea level (transgression). Mean sea level rise relative to the deposition centers led to landward migration of the areal extent of the fine-grained sediments and typically led to burial and preservation of the sandy material. These sequences cycled back and forth on the New Jersey Coastal Plain in Cretaceous and Tertiary time (Sugarman and others, 1993). A section of sediment that contains the deposits from both a regressive and transgressive cycle has been named "the New Jersey cycle" by Sugarman and others (1993). Typically such a cycle might comprise a single member in a geologic formation or might contain several named geologic formations.

Groups of sequences within the large stack of sediments forming the New Jersey Coastal Plain may contain more sand or more silt depending upon whether a large-scale transgression or regression occurred lasting a substantial part of a major period of geologic time. The mineralogic, chemical, and isotopic composition of this stack of sediments from the early Cretaceous time period to modern sediments forming the New Jersey Coastal Plain are complex and their relation to sea level, sediment supply, and climate of the individual time periods were extensively studied to understand the relations between geologic and climatic process, but the exact nature of interactions remain unresolved (Miller and others, 1998a; Miller and others, 2003). Depending upon the relative sea level, a sequence or group of sequences, might be predomi-

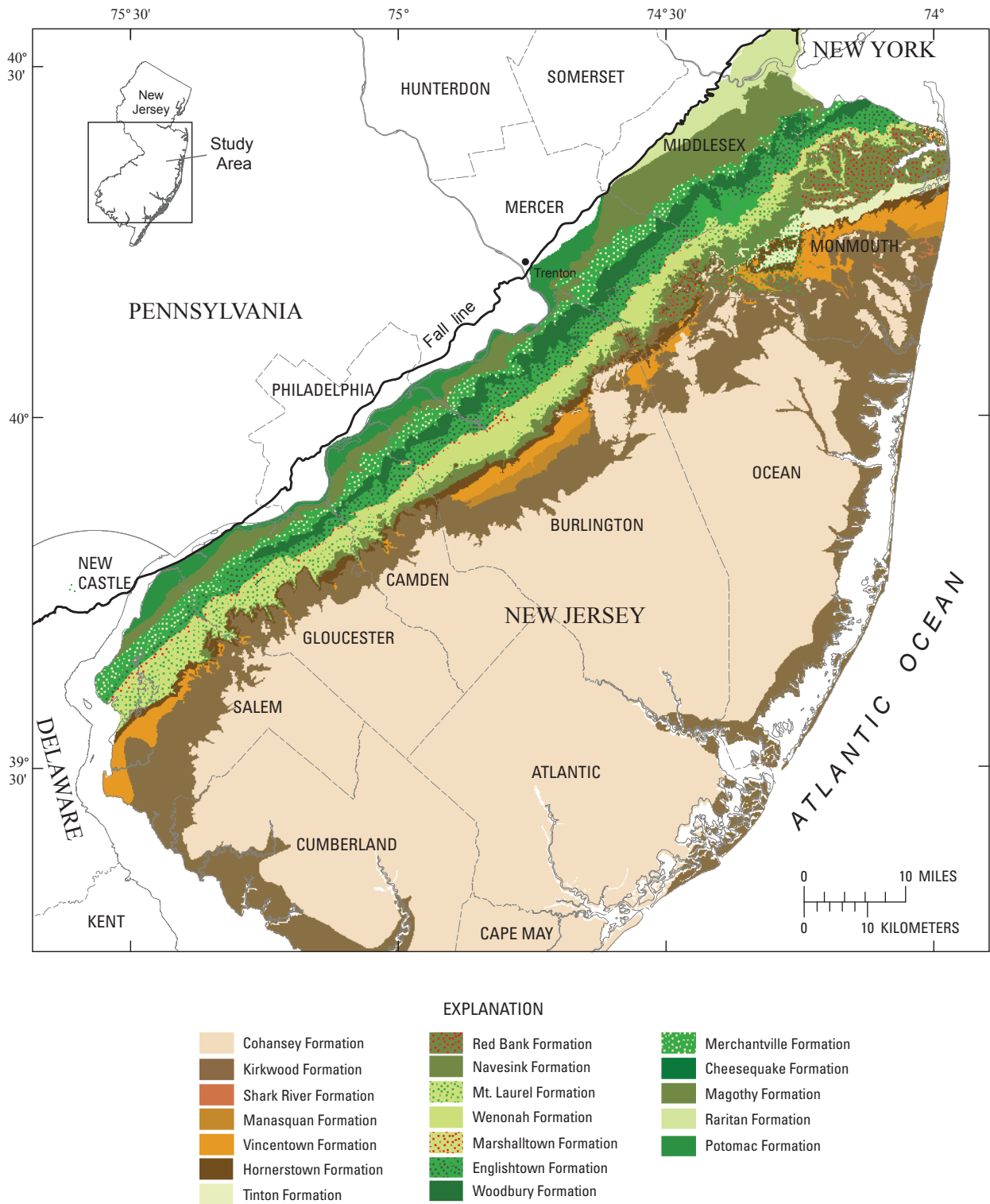


Figure 2. Location of study area and geologic outcrops in the New Jersey Coastal Plain.

nantly formed in marine, marginal marine, or non-marine depositional environments where shelf-, beach-, or fluvial-deltaic-type depositional processes might predominate, respectively. These groups of sequences in the New Jersey Coastal Plain were broadly classified through geologic time by Owens and Sohl (1969).

Substantial sandy units were deposited in the early to late Cretaceous age primarily as fluvial and deltaic deposits, forming sediments of group 1 of Owens and Sohl (1969), and again in the Miocene age. The mostly silty, clayey, and glauconitic units containing only minor amounts of sand were deposited in the late Cretaceous to early- to mid-Tertiary period (Paleocene to Oligocene), representing a long time of substantial rise in sea level (Olsson and others, 1988) resulting primarily in shelf-type deposition with only minor beach- or deltaic-type sedimentation; these form sediments of group 2 of Owens and Sohl (1969). The predominant clay mineral in these marine-deposited formations is montmorillonite, or infrequently, illite (Owens and others, 1961). The relative positions of the sandy aquifer units and silt or clay confining units form the typical tabular confined sand aquifers in the New Jersey Coastal Plain. Substantial sandy units were deposited again in the lower to middle Miocene period in marginal marine environments, forming sediments of group 3 of Owens and Sohl (1969). Surficial fluvial sediments form sediments of group 4 of Owens and Sohl (1969).

Hydrogeologic Setting

The sediments in the study area are primarily silty clays and glauconitic clays interbedded with thin, continuous to discontinuous, mostly marginal marine or shallow marine sand lenses and sheets. The sand lenses and sheets form the aquifers in the area. These thin sands form aquifers that are the predominant or sole source of drinking water in some small and sparsely populated municipalities of southern New Jersey that are centered on the outcrop or are slightly to the east of the outcrop of the geologic formations that form these aquifers. The location of the outcrop of the geologic formations that compose these aquifers is shown in figure 2. The relative positions of the sandy aquifer units and silt or clay confining units are shown in cross-section in figure 3. Delineation of the hydrogeologic units of the region is shown in table 2.

The Wenonah-Mount Laurel aquifer and the Englishtown aquifer system are the most utilized for water supply of these sand bodies (table 3). These aquifers sometimes are referred to collectively as the “lesser aquifers” or “minor subregional aquifers” of southern and central New Jersey because of their limited extent (fig. 2) and limited use (table 3), as opposed to the region-wide use of the more extensive and more productive Kirkwood-Cohansey and Potomac-Raritan-Magothy aquifer systems. In this report, the term “lesser aquifers” will be used to refer to the aquifers collectively. The aquifers do have appreciable importance, especially in Monmouth County in central New Jersey and in Camden and Gloucester Counties in southwestern New Jersey.

Many of the municipalities with large populations use water from these aquifers to augment other sources of water supply. Production wells generally are located only in the most productive parts of the aquifers; in other areas, private self-supply wells are the primary source of potable water. Many private domestic wells in the area draw water from these aquifers. The number of private supply wells that tap the aquifers decreases with increasing depth below land surface of the sand body that forms the aquifer. A recent estimate (2000) indicates that approximately 23 million gallons per day combined was withdrawn from these aquifer systems (table 3), nearly identical to the published estimate from 1994 (Nawyn, 1997).

The limited extent of these lesser aquifers is related to the moderately deep marine depositional environment of all the sand bodies, which typically took the form of offshore sand bars. The exception is the Englishtown Formation that was deposited as a delta of somewhat limited size. Sugarman (1992) and Zapecza (1989) classify the Englishtown aquifer system as a “major” aquifer in New Jersey, but it is considered a subregional (lesser) aquifer in this study. These sands form an important aquifer system in east-central New Jersey, especially in Monmouth County (Nawyn, 1997). The sands of the Englishtown Formation are used minimally as an aquifer system in southwestern New Jersey (except locally in central Camden and Burlington Counties) (Cauller and others, 1999). Leahy and Martin (1993) also do not consider the aquifer system to be highly productive throughout its extent in New Jersey. The other aquifers in the region are clearly classified as minor (lesser): the Vincentown aquifer and Wenonah-Mount Laurel aquifer are used extensively in local areas, primarily in Monmouth County. The basal part of the Wenonah Formation and the thin clayey Marshalltown Formation form the thin, leaky confining unit between the Wenonah-Mount Laurel aquifer and the Englishtown aquifer system (Seaber, 1965). Overlying the Wenonah-Mount Laurel aquifer are several silty and clayey glauconitic, early Tertiary age formations that grade upward into occasional thin sand units that produce water locally. The Vincentown Formation is the most heavily used of these thin sand bodies in the area and, where productive, is called the Vincentown aquifer. Several additional thin sand bodies that produce water locally are the Red Bank Sand and the Hornerstown Sand (Seaber, 1965).

Each of these lesser aquifers is composed of hydraulically conductive, southeastward-dipping sandy geologic formations, interbedded between clay units in the subsurface (Zapecza, 1989). Aquifer thickness ranges from less than 25 ft to approximately 100 ft; the Englishtown aquifer system could be as thick as 200 ft in places. The geologic units are all marine deposits except for parts of the Englishtown Formation (Sugarman, 1992). The units separating the sand units are glauconitic, fossiliferous, marine clays and silts sparsely interbedded with sandy silt. In the subsurface, these clays and silts form confining units. Thick sand bodies that are highly productive are discontinuous or thin rapidly.

The predominant source of recharge is precipitation that falls directly onto the aquifer outcrop. Water is recharged in,

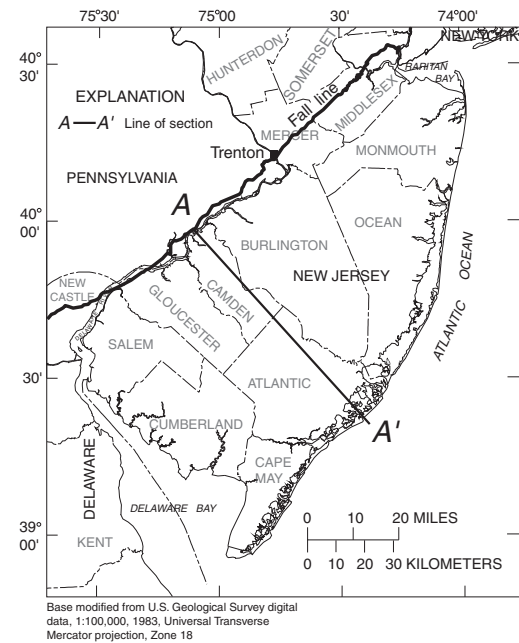
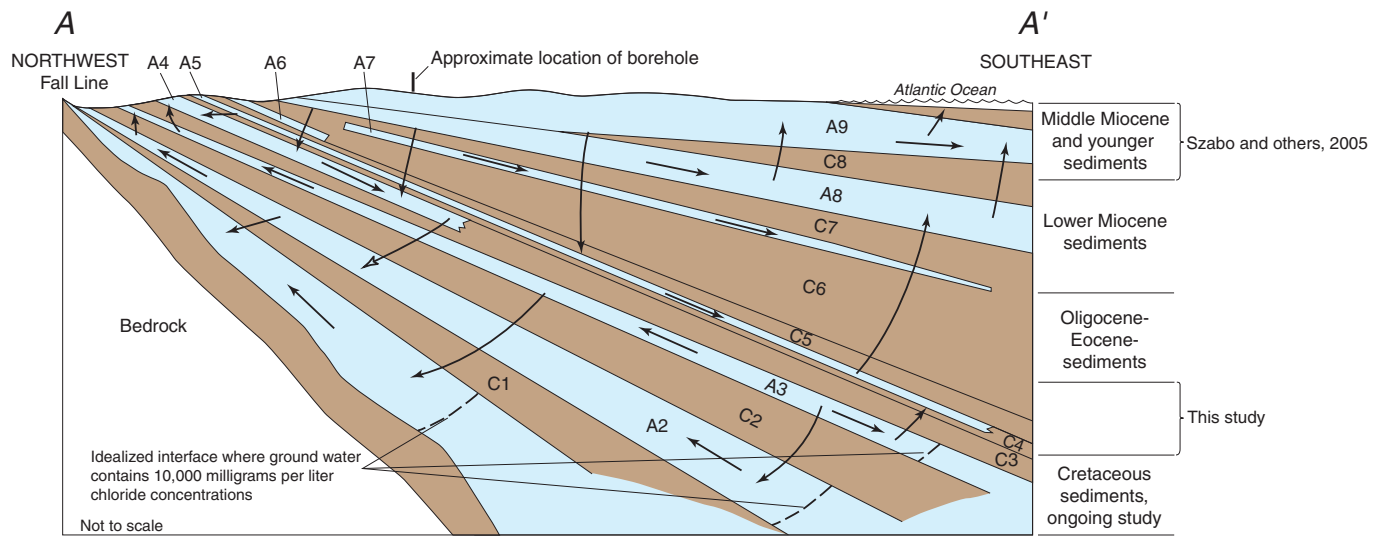


Figure 3. Generalized representation of simulated prepumping flow in a hydrogeologic section through the Coastal Plain of southern New Jersey (Modified from Martin, 1998).

10 Occurrence of Radium in Water, Southwestern and South-Central New Jersey

Table 2. Geologic and hydrogeologic units of the New Jersey Coastal Plain.

[Shaded units are those discussed in this report; *, not designated as a formal aquifer by Zapecza (1989)]

SYSTEM	SERIES	GEOLOGIC UNIT	HYDROGEOLOGIC UNIT	
Quaternary	Holocene	Alluvial deposits	Undifferentiated	
		Beach sand and gravel		
	Pleistocene	Cape May Formation		Kirkwood-Cohansey aquifer system
Tertiary	Miocene	Pennsauken Formation	Kirkwood-Cohansey aquifer system	
		Bridgeton Formation		
		Beacon Hill Gravel		
		Cohansey Sand		
		Kirkwood Formation		“Upper” Wildwood-Belleplain confining unit
				Rio Grande water-bearing zone
				“Lower” Wildwood-Belleplain confining unit
	Atlantic City 800-foot sand aquifer			
	Oligocene	Piney Point Formation	Piney Point aquifer	
	Eocene	Shark River Formation	Composite confining unit	
	Paleocene	Vincentown Formation	Vincentown aquifer	
Hornerstown Sand		Hornerstown Sand*		
Cretaceous	Upper Cretaceous	Tinton sand	Wenonah-Mount Laurel aquifer	
		Red Bank Sand		
		Red Bank Sand		
		Navesink Formation		
		Mount Laurel Sand		
		Wenonah Formation		
		Marshalltown Formation		Marshalltown-Wenonah confining unit
		Englishtown Formation		Englishtown aquifer system
		Woodbury Clay		Merchantville-Woodbury confining unit
		Merchantville Formation		
	Lower Cretaceous	Magothy Formation	Potomac-Raritan-Magothy aquifer system	Upper aquifer
		Raritan Formation		Confining unit
		Potomac group		Middle aquifer
		Confining unit		
		Lower aquifer		
Pre Cretaceous	Bedrock	Bedrock confining unit		

Modified from Zapecza, 1989 and Sugarman, 2001

Table 3. Number of wells sampled in each aquifer or water-bearing unit in the New Jersey Coastal Plain for determination of radium-224 and other radionuclide concentrations, 1997–2001, and water withdrawals reported in 2000.

[Aquifers sorted youngest to oldest; NA, not applicable; **bold**, radium-224 data presented in this report; withdrawal data from unpublished data on file at New Jersey Water Science Center; <, less than]

Number of sampled wells for this study	N.J. Coastal Plain aquifers or water bearing units	Withdrawal (Million gallons per day)	Radium-224 concentration data reported
NA	Kirkwood-Cohansey aquifer system	81	Szabo and others, 2005
NA	Atlantic City 800-foot sand	21	Unpublished
NA	Rio Grande water bearing zone	<1	Not sampled
10	Vincentown aquifer	1	This study
2	Hornerstown Sand	<1	This study
NA	Tinton Sand	<1	Not sampled
1	Red Bank Sand	<1	This study
12	Wenonah-Mount Laurel aquifer	7.5	This study
14	Englishtown aquifer system	7.7	This study
NA	Potomac-Raritan-Magothy aquifer system	146	Focazio and others, 2001

and flows downgradient from, surficial outcrops of each of the sand deposits present along a ridge of topographic highs located primarily in southwestern and south-central New Jersey. The sandy area of the outcrop (fig. 2) provides the predominant source of recharge for the subsurface confined parts of the aquifers (fig. 3; Martin, 1998). Shallow ground water flows from the topographic highs either to local streams in the outcrop area or along deep flow systems to discharge to the Delaware Bay (Martin, 1998). Less than 10 percent of the recharge water passes vertically through the confining units to the aquifer beneath (Martin, 1998). The aquifer systems are conductive, but conductivity generally decreases downdip (to the southeast) where the formations generally become silty. Martin (1998) provides a large-scale numerical flow model of the region, which has been used to evaluate the regional flow system.

Vincentown Aquifer

The Vincentown Formation in outcrop (fig. 2) and in the shallow subsurface (fig. 3) is dominated by brown, gray, or dark greenish-gray medium-grained massive quartzose sand that forms the Vincentown aquifer. Locally, there are abundant shell materials, glauconite, and mica. Facies range from medium-grained massive quartz sand to somewhat finer-grained glauconitic and shelly sand. The depositional environment was massive, nearshore marine sand, possibly an offshore sand bar, containing small dispersed patch reefs (Sugarman, 1992). The formation is the most rich in shell beds of all the sandy formations in the New Jersey Coastal Plain and is the only one with extensive calcite cement (Owens and others, 1961). The formation is thickest (more than 100 feet thick) in

Monmouth County in east-central New Jersey, the area where it is used mostly for water supply. The formation grades to silty sand then to silt downdip from the outcrop (Olsson and others, 1988; Sugarman, 1992). A thick, clayey, glauconitic shell bed is found at or near the base of the formation; this could be a zone of elevated concentrations of radionuclides. The frequently occurring fine-grained and radioactive strata in the sediment composing the Vincentown aquifer causes elevated gamma-ray readings on borehole geophysical logs that may make identification of the unit from that data difficult (Zapecza, 1989). Beyond Monmouth and Ocean Counties, the Vincentown Formation is silty and produces appreciable quantities of water only locally; the Vincentown aquifer is not an important source of water in any part of southwestern or south-central New Jersey.

Hornerstown and Red Bank Sands

The Hornerstown Sand is clayey coarse- to medium-grained glauconitic sand. The base is unconformable with the underlying formations (Owens and others, 1998), is extremely glauconitic (Owens and others, 1961; Olsson and others, 1988) and occasionally contains uranium-rich phosphate (Sugarman, 1998). The formation is thin (5–25 feet) and spotty in occurrence. For much of its extent, the Hornerstown Sand overlies the dark gray to black typically radioactive (phosphorite-rich) Navesink Formation. Because of the frequent occurrence of radioactive phosphorite-rich beds in each formation, they are difficult to distinguish solely by borehole gamma-ray measurement (Zapecza, 1989). The occurrence of the productive sand unit is so infrequent that the Hornerstown Sand is not even considered a local aquifer (Zapecza, 1989) except in parts of

eastern Monmouth County. For individual wells, it is difficult to distinguish whether the screen is placed in the Hornerstown, Red Bank, or Tinton Sand because the occurrence of each is so limited.

The Red Bank Sand consists of two fine-grained sand members that are gray, micaceous, quartzose, and only slightly glauconitic. The basal unit is conformable with the underlying Navesink Formation, is gradational in texture, and locally may be strongly glauconitic (Owens and others, 1998). This basal unit typically is dark in color, silty to clayey, and micaceous. Radioactive strata at the base occur sporadically. The upper sand is fine- to coarse-grained, locally is slightly glauconitic, and typically is thicker and coarser-grained than the basal sand. The contact between the two sand lithofacies is gradational. The sand unit is thickest (100–150 ft) in Monmouth County but is spotty in occurrence to the southwest. Where the sand is thickest in Monmouth County, it can be distinguished by low gamma radiation from the surrounding units (Zapecza, 1989). The formation becomes silty downdip from the outcrop. The Red Bank Sand produces substantial quantities of water locally, primarily in eastern Monmouth County. The Red Bank Sand is classified an unmapped lesser aquifer by Zapecza (1989).

Wenonah-Mount Laurel Aquifer

The Wenonah-Mount Laurel aquifer is composed of the sand of the Mount Laurel Formation (fig. 2) and locally the upper part of the Wenonah Formation (fig. 3) where this latter unit is not composed predominantly of silt. The Mount Laurel Formation is a pale olive, slightly clayey, slightly glauconitic fine- to medium-grained massive to bedded quartz sand with scattered mica, siderite, and phosphate grains and lignite fragments throughout. Shell beds are common and contain many species and multiple fauna (Minard and others, 1961). The formation is moderately thin (5–60 ft thick) and the sandy part can be spotty in occurrence. The formation can change locally within a short distance from the medium-grained sand to dark greenish gray, slightly micaceous, glauconitic silt with intermixed very fine sand. A layer of uranium-rich phosphate pebbles typically characterizes the upper boundary of the Mount Laurel Formation with the overlying Navesink Formation throughout much of the Coastal Plain (Sugarman, 1998). The upper parts of the Wenonah Formation consist of very slightly glauconitic, micaceous, carbonaceous, fossiliferous, clayey fine sand or silt with abundant lignite fragments. Pyrite is occasionally present (Owens and others, 1961). The Wenonah Formation grades to silt at its base. It is moderately thin (5–60 ft thick), and the sandy part often forms only the upper half or upper third of the unit. The formations were deposited in shore face marine environments; the sandy parts were deposited as offshore sand bars or submerged delta fronts (Sugarman, 1992). Locally, the sand-on-sand contact can result in a single silt-sand aquifer that varies in thickness. The productivity at any location is based on the thickness and silt content of the materials composing the aquifer. The

aquifer system is thickest (about 100 ft thick) in southwestern New Jersey (western Salem, and central Gloucester and Camden Counties) where it is used mostly for water supply. To the southwest (Salem County), the silt content increases and the productive sands decrease accordingly. The aquifer also is used for water supply in central and eastern Monmouth County. Large cones of depression are present in central Gloucester and Camden Counties and central Monmouth County (Lacombe and Rosman, 2001).

Englishtown Aquifer System

The Englishtown Formation (fig. 2) is fine- to medium-grained feldspathic and quartzose, pink to gray sand that occasionally grades to shelly, slightly sandy, micaceous, feldspathic, occasionally pyritic, and carbonaceous or lignitic silt. Even fossilized logs are known to be present. These features are indicative of deposition in a deltaic environment. The formation is thickest (200 ft) in Monmouth County (Sugarman, 1992) and remains sandy and thick a substantial distance downdip from the outcrop (fig. 3); thus, it can produce significant quantities of water in Monmouth County and Ocean County. The Englishtown Formation thins considerably to the southwest, and sandy units become thin and erratic in occurrence in southwestern New Jersey (fig. 3) (Zapecza, 1989) where slightly shelly silt beds predominate (Minard and Owens, 1960; Olsson and others, 1988). Minard and Owens (1960) hypothesize that the distal parts of the small delta forming the sandy deposits of the Englishtown Formation were rapidly inundated by seawater in response to possible local subsidence.

The Englishtown aquifer system is a major source of water in Monmouth and Ocean Counties (Seaber, 1965; Nichols, 1977; Zapecza, 1989; Sugarman, 1992; Leahy and Martin, 1993; Nawyn, 1997). A large cone of depression, present in eastern Monmouth County and northeastern Ocean County (Lacombe and Rosman, 2001), was reported as long ago as 1965 (Seaber, 1965). The geochemical evolution of water chemistry downdip along flowpaths of the confined part of the Englishtown aquifer system (fig. 3) in east-central New Jersey, which ranges from calcium bicarbonate type to sodium bicarbonate type, is documented by Seaber (1965) and Back (1966). Transmissivity in the Englishtown aquifer system decreases strongly to the southwest as the geologic material becomes fine-grained (Nichols, 1977), and little water is produced from the aquifer in the southwestern part of the State (Zapecza, 1989).

Land Use

The area underlain by the outcrops of the formations composing the Vincentown and Wenonah-Mount Laurel aquifers, the Englishtown aquifer system, and Red Bank Sand is almost equally divided among urban, agricultural, and non-developed land uses (Anderson and others, 1976). Urbanization/suburbanization has increased substantially from 1986 to

1997, primarily on land formerly used for agricultural purposes. The net increase in urban land is approximately 19,000 acres from the combined areas of the geologic outcrops; this urbanization has occurred mostly in central Monmouth, central Burlington, and central Gloucester Counties.

Previous Investigations of Radionuclide Occurrences in Water and Sediment in Southern and Central New Jersey

Previous investigations of the general radioactivity of the Coastal Plain of New Jersey indicate that while radioactivity in sediment is typically low, there is substantial variability among formations and even among individual strata within formations. Many of the formations comprising the “inner” Coastal Plain region, including those that compose the aforementioned lesser aquifers are somewhat more radioactive than other Coastal Plain formations on either the local or the lesser scale. Information concerning radioactivity in water is geographically much more limited than those concerning the sediment. The USGS in cooperation with the NJDEP has conducted a series of detailed studies of natural radioactivity in water in the southern New Jersey Coastal Plain, but most of the efforts to date have focused on water from the sand and gravel Kirkwood-Cohansey aquifer system.

Ground Water

Zapeczka and Szabo (1989) first reported that elevated radium concentrations (greater than 5 pCi/L) in ground water in southern New Jersey are found in the Kirkwood-Cohansey aquifer system associated with the outcrop of the Bridgeton Formation. The presence of elevated concentrations of Ra-226 and Ra-228 in water from the Kirkwood-Cohansey aquifer system were detailed by Kozinski and others (1995) and Szabo and dePaul (1998). Kozinski and others (1995) found that concentrations of Ra were highest in acidic (pH less than 4.8), shallow to medium-depth water containing concentrations of nitrate greater than 3 to 5 mg/L. Kozinski and others (1995) also demonstrated that agricultural land is most likely to be found overlying the Bridgeton Formation outcrop. Szabo and others (1997) with the use of geochemical models indicated that acidification, desorption, and ion-exchange are the geochemical processes likely result in the preferential occurrence of Ra with acidic, nitrate-bearing water and that this correspondence does not occur by chance. Thorough evaluation of flow path orientations, water residence times, and geochemical processes for parts of the Kirkwood-Cohansey aquifer system, all of which might affect radium occurrence in the water, were conducted by Szabo and others (1996), Szabo and others (1997), Rice and Szabo (1997), and Kaufman and others (2001).

The presence of Ra-224 in the Kirkwood-Cohansey aquifer system was initially documented by Parsa (1998) and Szabo and others (1998). Using samples from the aquifer,

Parsa (1998) established that measurement of gross alpha-particle activity within 48 hours after sample collection is important to determine the true amount of alpha-particle activity in the water if Ra-224 is present. The work of Szabo and others (2005) indicates that Ra-224 is widely prevalent in water from the Kirkwood-Cohansey aquifer system and also is associated with acidic water.

In their initial compilation of radon-222 concentrations in ground waters in New Jersey, dePaul and others (2000) indicated that concentrations between 300 and 4,000 pCi/L are found in townships in the southwestern and central parts of the State. The townships that contain water with radon concentrations in this range are underlain by the western part of the Kirkwood-Cohansey aquifer system, especially where the Bridgeton Formation is present, the Potomac-Raritan-Magothy aquifer system, the Vincentown and Wenonah-Mount Laurel aquifers, and the Englishtown aquifer system. Because the compilation was completed on the regional scale, the aquifer in which the sampled wells were screened was not always identified and radon-222 concentration distribution characteristics could not be described in terms of source aquifers.

Discussion and description of the issues concerning radioactivity in water from the Kirkwood-Cohansey aquifer system from a public health perspective were provided by the NJDEP (New Jersey Department of Environmental Protection, 1997). The NJDEP recommends that homeowners in southern New Jersey in order to save laboratory costs can assume that all gross alpha-particle activity present in private self-supply wells is from radium, and when the gross alpha-particle activity is greater than 5 pCi/L, the MCL for combined radium, the homeowners consider taking action to reduce radium exposure through ingestion by treating the water or by selecting an alternate source. The New Jersey Department of Health and Senior Services (NJDOHSS) documented increased frequency of bone cancer occurrence in parts of the State where radium in drinking water is high (greater than the MCL) (Cohn and others, 2003).

Sediment

Many of the formations that compose the local lesser aquifers are somewhat more radioactive than the other formations in the New Jersey Coastal Plain. The radioactivity in the sediment has been investigated both on regional and local scales. Duval (1991) in a comprehensive regional investigation indicates that regions overlying the “inner” Coastal Plain contained the most radioactive sediments in southern New Jersey. The areas where natural surficial gamma radioactivity is most elevated relative to the rest of the southern New Jersey region overlie the Vincentown Formation and associated Paleocene glauconitic clays and marls. Muessig and others (1992) in a follow-up investigation similarly identify local surficial gamma anomalies in this region. The gamma anomalies appear to be associated most typically with the Vincentown Formation, Hornerstown Sand, Red Bank Sand, and Navesink Formation in Burlington and Monmouth Counties. Notable

gamma anomalies in association with glauconitic beds and phosphatic pebbly shell beds in the Vincentown Formation, Navesink Formation, and the Hornerstown Sand have been detected in subsurface geophysical logging operations at individual wells and are described by Rosenau and others (1969), Zapezca (1989), and Miller and others (1998b; 1999). Natural gamma-ray geophysical logs along a hydrologic section parallel to strike along the entire southern New Jersey Coastal Plain consistently indicate the increase in natural gamma-ray activity especially for the Navesink Formation, Vincentown Formation, and the Hornerstown Sand, though locally the Mount Laurel Sand, the Wenonah Formation, and even the Englishtown Formation have elevated natural gamma-ray activity two to four times that of typical radioactivity for the geologic strata of the region (fig. 4).

The exact stratigraphic position of the radioactive layers differs within the individual formations locally. The occurrence of elevated gamma radioactivity typically is related to stratigraphic sequence boundaries (Miller and others, 1998b). The exact position of the stratigraphic sequence boundaries differs within the individual formations in terms of thickness of the formations (Miller and others, 1998b).

Gundersen and Peake (1992) document that the highest concentrations of radon in soil gas in southern New Jersey are in soils developed on the Englishtown and Navesink Formations, and the Hornerstown Sand; radon concentrations in the New Jersey Coastal Plain are, in general, directly proportional to uranium concentration in the accompanying geologic strata (Szabo and others, 1997). Gundersen and Peake (1992) measured the highest concentration (16, 200 pCi/L) of radon in soil gas overlying the Navesink Formation in southwestern New Jersey and report that the second and third highest concentrations are in soils developed on the Hornerstown Sand and Englishtown Formation, respectively. They also report somewhat elevated concentrations of radon gas in soils that overlie the Wenonah and Mount Laurel Formations. Gundersen and Peake (1992) note the occurrence of phosphatic materials in the Navesink and Englishtown Formations and hypothesize that these are uranium-rich. They also hypothesize that the glauconite in the Hornerstown Sand, Mount Laurel Sand, and Wenonah Formations may be a source of the radon in the soils overlying those formations. Glauconite is sparse in the Englishtown Formation and has not been substantiated as the source of elevated radon there, although Miller and others (1999) document glauconite-rich layers within the Englishtown Formation that are associated with elevated natural gamma-ray activity.

Thin zones of uranium enriched strata within the geologic materials composing parts of the Vincentown and Wenonah-Mount Laurel aquifers, the Englishtown aquifer system, and the Hornerstown and Red Bank Sands have been studied by Sugarman (1999). Phosphatic uranium-rich nodules or beds are present at the contacts between the Hornerstown Sand, the Tinton Sand, and the Navesink Formations and between the Mount Laurel Sand and the Navesink Formations. Sugarman (1999) reports a maximum concentration of U of 46.5 ppm

(parts per million) at the Navesink Formation and Mount Laurel Sand contact. Uranium-rich basal strata are present within the Englishtown Formation, but Sugarman (1999) does not use the term "phosphatic" to describe them. A zone of radioactive shell beds is described by Miller and others (1999) near the top of the Hornerstown Sand in Camden County.

Zapezca and Szabo (1989) report that elevated surficial natural gamma-ray activity also is associated with the outcrop of the Bridgeton Formation. The Bridgeton Formation is present in a few areas overlying some of the aquifers of interest in this study, especially in southwestern New Jersey, but the greatest areal extent of the Bridgeton Formation overlies the Kirkwood Formation and the Cohansey Sand. The contribution from the Bridgeton Formation to the elevated natural gamma-ray activity reported within the study area is thus limited.

Methods

A regional network of 39 wells was sampled in order to assess the distribution of gross alpha-particle activity as well as the concentration of Ra-224 and other radium isotopes and concentrations of inorganic constituents in the water of the Vincentown and Wenonah-Mount Laurel aquifers, the Englishtown aquifer system, and the Hornerstown Sand and Red Bank Sand. Water from all the wells was analyzed for gross alpha-particle activity, and water from 28 of the 39 also was analyzed for the concentration of Ra isotopes. Statistical methods were used to compare the distributions of Ra radionuclides to ancillary water constituents. Comparison with land-use characteristics was given only a cursory examination with only minimal statistical tests because too few samples were collected to ensure adequate numbers for characterization of selected land-use categories.

Design of Sampling Network

The 39 wells were selected for the sampling network to provide an approximately equal number of sampled wells to represent the following groups (aquifers): Vincentown aquifer plus Hornerstown and Red Bank Sands (13 wells), Wenonah-Mount Laurel aquifer (12 wells), and Englishtown aquifer system (14 wells). The regional network of sampled wells was designed to be generally representative of the entire areal extent of the aquifers in the study area, although sampling density was not uniformly distributed over the extent of the aquifers. The somewhat limited extent of the number of sampled wells and their limited distribution is related in part to the moderately deep marine depositional environment of all the sand bodies that formed as offshore sand bars, resulting in the somewhat localized occurrence of sand bodies thick enough to be productive aquifers. Of the groups, the Englishtown aquifer system, was sampled most uniformly in the broadest area because the sediments forming it, while deposited as a

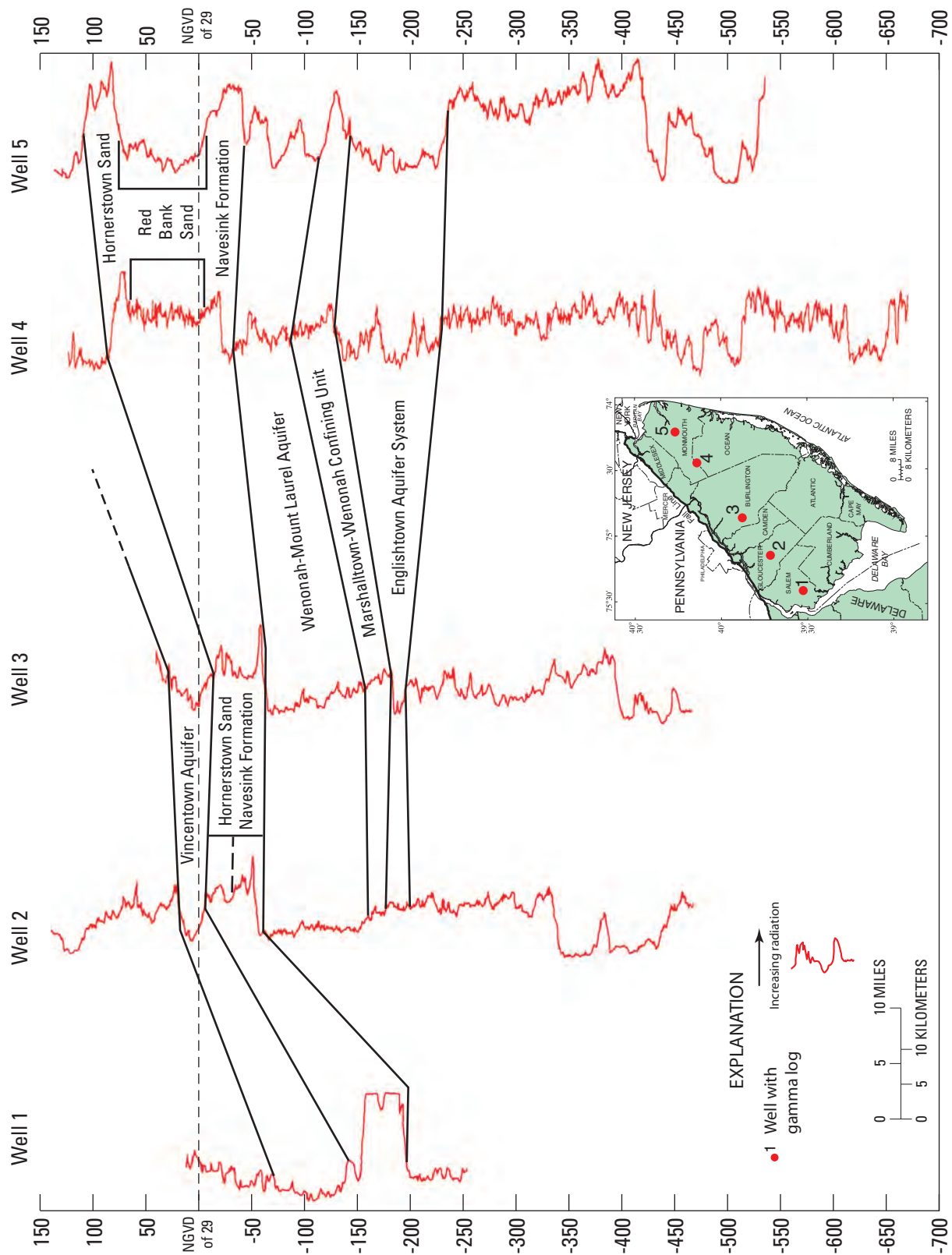


Figure 4. Generalized hydrogeologic cross section along strike of the New Jersey Coastal Plain showing natural gamma-ray logs in the late Cretaceous and Paleocene age hydrogeologic units (Modified from Zapezca, 1989).

delta of limited size, are moderately thick throughout most of their extent. Preference in sample locations was given to areas where extensive withdrawals are made for drinking-water supply. Thus, most sampled wells completed in the Vincetown aquifer plus Hornerstown Sand and Red Bank Sand (8 of 13 wells) are in Monmouth County, sampled wells in the Wenonah-Mount Laurel aquifer are primarily in Salem County (4 of 12) and Monmouth County (6 of 12), and most sampled wells in the Englishtown aquifer system (8 of 14 wells) are in the adjoining areas of Mercer, Monmouth, and Ocean Counties (fig. 2). Regional differences in aquifer hydrology and chemistry were addressed in the selection process by choosing wells in as many of the areas with substantive water use as possible and including wells completed in both unconfined and confined parts of the aquifers. A larger number of wells in unconfined parts of each aquifer were selected to test the hypothesis that hydrological and chemical conditions conducive to the mobilization of Ra and similar to those present in the Kirkwood-Cohansey aquifer system (unconfined with low pH and high nitrate concentrations) also are present in these aquifer systems; these wells also were selected to determine effects of land use on water quality. The wells in the developed areas were distributed about evenly between agricultural and residential areas. Sampling density was lowest in the central part of the outcrop area of the aquifers, specifically Burlington County because of the sparse population in the area (Watt, 2000). The selected wells are distributed in 16 drainage basins (Hydrologic Unit Code 11; see Ellis and Price, 1995, for definition) that cover approximately 62 percent of the total surface area of the outcrop of the aquifers.

The sampling network includes 11 community wells, 11 private self-supply and irrigation wells, and 17 observation wells (appendix 1). Observation wells and private self-supply wells form the majority of the well network because, in most areas where these aquifers are present, production wells do not exist, because either population is sparse (rural communities) or the aquifer is not thick and productive enough to support a large volume of pumping. The observation wells were used to supplement private self-supply wells to maximize the geographic distribution of water-quality data collected. Information on the construction, altitude, and location of wells included in this report (appendix 1) are stored in the Ground-Water Site Inventory (GWSI) database maintained by the USGS. In this database, wells are assigned a 6-digit unique well number that consists of a 2-digit county code followed by a 4-digit sequence number. County codes used in this study are 05 (Burlington), 07 (Camden), 15 (Gloucester), 21 (Mercer), 25 (Monmouth), 29 (Ocean), and 33 (Salem). Well number 051478, for example, is the 1,478th well inventoried in Burlington County. Data tables in the appendixes are not sorted by the USGS well number, however, but by aquifer and geographic location, south to north, to facilitate hydrologic and geographical analysis of the data. The USGS well number is reported to facilitate comparison with previously published data using the USGS well numbers. The quality-assurance data and water-quality data reported in appendixes 2 and 3

are stored in the USGS National Water Information System (NWIS) database.

Sampling Procedures

Samples were collected using “ultra-clean” field techniques designed for low-level trace element sampling in order to eliminate possible contamination from airborne particulates, sample handling, and manufacturing or detergent residues as described by Ivahnenko and others (1996). Samples were collected only after the evacuation of three borehole volumes of water and upon stabilization of field parameters (pH, water temperature, dissolved oxygen, specific conductance and turbidity (Wilde and Radtke, 1999)). Observation wells were sampled using a portable variable-speed stainless steel submersible pump cleaned in the laboratory between each sample collection (Ivahnenko and others, 2001). All samples for radionuclides, trace elements, major cations, nutrients, and anions were filtered using a 0.45 micron disposable polysulfone capsule filter and were collected within a portable glove chamber (Ivahnenko and others, 1996). Samples for analysis of radionuclides, trace elements, and major cations were preserved within a separate portable glove chamber onsite immediately upon collection with laboratory-grade nitric acid. Filters and sample tubing were discarded after a single use.

Quality-Assurance Program

The quality-assurance program included 11 field-equipment blanks and a sequential duplicate sample that were collected randomly throughout the sampling period. Approximately 33 percent of the samples were submitted to the laboratory with accompanying equipment blanks; one sample was collected with a sequential replicate submitted as a blind sample to the analyzing laboratory. The equipment blanks, using USGS certified inorganic blank water (IBW), were collected both in the field and the laboratory using the same protocols as the environmental samples. Results from equipment blanks (appendix 2) were closely monitored to ensure that contamination of the samples had not occurred during the field sampling process or during handling in the laboratory. The equipment blanks were analyzed for concentrations of a wide variety of constituents including trace elements and radium isotopes, which are indicative of contamination during sample handling.

Analytical Methods

Water samples were analyzed for Ra-224 and Ra-226 using alpha spectrometry, a procedure widely used for the first time by Focazio and others (2001). Concentrations of individual radionuclides other than Ra-224 and Ra-226 were determined using standard methods approved by the USEPA (Krieger and Whittaker, 1980).

Radium-224 and Radium-226

The alpha-spectrometric technique used was slightly modified from the initial method of Sill and others (1979) and Sill (1987). The advantage of alpha spectrometry to analyze for Ra-224 and Ra-226 concentrations relative to other analytical methods is that the technique can be used to determine the concentration of these and the other alpha-particle emitting radionuclides of radium (Ra-223) from one sample aliquot. Furthermore, background activity of the alpha-particle counting instruments typically is very low (Knoll, 1989) unless the counting chamber or detector itself has been contaminated with alpha-emitting radionuclides from a poorly prepared, highly radioactive, or gaseous sample; low background activity allows for quantification of very low concentrations. Determination of the concentrations of Ra-224 and Ra-226 requires the isolation of radium from the water sample by co-precipitation with a barium-sulfate carrier and purification of the precipitate, which is then collected on filter paper (Sill and Williams, 1981). The radium-bearing barium sulfate precipitate is placed in a vacuum chamber at a standard distance (determined and fixed within each laboratory to optimize counting efficiency based on the detector geometry) from the silicon semiconductor detector. Uniform size of these crystals is necessary to ensure that the radium is a uniform distance from the detector across the entire precipitate-bearing planchet (Sill and Williams, 1981; Focazio and others, 2001). The uniform sample geometry improves the precision and accuracy of the alpha spectrometry measurement technique for Ra. The detector can determine the amount of alpha radiation that is emitted at known energies enabling quantification of individual radionuclide concentrations on the basis of the known energy of emissions for each radionuclide and the magnitude of the detector response at the energies. The alpha-spectrometric determination of Ra-224 concentrations required a single count for 100 minutes. After the counting procedure was complete, the concentration of Ra-224 and of Ra-226 was calculated back to the time of sample collection using the known rate of radioactive decay.

Radium-228

Concentrations of radionuclides other than Ra-224 and Ra-226 were determined using standard methods approved by the USEPA (Krieger and Whittaker, 1980; U.S. Environmental Protection Agency, 1997). Concentrations of Ra-228 were determined primarily by the beta counting of the ingrown Ac-228 progeny (Krieger and Whittaker, 1980; U.S. Environmental Protection Agency, 1997).

Gross Alpha-Particle and Beta-Particle Activities and Radon-222

Gross alpha-particle and beta-particle activities were analyzed within 48 hours (maximum allowable, 72 hours)

after sample collection, as recommended by USEPA (U.S. Environmental Protection Agency, 2000b) on the basis of studies of Parsa (1998) and Szabo and others (1998) and were determined using planchet counting for 100 minutes with thorium-230 (Th-230) and cesium-137 (Cs-137) as the standards. Unlike the approach for individual radionuclide concentrations, neither gross alpha-particle nor gross beta-particle activity was calculated back to the time of sample collection because these measurements represent the overall alpha-particle and beta-particle activity of the mix of all the radionuclides present in the sample in the given period of time when the measurement was made. Unless the concentration of all the radionuclides present in the sample is specifically known, time-dependent corrections of gross alpha-particle and beta-particle activities cannot be made. Concentrations of radon-222 (Rn-222) were determined by liquid scintillation counting within 48 hours of collection (Pritchard and Gesell, 1977).

Reporting of Results of Analysis of Radionuclides

The raw, unrounded values for all radionuclide concentrations or activities in picocuries per liter (pCi/L) are reported directly by the laboratory. The laboratory also reports the precision estimate (PE), which is another term for measurement uncertainty or measurement error, computed at two-standard deviations about the count value (and thus labeled 2-SIGMA PE). The laboratory used for each analysis provides the 2-Sigma PE because the rate of radioactive decay varies at any instant in time even if the long-term decay rate is stable. The degree of error of the radioactivity measurement is the confidence interval expressed as two standard deviations – that is, 95 of 100 measurements of radioactivity of the sample would fall in the range denoted by the reported radioactivity, plus or minus the reported degree of error.

Background activity of the alpha-particle counting instruments typically is low because alpha particles are strongly attenuated in air (Knoll, 1989). For analysis with low background, the sample-specific minimum detectable concentration (SSMDC) for each sample is computed individually on the basis of the instrument operating conditions at the time of analysis. This minimum quantity generally differs from the background count by three times the standard deviation of the background count. The SSMDC is reported in appendixes 2 and 3 for each analysis (in the column designated SSMDC) for each radionuclide, when available. Because gross alpha-particle and gross beta-particle activity are somewhat insensitive, in some cases concentrations less than the pre-established laboratory reporting level (LRL) are simply reported as less than that value (3 and 4 pCi/L for gross alpha-particle and beta-particle activity, respectively). This reporting decision was made because sample aliquots must be considerably larger than the standard size for quantification of gross alpha-particle and beta-particle activity less than 3 and 4 pCi/L, respectively. The analytical and reporting terms for radionuclides are defined in the Glossary.

Ancillary Inorganic and Organic Constituents

Concentrations of non-radioactive inorganic and organic constituents were determined by standard methods (Fishman and Friedman, 1989). Trace-element concentrations in pumping equipment blank samples were determined by inductively coupled plasma mass spectrometry (ICP-MS) (Faires, 1993), whereas trace-element concentrations in the environmental samples were determined by a combination of ICP-MS and inductively coupled plasma optical emission spectroscopy (ICP-OES) (Fishman and Friedman, 1989).

Land-Use Classification

Land use was attributed to each of the well sites by determining a potential contributing area and then calculating the percentage of land use within this feature. Potential contributing areas were delineated by applying a circular buffer around the wellhead, then modifying the buffer using natural hydrologic features and boundaries, such as watershed boundaries, streams, or headwater divides. The depth of intake and pumping capacity determined the initial radius of this buffer. Buffered areas then were clipped by natural hydrologic boundaries, such as level 1 or 2 perennial streams and surface-water divides that might coincide with a ground-water divide. Then only those areas within the resulting polygon that are upgradient from the well location (either hydraulically or topographically) were chosen. Where water-level elevation data for surficial aquifers were absent or inadequate, the results of the digital elevation model (DEM) were substituted; in most cases the model approximated flow direction and gradient sufficiently.

Because of the small data set and the potential for many combinations of land-use categories with too few samples, data were consolidated into only two categories on the basis of a predominance of two factors: land with human activity (agriculture, urban, suburban) or without it (forested, wetland, barren). The presence of even a small amount of agricultural land (10 percent) within the appropriate contributing area about the well can impart a distinct chemical imprint to the water (Szabo and others, 2005).

Statistical Analysis of Radionuclide Occurrence

Relations among Ra-224, Ra-226, Ra-228, and other inorganic constituents were characterized by use of Spearman correlations. This statistical test is a non-parametric statistical technique that determines the co-linearity of the ranked values of two continuous variables (Helsel and Hirsch, 1992). Results of the statistical tests were considered significant at the 95 percent confidence level. At this confidence level, the implication is that the sampling, if repeated 100 times, would result in a correlation among the variables 95 times; in other words, there is only one chance in 20 of obtaining the correlation by random chance. Comparisons of concentration distributions

for Ra isotopes and inorganic constituents among groups of data (groups by aquifer) were made using the Wilcoxon rank-sum nonparametric test, the Kruskal-Wallis nonparametric test, and the Tukey-Kramer multiple comparison test, which are based on the ranked concentration of the data (Helsel and Hirsch, 1992). The Wilcoxon rank-sum test, which is used to evaluate whether the distribution of two sample populations are the same, was used to determine whether concentrations of radionuclides differed between two classes of data (samples grouped geographically from the central and southwestern outcrop areas, grouped by land use as occurring in developed or undeveloped land, or samples grouped hydrologically as from confined or unconfined parts of aquifers). The Kruskal-Wallis test was used to determine whether concentrations of radium-224 differed among several groups (aquifers). This procedure evaluates whether more than two sample populations are identical by testing the null hypothesis that the individual group mean rank is identical to that for the entire data set. If the null hypothesis was rejected (groups differed from the overall population data set) then the Tukey-Kramer multiple comparison test was used to determine which of the population rank means significantly differed from one another. Where category sample size was small (less than 10), the exact form of the comparison tests rather than the approximation was used.

Occurrence of Radium-224, Radium-226, Radium-228, and Gross Alpha-Particle Activity in the Ground Water

Concentrations of Ra-224, Ra-226, Ra-228, Rn-222, other radionuclides, and gross alpha-particle and beta-particle activity in equipment blank samples are presented in appendix 2, and those in the 39 samples of ground water are presented in appendix 3, as are concentrations of ancillary inorganic constituents. Not all constituents were analyzed for in equipment blank samples. Locations of the sampled wells and the concentration distribution of Ra-224 are shown in figure 5. A summary of the frequency of occurrence of specified concentrations and distributional statistics is reported in table 4.

Quality Assurance

Contamination at the single pCi/L level was not detected in any equipment blank sample for the target radionuclides (radium isotopes) for this study (appendix 2). Several blank samples exhibited the possible presence of minor amounts of radium-228 at concentrations less than 1 pCi/L (quantifiable concentration in two samples at 0.55 and 0.86 pCi/L), however. Beta-particle counting used for the determination of radium-228 produces somewhat larger precision estimates (PEs) and SSMDs than the measurement techniques for alpha-emitting radium isotopes, especially alpha-spectroscopy;

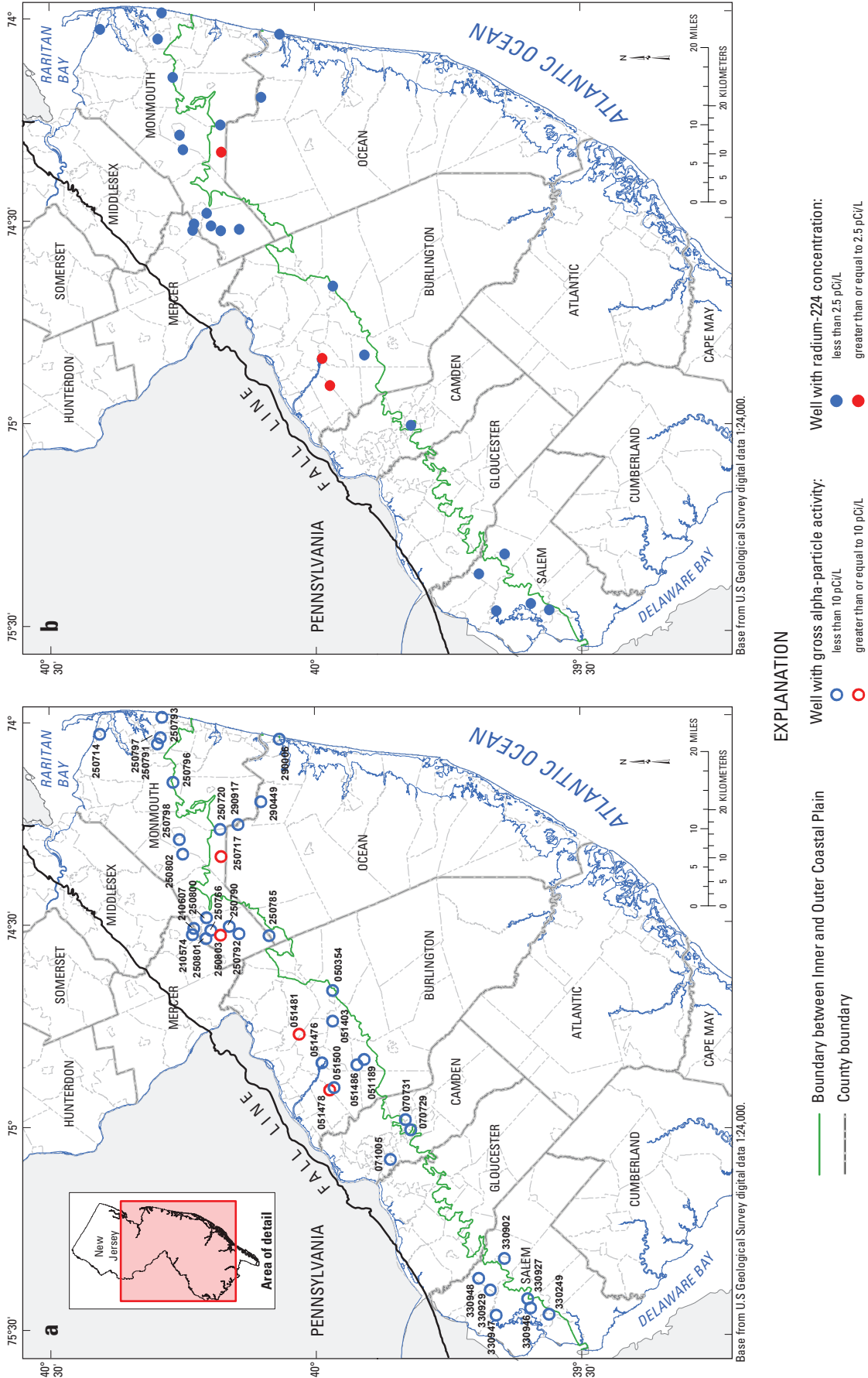


Figure 5. Location of wells sampled for, and distribution of, Ra-224 concentrations and gross alpha-particle activity in water from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999 –2001.

therefore, concentrations of low levels of radium-228 (less than 0.5 pCi/L) are difficult to quantify. The precision estimate associated with each Ra-228 sample result (0.29-0.91 pCi/L) was about the magnitude of the SSMDs, indicating poor precision of the results at the low concentration levels, and Ra-228 concentrations detected in the blank samples may be artifacts of the analytical method. These results indicate that samples likely were not contaminated with radium at a level of 1 pCi/L along any step of sample collection, sample handling, or sample analytical process, but rather that the analytical results for Ra-228 concentrations are imprecise below 1 pCi/L concentration level. The absence of detectable Ra-224 and Ra-226 in the same equipment blank samples analyzed with the more sensitive alpha-spectroscopy technique is consistent with the interpretation that the low (less than 1 pCi/L) concentrations of Ra-228 present might be artifacts of the analytical method. Concentration results for radium-228 less than 0.86 pCi/L, the highest concentration detected in an equipment-blank sample, are relatively unreliable.

One blank sample exceeded 1 pCi/L for lead-210 (1.1 pCi/L); the detected lead-210 was attributed to short-term contamination in the analyzing laboratory that required correction through a series of equipment de-contamination steps (A.H. Mullin, USGS National Water Quality Laboratory, oral commun., 2000). The analysis for lead-210 also uses a beta-counting technique. The laboratory contamination identified for lead-210 in 2000 was removed by decontamination procedures, and the results for blank samples collected in 2001 did not indicate the detectable presence of lead-210.

Results of analysis of the replicate sample indicated the difference between analytical results for radium isotopes in the sequential duplicate was + 0.1 pCi/L. The repeatability of results indicates the sample matrix is not a source of interference.

Sample contamination at the microgram-per-liter level was not detected for mercury, lead, copper, or zinc, though copper and zinc were each detected in one sample at about 0.5 $\mu\text{g/L}$; these trace elements are typical aerosol contaminants. The results indicate that aerosols did not contaminate samples during either field or laboratory handling. Furthermore, sample contamination at the microgram per liter level was not detected for chromium, manganese, nickel, molybdenum, or iron, possible contaminants from stainless-steel portable submersible sampling pump components (Ivahnenko and others, 2001). Orthophosphate was detected at concentrations about 0.005 to 0.015 mg/L in four blank samples; the sampling pump was decontaminated using a phosphate-free soap solution, so the source of the phosphate is not readily apparent, and the absence of phosphate in the detergent was not verified with independent analysis. The quality-assurance samples demonstrate that the analytical results obtained from the ground-water samples are free of random low-level sample contamination resulting from sample handling in the field and laboratory and are reproducible.

Gross Alpha-Particle Activity

Gross alpha-particle activities ranged from less than 3 to 16.0 pCi/L with a median value of less than 3 pCi/L for the entire data set from these aquifers. This median indicates that at least 50 percent of the 39 samples in this investigation did not exceed the 3 pCi/L LRL for gross alpha-particle activity. The gross alpha-particle activity was 3 pCi/L or less for 24 of the 39 sampled wells. The highest gross alpha-particle activity of 16.0 pCi/L was in a sample from an observation well (250717) completed in the Vincentown aquifer in an undeveloped (forested) area of central Monmouth County (fig. 5). Of the 39 samples, this sample was the only one to exceed the gross alpha-particle activity MCL of 15 pCi/L. A histogram of the activities in the 39 samples shown in percent of total samples collected indicates the small percentage (less than 10 percent) had gross alpha-particle activity greater than 10 pCi/L (fig. 6). Three samples as shown in figure 6 had gross alpha-particle activity greater than 10 pCi/L but less than 15 pCi/L (two from the Englishtown aquifer system and one from the Wenonah-Mount Laurel aquifer) and three more had greater than 5 pCi/L but less than 10 pCi/L (again two from the Englishtown aquifer system and one from the Wenonah-Mount Laurel aquifer). All the samples with gross alpha-particle activities greater than 5 pCi/L were from wells completed in unconfined parts of the respective aquifers. Of 39 samples, the 7 with gross alpha-particle activity greater than 5 pCi/L represent 18 percent of the data set. Radium concentrations were measured for five of these seven samples. For all five of the samples, concentrations of Ra-228 were greater than 1 pCi/L, and those of Ra-226 and Ra-224 were greater than 1 pCi/L in four of the five. Uranium, which has three alpha-particle emitting radionuclides, was analyzed for in a subset of samples including the sample with the highest gross alpha-particle activity, but uranium was not detected in any of the samples (appendix 3) and is not considered a major source of radioactivity in the water in the aquifers (though the presence of elevated concentrations of uranium (maximum, 46.5 parts per million in phosphate nodules) in the aquifer sediments is clearly documented by chemical analyses performed by Sugarman (1999). The NJDEP recommends to homeowners in southern New Jersey that they assume that all gross alpha-particle activity present in private self-supply wells is from radium (New Jersey Department of Environmental Protection, 1997); the recommendation is consistent with the absence of uranium in water from these aquifers that contain uranium-rich sediment beds.

Less than 3 percent of the wells yielded samples that exceeded the 15-pCi/L gross alpha-particle MCL. The third quartile (75th percentile) for gross alpha-particle activity was equal to 4.62 pCi/L, however. Although the number of wells sampled in these aquifers is small, the geographic distribution is generally representative of the extent of the aquifers, and the data indicate that slightly less than 25 percent of the sampled wells had a level of gross alpha-particle activity to be of concern using the conservative 5-pCi/L criterion suggested by

Table 4. Statistical summary of concentrations of radionuclides and selected physical properties and chemical constituents in 39 filtered water samples from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999 –2001.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; pCi/L; picocuries per liter; Min, minimum; <, less than]

Constituent	Number of samples analyzed	All Samples						
		Percentiles						
		Min	10th	25th	50th (median)	75th	90th	Maximum
Oxygen, dissolved (mg/L)	38	<.1	0.1	0.13	2.04	6.89	8.7	9.28
Specific conductance (uS/cm)	38	48	113	171	220	369	534	1053
Dissolved solids (mg/L)	32	30	68	90	126	217	263	528
pH, standard units	38	4.17	4.4	5.1	5.58	7.34	8.2	8.4
Calcium (mg/L)	38	0.72	2.25	9.88	17.105	26.12	39.93	87.64
Magnesium (mg/L)	38	0.55	1.1	2.4	3.13	8.85	14.64	16.17
Sodium (mg/L)	38	1.4	1.56	2.49	4.655	20.92	58.71	164.3
Potassium (mg/L)	38	0.73	1.12	2.31	3.025	4.28	6.07	9.54
Chloride (mg/L)	38	0.81	1.76	5.2	14.76	41.31	118.27	273.23
Iron (ug/L)	38	<10	<10	<10	81	769	4908	29389
Barium (ug/L)	38	6.19	18.36	28.61	50.8	70.41	141.81	184.03
Manganese (ug/L)	38	2.2	6.16	13.72	53.33	102.11	174.88	320.3
Strontium (ug/L)	24	14.61	35.08	50.88	139.5	181.22	363.43	426.02
Boron (ug/L)	31	6.41	8.89	11.77	16.69	22.36	38.48	104.66
Silica (mg/L)	38	3.26	6.31	7.64	10.96	13.99	22.42	45.04
Sulfate (mg/L)	38	0.32	3.11	6.9	21.87	40.34	53.81	83.71
Nitrite plus nitrate (mg/L)	38	<.05	0.05	0.05	0.19	4.41	10.96	12.46
Acid neutralizing capacity (mg/L)	33	<1	2.311	3.41	9.57	69.09	95.87	211.67
Alpha-particle activity, gross (pCi/L)	38	<3	<3	<3	<3	4.62	10.71	16
Beta-particle activity, gross (pCi/L)	37	<4	<4	<4	5.19	7.46	9.78	14.66
Radium-224 (pCi/L)	28	<.5	<.5	<.5	<.5	<.5	2.56	2.7
Radium-226 (pCi/L)	28	<.5	<.5	<.5	<.5	<.5	1.31	3.21
Radium-228 (pCi/L)	28	<.5	<.5	<.5	<.5	0.87	2.02	4.3
Radium-226 plus radium-228 (pCi/L)	28	<1	<1	<1	<1	1.03	4.35	5.21
Radon-222 (pCi/L)	18	81	84	242	399	556	812	1836

22 Occurrence of Radium in Water, Southwestern and South-Central New Jersey

Table 4. Statistical summary of concentrations of radionuclides and selected physical properties and chemical constituents in 39 filtered water samples from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999–2001.—Continued

[mg/L, milligrams per liter; $\mu\text{g/L}$, micrograms per liter; $\mu\text{S/cm}$, microsiemens per centimeter at 25 degrees Celsius; pCi/L; picocuries per liter; Min, minimum; <, less than]

Samples from unconfined parts of the aquifers								
Constituent	Number of samples analyzed	Percentiles						
		Min	10th	25th	50th (median)	75th	90th	Maximum
Oxygen, dissolved (mg/L)	26	0.1	0.3	2	6.3	7.44	9	9.28
Specific conductance (uS/cm)	26	48	64	173	236	499	534	1053
Dissolved solids (mg/L)	20	30	51.1	83.55	136	223.5	256.5	528
pH, standard units	26	4.17	4.4	4.9	5.2	5.6	5.75	6.73
Calcium (mg/L)	26	0.72	1.36	3.42	12.48	23	28.77	38.09
Magnesium (mg/L)	26	0.55	1.1	2.62	4.1	10.94	15.21	16.17
Sodium (mg/L)	26	1.4	1.69	3.62	9.48	32.8	61.82	164.3
Potassium (mg/L)	26	0.73	1.12	1.74	3.025	4.17	6.07	8.75
Chloride (mg/L)	26	3.54	6.07	13.74	21.44	70.78	127.25	273.23
Iron (ug/L)	26	<10	<10	<10	16.46	132.18	3754	29389
Barium (ug/L)	26	6.53	18.36	29.93	50.8	92.64	146.51	184.03
Manganese (ug/L)	26	2.2	5.56	23.19	60.29	115.47	174.88	320.3
Strontium (ug/L)	12	14.61	32.11	36.96	71.46	128.33	162.05	209.07
Boron (ug/L)	19	6.41	6.78	10.91	19.34	22.66	81.04	104.66
Silica (mg/L)	26	3.26	5.74	6.72	8.64	13.27	16.7	45.04
Sulfate (mg/L)	26	0.32	3.1	10.63	25.13	49.31	73.87	83.71
Nitrite plus nitrate (mg/L)	26	<.05	0.05	0.17	2.935	7.51	11.58	12.46
Acid neutralizing capacity (mg/L)	21	<1	<1	2.1	5.66	8.29	10.82	24.8
Alpha-particle activity, gross (pCi/L)	26	<3	<3	<3	3.1	6.6	11.1	16.01
Beta-particle activity, gross (pCi/L)	25	<4	<4	4	5.69	8.38	10.45	14.66
Radium-224 (pCi/L)	16	<0.5	<0.5	<0.5	<0.5	1.07	2.7	2.7
Radium-226 (pCi/L)	15	<0.5	<0.5	<0.5	<0.5	1.1	1.75	3.21
Radium-228(pCi/L)	15	<0.5	<0.5	<0.5	0.63	1.56	3.25	4.3
Radium-226 plus radium-228 (pCi/L)	16	<1	<1	<1	<1	2.99	4.8	5.21
Radon-222 (pCi/L)	12	84	167	240	399	548	596	1836

Table 4. Statistical summary of concentrations of radionuclides and selected physical properties and chemical constituents in 39 filtered water samples from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999–2001.—Continued

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; pCi/L; picocuries per liter; Min, minimum; <, less than]

Samples from confined parts of the aquifers								
Constituent	Number of samples analyzed	Percentiles						
		Min	10th	25th	50th (median)	75th	90th	Maximum
Oxygen, dissolved (mg/L)	12	<.1	<.1	<.1	0.1	0.17	0.21	0.41
Specific conductance (uS/cm)	12	144	149	161.5	199	251	458	555
Dissolved solids (mg/L)	12	85.5	87.5	95	118.5	152	288	320
pH, standard units	12	6.63	7.1	7.42	8.1	8.21	8.3	8.4
Calcium (mg/L)	12	12.74	16.36	22.59	23.36	43.37	83.54	87.64
Magnesium (mg/L)	12	0.92	1.39	1.685	2.575	4.355	4.64	5.91
Sodium (mg/L)	12	1.52	1.56	1.855	2.545	2.89	11.71	20.92
Potassium (mg/L)	12	2.03	2.06	2.38	3.125	4.845	5.5	9.54
Chloride (mg/L)	12	0.81	1.25	1.67	3.285	5.74	8.31	63.33
Iron (ug/L)	12	46.49	85.69	173.91	475.47	1486.8	4908	29148
Barium (ug/L)	12	6.19	18.89	27.165	46.62	61.38	79.8	97.35
Manganese (ug/L)	12	6.16	7.26	11.54	36.59	74.28	125.8	258.27
Strontium (ug/L)	12	45.01	97.73	144.55	175.83	301.0	391.3	426.02
Boron (ug/L)	12	9.2	9.93	13.67	16	21.37	31.09	38.48
Silica (mg/L)	12	10.24	11.08	11.485	13.47	19.27	31.92	34.71
Sulfate (mg/L)	12	4.86	5.85	6.15	9.6	26.16	29.29	34.84
Nitrite plus nitrate (mg/L)	12	<.05	<.05	<.05	<.05	<.05	<.05	<.05
Acid neutralizing capacity (mg/L)	12	55	60.26	67.89	82.06	99.77	148.85	211.67
Alpha-particle activity, gross (pCi/L)	12	<3	<3	<3	<3	<3	3.58	3.79
Beta-particle activity, gross (pCi/L)	12	<4	<4	<4	4.58	6.99	7.78	8.18
Radium-224 (pCi/L)	12	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.5
Radium-226 (pCi/L)	12	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Radium-228 (pCi/L)	12	<0.5	<0.5	<0.5	<0.5	0.5	0.73	0.97
Radium-226 plus radium-228 (pCi/L)	12	<1	<1	<1	<1	<1	<1	<1
Radon-222 (pCi/L)	6	81	81	303	391	574	812	812

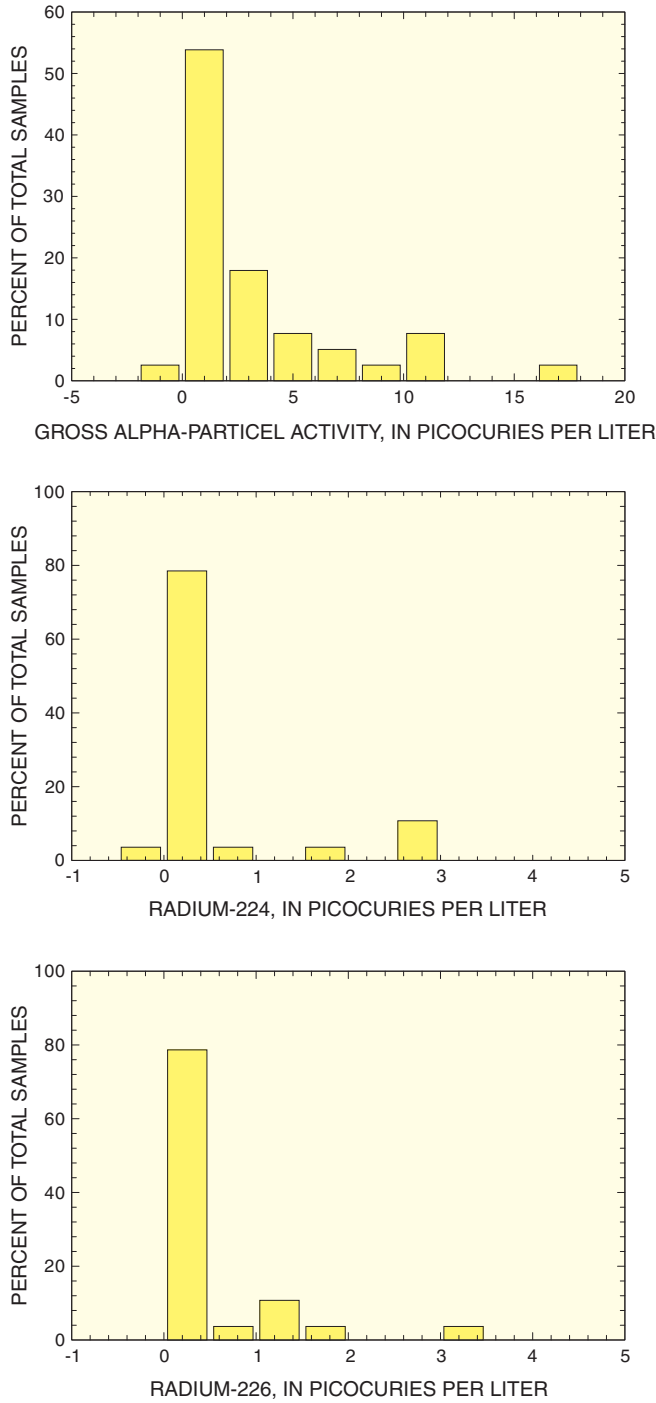


Figure. 6 Gross alpha-particle activity, and concentrations of radium-224 and radium-226 in water samples collected from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999 –2001.

NJDEP (The NJDEP recommends that when the gross alpha-particle activity is greater than 5 pCi/L, the MCL for combined radium, the homeowners in southern New Jersey consider taking action to reduce radium exposure through ingestion (New Jersey Department of Environmental Protection, 1997).

Gross alpha-particle activity had a median value of less than 3 pCi/L for the data set obtained for each aquifer (table 4). Interestingly, the third quartile (75th percentile) was equal to 4.62 pCi/L for the Wenonah-Mount Laurel aquifer, which is consistent with (representative of) the population distribution of the entire data set. The third quartile was equal to 6.12 pCi/L for the Englishtown aquifer system and was equal to 3.11 pCi/L for the Vincentown aquifer and the Hornerstown and Red Bank Sands, despite the fact that the highest gross alpha-particle activity of 16 pCi/L was from a well completed in the Vincentown aquifer. For the Englishtown aquifer system, 4 of 14 (28 %) wells sampled had gross alpha-particle activity greater than 5 pCi/L, and the maximum activity was 11.36 pCi/L. These four wells in the Englishtown aquifer system were all shallow and completed in the unconfined part of the aquifer in Burlington County (fig. 5).

Only 2 of 10 wells sampled in confined parts of the aquifers had water with gross alpha-particle activity greater than 3 pCi/L. The maximum gross alpha-particle activity for a well in a confined part of one of the sampled aquifers was 3.79 pCi/L for well 070731 completed in the Englishtown aquifer system.

Radium-224

Radium-224 was detected at concentrations greater than 1.0 pCi/L in 4 of the 39 water samples (10 percent) from the Vincentown and Wenonah-Mount Laurel aquifers, the Englishtown aquifer system, and the Hornerstown and Red Bank Sands (fig. 6; table 4; app. 3). Concentrations ranged from less than 0.5 pCi/L to 2.70 pCi/L (table 4). The median value for concentrations of Ra-224 was less than 0.5 pCi/L for the entire 39-well data set as well as the smaller data sets acquired from each aquifer (table 4). The highest Ra-224 concentration of 2.70 pCi/L was present in two samples, one from the Vincentown aquifer (well 250717) and one from the Englishtown aquifer system (well 051476). Both wells are shallow (less than 50 feet in depth) and completed in the unconfined parts of the aquifers. The water from well 250717 had gross alpha-particle activity of 16 pCi/L and thus exceeded the MCL of 15 pCi/L. The remaining samples with Ra-224 concentrations greater than 1.0 pCi/L were also from shallow wells in the unconfined parts of the aquifers (well 051478 in the Englishtown aquifer system with 2.56 pCi/L and well 250803 in the Wenonah-Mount Laurel aquifer with 1.62 pCi/L). None of 12 wells sampled in the confined parts of the aquifers produced water with a Ra-224 concentration greater than 0.5 pCi/L. The generally low concentrations of Ra-224 are consistent with the low gross alpha-particle activities of water from the aquifers.

Radium-226 and Radium-228

The concentrations of Ra-226 and Ra-228 in water from the lesser aquifers ranged from less than 0.5 to 3.21 pCi/L and less than 0.5 to 4.3 pCi/L, respectively (table 4; app. 3). The median values for Ra-226 and Ra-228 concentrations were less than 0.5 pCi/L, whereas the third quartile values (75th percentile) were 0.82 and 0.95 pCi/L, respectively. Most of the samples contained all three isotopes of Ra (Ra-224, Ra-226, and Ra-228) in concentrations less than 1 pCi/L (app. 3). The maximum concentration of Ra-226 was from the shallow well 250803 completed in the unconfined part of the Wenonah-Mount Laurel aquifer (fig. 5); the maximum concentration of Ra-228 was from the shallow well 051476 completed in the unconfined part of the Englishtown aquifer system. For all five of the samples in which the concentration of Ra-228 was greater than 1 pCi/L and for four of the five samples in which the concentration of Ra-226 was greater than 1 pCi/L, gross alpha-particle activity also was greater than 5 pCi/L.

The combined Ra in the water from these lesser aquifers ranged from less than 1 pCi/L to 5.21 pCi/L. The combined Ra-226 plus Ra-228 concentration was greater than the 5-pCi/L MCL for 2 of the 28 samples (7 percent). The sample with the highest Ra-226 plus Ra-228 concentration of 5.21 pCi/L was from the same shallow well, 250803, completed in the unconfined part of the Wenonah-Mount Laurel aquifer that also produced the water with the highest Ra-226 concentration. For a second sample (well 051476), the Ra-228 concentration was 4.3 pCi/L; a complex matrix resulted in the inability to quantify the concentration of Ra-226 with certainty, but the qualified result was reported as an estimated value of 0.9 pCi/L. The measured gross alpha-particle activity for the sample was 9.57 pCi/L. The 2.7 pCi/L of Ra-224 determined in the same sample could result in gross alpha-particle activity of 7.3 pCi/L 48 hours after sample collection when Ra-224 decay and progeny ingrowth are considered (Parsa, 1998). The approximately 2.3 pCi/L difference indicates the likely presence of other alpha-particle emitting radionuclides than just Ra-224 and progeny, providing independent confirmation of the possible presence of detectable amounts of alpha-particle emitting Ra-226. A third sample (well 051478) contained a concentration of combined Ra of 4.35 pCi/L.

The concentration of Ra-224 was the greatest among the three Ra radioisotopes studied in only one of the six samples where at least two of the three isotopes were present in concentrations greater than 1 pCi/L. Of those six samples, the concentration of Ra-228 was greatest in three and that of Ra-226 was greatest in two. In three of those six samples, the concentration of Ra-226 was greater than that of Ra-224; all three samples were from wells completed in the Wenonah-Mount Laurel aquifer. If the criterion were relaxed to include samples that contained the quantifiable concentration of one Ra isotope at 0.5 pCi/L or more, 11 samples would be included, and Ra-228 would be the radioisotope with the highest concentration in 8 of the 11 samples, all from either the Vincentown aquifer or the Englishtown aquifer system. For

these eight samples, the ratios of Ra-224 to Ra-228 were close to 1.0 as expected. Four of the five samples that contained a Ra-228 concentration of 1 pCi/L or greater also contained a Ra-224 concentration greater than 1 pCi/L. The 1:1 ratio was expected because both Ra-224 and Ra-228 originate from the Th-232 radioactive decay chain. The 1:1 ratio between these two isotopes has been observed in waters both locally and nationally (Szabo and others, 2005; Focazio and others, 2001).

In samples from wells 250803 and 330948, completed in the Wenonah-Mount Laurel aquifer, concentrations of Ra-226 were appreciably in excess of the concentrations of Ra-228 and Ra-224 (Ra-226 of 3.21 pCi/L as opposed to 1.62 and 2.0 pCi/L, respectively, and Ra-226 of 1.31 pCi/L as opposed to 0.9 and 0.4 pCi/L, respectively). Samples with a concentration of Ra-228 substantially in excess of the concentration of Ra-226 were collected from the Englishtown aquifer system (Ra-228 and Ra-226 concentrations of 4.3 and 0.9 pCi/L, respectively, for well 051476, and 3.25 and 1.1 pCi/L, respectively, for well 051478). Too few samples were collected to state with a high degree of statistical certainty that water in the Wenonah-Mount Laurel aquifer is enriched in Ra-226 relative to Ra-228 or that the opposite is true for the Englishtown aquifer system.

Significance of Radium-224 Concentrations for Gross Alpha-Particle Activity

The identification of Ra-224 as an important naturally occurring isotope in ground water has raised questions regarding the interpretation of gross alpha-particle activity analysis. The occurrence of Ra-224 in an appreciable amount could account for the elevated gross alpha-particle activity that cannot be ascribed to the presence of Ra-226. The likely degree of correspondence of occurrence (termed co-occurrence) of the Ra radionuclides indicates that samples that contain Ra-226 likely also contain Ra-224 and elevated gross alpha-particle activity.

Ratio of Radium-224 to Gross Alpha-Particle Activity

The moderately low frequency of detection, as well as the absence of Ra-224 concentrations greater than 3 pCi/L, indicates that the occurrence of Ra-224 is not an appreciable factor affecting the quality of water in the Vincentown and Wenonah-Mount Laurel aquifers, the Englishtown aquifer system, and the Hornerstown and Red Bank Sands with regard to the MCL for gross alpha-particle activity. The MCL for gross alpha-particle activity was rarely exceeded, a result consistent with the relatively low measured concentrations of Ra-224. Radium-224 was detected at concentrations greater than 1

pCi/L in 4 of the 28 samples of water from these lesser aquifers. A substantial part of the gross alpha-particle activity in those samples was from Ra-224 and progeny. The maximum Ra-224 concentration of 2.7 pCi/L could result in gross alpha-particle activity of 7.3 pCi/L 48 hours after sample collection when Ra-224 decay and progeny ingrowth are considered (Parsa, 1998). The 7.3 pCi/L of gross alpha-particle activity represents slightly less than one-half the value of the MCL for alpha radiation in water. A concentration of 3.71 pCi/L is considered appreciable for Ra-224 because these levels result in a gross alpha-particle activity of 10 pCi/L 36 to 48 hours after sample collection when ingrowth of Ra-224 progeny radionuclides is considered (Parsa, 1998). In such a case, the summed alpha-particle activity could equal or exceed the 15-pCi/L MCL for gross alpha-particle activity if radium-226 is present in a concentration of about 5 pCi/L.

The ratio of gross alpha-particle activity to Ra-224 in water where both were quantifiable was greater than 5 to 1 (fig. 7) for the Vincentown and Wenonah-Mount Laurel aquifers and less than 5 to 1 for the Englishtown aquifer system. As examples, ratios of 5.93 to 1, 6.86 to 1, and 7.71 to 1 were determined for water from wells 250717, 250803, and 250796, respectively, completed in either the Vincentown or Wenonah-Mount Laurel aquifer. Ratios of 3.54 to 1 and 4.18 to 1 were determined for water from wells 051478 and 051476, respectively, completed in the Englishtown aquifer system. The ratio is 2.77 to 1 for gross alpha-particle activity measured 48 hours after sample collection to Ra-224 in water in which no other alpha-particle emitting radionuclide is present (Parsa, 1998). In the water samples from the Englishtown aquifer system, gross alpha-particle activity measured within 48 hours after sample collection was dominated by concentrations of Ra-224 and progeny. This result is consistent with the dominance of Ra-224 and Ra-228 in water in this aquifer system. For water from either the Vincentown or Wenonah-Mount Laurel aquifers, the concentration of Ra-224 accounts for an appreciable, but not an overwhelming, part of the gross alpha-particle activity. The occurrence of Ra-226 in an appreciable amount could account for the elevated gross alpha-particle activity that cannot be ascribed to the presence of Ra-224 in those two aquifers.

Correlations Among Concentrations of Radium-224, Radium-226, and Radium-228, and Gross Alpha-Particle Activity

There was a significant and strong correlation between concentrations of Ra-224 and the gross alpha-particle activity determined within 48 hours after sample collection for wells completed in the unconfined parts of the aquifers (r , the Spearman rank correlation coefficient, was +0.86; table 5; fig. 7) despite the fact that the concentration of Ra-226 often equaled or exceeded the concentration of Ra-224. (The entire sample set was not considered because Ra radionuclides frequently were not detectable in water from the wells completed

in confined parts of the aquifers. The correlation between concentrations of Ra-226 and the gross alpha-particle activity determined within 48 hours after sample collection was even more significant and strong than that of Ra-224 (r , +0.91; table 5). The same pattern held for the data for each aquifer individually. The strongest correlation between concentrations of Ra-224 and the gross alpha-particle activity determined within 48 hours after sample collection occurred for samples from the unconfined parts of the individual aquifers; the weakest correlation was for the confined parts of individual aquifers. The strongest correlation between concentrations of Ra-226 and the gross alpha-particle activity determined within 48 hours after sample collection was also for samples from the unconfined parts of the individual aquifers.

The three highest measured concentrations of Ra-226 (1.31-3.21 pCi/L) were for waters from the Vincentown and Wenonah-Mount Laurel aquifers; the corresponding Ra-224 concentrations ranged from 0.4 to 2.7 pCi/L, and the gross alpha-particle activity ranged from 4.6 to 16 pCi/L. Thus, the concentration of Ra-226 accounted for nearly as much of the alpha-particle activity as the concentration of Ra-224 in the Vincentown and Wenonah-Mount Laurel aquifers. The ratio of the concentrations of Ra-224 to Ra-226 was as low as 0.50 in water from well 250803 completed in the unconfined part of the Wenonah-Mount Laurel aquifer. The ratio typically ranged from 1.0 to 2.7 for water from the Vincentown aquifer and Englishtown aquifer system (fig. 7).

The concentration of Ra-224 correlated significantly with that of Ra-228 (r , +0.71), Ra-226 (r , +0.86) and combined radium (r , +0.81) (table 5; fig. 7) in water from the unconfined part of these aquifers. (The correlation was about equally strong when all the samples were considered; however, the complete data set is not considered further here because of the general absence of quantifiable Ra concentrations in water from confined parts of the aquifers. The correlation statistic for the entire data set simply reflects the correlation observed in the unconfined parts of the aquifers.) The stronger correlation of the concentration of Ra-224 with that of Ra-226 as opposed to Ra-228 is somewhat surprising given that Ra-224 and Ra-228 are part of the same decay series (the Th-232 chain), whereas Ra-226 is part of the U-238 decay series. The strong correlation for concentrations of Ra-224 to concentrations of Ra-228 has been observed on the National scale (Focazio and others, 2001) and in samples from the Kirkwood-Cohansey aquifer system in New Jersey (Szabo and others, 2005).

The degree of correlation of Ra-224 with Ra-228 (r , +0.76) in samples from the unconfined parts of all the lesser aquifers is similar to the degree of correlation of Ra-226 with Ra-228 (r , +0.70). The strong correlation among concentrations of Ra isotopes occurs because all are mobile under the same chemical conditions (Zapczka and Szabo, 1988) and because isotopes of Ra potentially can be mobilized by radionuclide recoil effects (Fleischer, 1980).

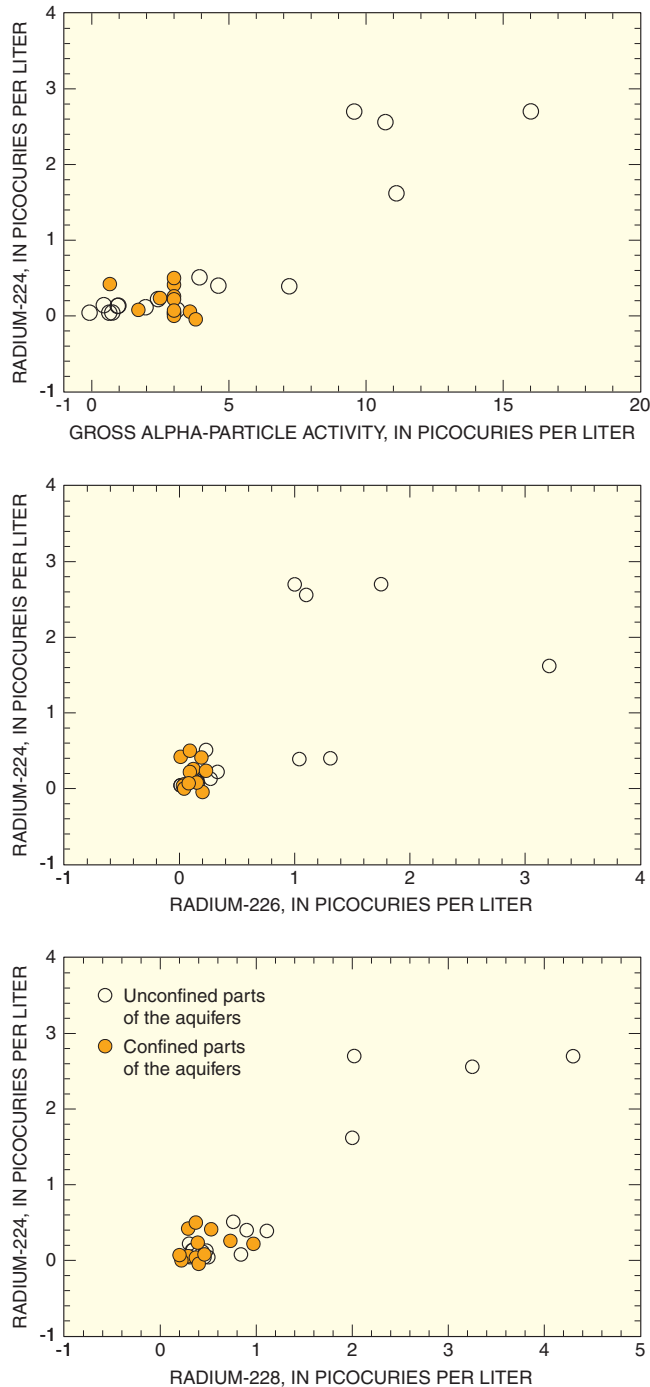


Figure 7. Relation of concentrations of radium-224 to gross alpha-particle activity, and to concentrations of radium-226 and radium-228 in water from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999–2001.

Factors That Affect Radium-224 Concentrations in the Ground Water

Relations among radionuclides and selected ancillary constituents, and statistically significant differences in concentrations of radionuclides, selected major ions, and pH, among hydrogeological groups for the lesser aquifers are reported in tables. Geochemical and hydrogeological factors that explain the occurrence of radioactivity and their significance for the various radionuclides present are discussed in the following sections.

Geochemical Factors and Land Use

The strong correlation among concentrations of Ra isotopes likely occurs because all are mobile under the same chemical conditions. Land use likely affects the geochemistry of the lesser aquifers. Geochemical characteristics of the waters from the aquifers are evaluated in the context of radium mobility and land use.

Relations Between Radium and pH

Concentrations of Ra-224, Ra-226, Ra-228, and gross alpha-particle activity were highest in the water where the pH was lowest within each aquifer and in water from all parts of all the aquifers as well, with one exception, the high Ra-226 concentration (1.31 pCi/L) in water from well 330948 completed in the Wenonah-Mount Laurel aquifer with a pH of 5.6. The median pH for the 39 samples in this study was 5.7. Ground water in the unconfined parts of the aquifers typically was acidic to slightly acidic; pH ranged from 4.17 to 6.73, with a median of 5.2 for these 27 samples. Results of the Wilcoxon rank sum test indicate that concentrations of Ra-224, combined Ra, and alpha-particle radioactivity in samples with a pH greater than 4.9 are statistically different from those in samples with pH less than 4.9; in all cases with the one exception noted above, the concentrations of Ra-224 and Ra-228 or gross alpha-particle activities were highest in samples with the lowest pH. Of the nine samples with a pH less than or equal to 4.9, all of which were from the unconfined parts of the aquifers, two (22 percent) contained Ra-228 concentrations of 2.5 pCi/L or greater, four (44 percent) contained Ra-228 concentrations of 2.0 pCi/L or greater, three (33 percent) contained Ra-224 concentrations of 2.5 pCi/L or greater, and one contained a Ra-226 concentration of 2.5 pCi/L or greater. Of the six samples with a pH less than or equal to 4.8, all of which were from the unconfined parts of the aquifers, two contained Ra-228 concentrations of 2.5 pCi/L or greater, three contained Ra-224 concentrations of 2.5 pCi/L or greater, one contained a Ra-226 concentration of 2.5 pCi/L or greater, and four (67 percent) contained at least one isotope of Ra at a concentration of 2.5 pCi/L or greater (fig. 8). The two samples with concentrations of combined Ra in excess of the 5-pCi/L

Table 5. Spearman rank correlation coefficients for relations of radium-224, radium-226, and radium-228 to selected constituents in water samples from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and Hornerstown and Red Bank Sands (lesser aquifers), southwestern and central New Jersey, 1999–2001, and the Kirkwood-Cohansey aquifer system, southwestern and south-central New Jersey, 1997–1999.

[All coefficients shown are significant at the 95-percent confidence level; --, indicates that the correlation coefficient is not significant]

Radioisotope	Gross alpha-particle activity	Gross beta-particle activity	Lesser aquifers, all samples																	
			Radium-224	Radium-226	Radium-228	Combined radium	pH	Nitrite plus nitrate	Calcium	Magnesium	Sulfate	Chloride	Barium	Potassium	Strontium	Silica	Iron			
Radium-224	+50	+42	1	+64	+59	+68	-50	--	--	+39	--	--	--	--	--	--	--	-47	--	
Radium-226	+77	+64	+64	1	+68	+85	-62	--	--	--	--	--	--	--	--	--	--	-60	--	
Radium-228	+57	+45	+59	+68	1	+93	-58	--	-43	--	--	--	--	--	--	--	--	-62	--	
Lesser aquifers, unconfined																				
Radium-224	+86	+82	1	+86	+71	+81	-66	--	--	--	--	--	--	--	--	--	--	-67	--	
Radium-226	+91	+78	+86	1	+70	+89	-70	--	--	--	--	--	--	--	+54	--	--	-57	--	
Radium-228	+79	+73	+71	+70	1	+89	-67	--	--	--	--	--	--	--	--	--	--	-59	--	
Kirkwood-Cohansey aquifer system (Szabo and others, 2005)																				
Radium-224	+89	+87	1	+74	+91	+88	-36	+56	+48	+65	+47	+37	+47	+47	+47	+47	NA	NA	--	
Radium-226	+77	+71	+74	1	+79	+91	--	+62	+33	+59	+53	+33	+35	+44	+44	+44	NA	NA	--	
Radium-228	+83	+85	+91	+77	1	+95	-38	+60	+48	+64	+52	+32	+46	+45	+45	+45	NA	NA	--	

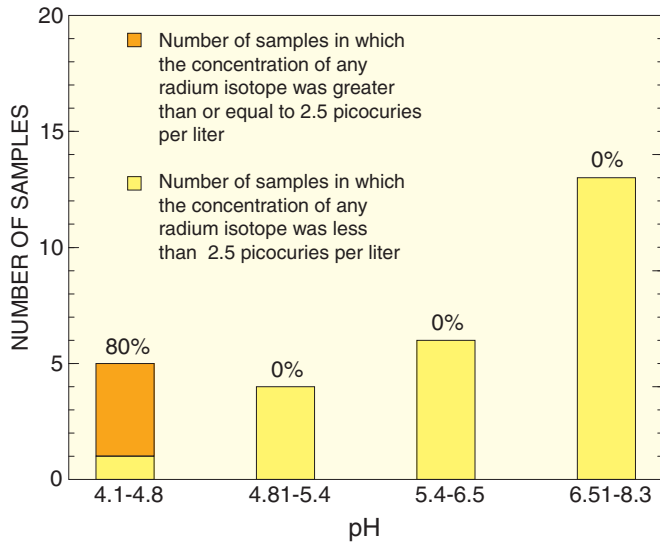


Figure 8. Number of water samples in which the concentration of any radium isotope exceeded 2.5 (pCi/L) picocuries per liter as a function of selected ranges of pH in water from the Vincentown and Wenonah-Mount Laurel aquifers, and the Englishtown aquifer system, southwestern and south-central New Jersey, 1999–2001.

MCL also had pH less than 4.9 (pH, 4.6 and 4.4). Of the 18 samples with pH greater than 4.9, only one radium isotope, Ra-226 exceeded 1 pCi/L. Of the nine samples with pH less than or equal to 4.9, five had the highest concentrations of Ra-228, four had the highest concentrations of Ra-224, two had the highest concentrations of Ra-226, and seven had the highest gross alpha-particle activities. Since waters with pH greater than 5.0 generally do not contain elevated activities of radium, the minor difference in pH among samples across the landscape is important (figs. 5 and 8).

Results of the Wilcoxon rank sum statistical test indicate that concentrations of Ra-224, Ra-226, Ra-228, and combined Ra, and alpha-particle radioactivity, as well as pH, in samples from the unconfined parts of the three aquifer groups do not differ statistically by aquifer group. The median pH for the 12 samples collected from the unconfined parts of the Vincentown aquifer was 5.49; for the 6 samples from the unconfined parts of the Wenonah-Mount Laurel aquifer, 5.4; and for the 9 samples from the unconfined parts of the Englishtown aquifer system, 5.2. In each aquifer, the four highest gross alpha-particle activities were in the waters with the lowest pH, except for one sample from the Vincentown aquifer. This sample, which had the fourth highest gross alpha-particle activity, had the fifth lowest pH.

Concentrations of Ra-224 exhibit a strong statistically significant inverse relation to pH (r , -0.66; table 5). Concentrations of Ra-226 and Ra-228 exhibit equally strong statistically significant inverse correlations with pH (r , -0.70 and -0.67, respectively).

As pH decreases, all isotopes of Ra (including Ra-224) become more mobile because the hydrogen ions effectively compete with Ra for the available sorption sites (Szabo and others, 1997). The sorption capacity of aquifer sediments is low; even a minor increase in free hydrogen ion content (decrease in pH) can result in substantially diminished sorption capacity.

Relations Between Radium and Nitrate

The concentration of nitrate initially was considered as a second criterion for determining the likely frequency of occurrence of combined Ra in concentrations greater than the 5-pCi/L MCL and the frequency of occurrence of Ra-224, Ra-226, and Ra-228 in concentrations greater than or equal to 2.5 pCi/L. The selection of nitrate as this second criterion was based on results of previous studies of water in the Kirkwood-Cohansey aquifer system of southern New Jersey by Szabo and others (2005), Szabo and dePaul (1998), and Kozinski and others (1995). Concentrations of Ra isotopes correlated strongly with concentrations of nitrate in water from the Kirkwood-Cohansey aquifer system (Kozinski and others, 1995, fig. 21b), and Szabo and others (2005) show that the difference in Ra occurrence was statistically significant even among waters with nitrate concentrations less than and greater than 3 mg/L. It was hypothesized on the basis of this evidence that concentrations of combined Ra would exceed the USEPA MCL of 5 pCi/L or that the individual isotopes of Ra-224, Ra-226, and Ra-228 would exceed a concentration of 2.5 pCi/L far more frequently in ground water that is acidic (pH less than 5.0) and contains high concentrations of nitrate than in water from areas without human activity (forested areas) in southern New Jersey (hereafter, high concentrations of nitrate are those that exceed 3 mg/L). Based on the strong correlations among Ra-224, Ra-226, Ra-228, combined Ra and gross alpha-particle activity, the hypothesis, if applicable, can be used to evaluate the frequency of occurrence of each of these radionuclides.

The concentration of nitrate does not show a statistically significant correlation with the concentration of any Ra isotope in water from the unconfined parts of the lesser aquifers (tables 4 and 5). With the exception of the Ra-226 concentration of 1.31 pCi/L in well 330948 (with pH of 5.6), no sample with pH greater than 5.0 had any Ra isotope concentration greater than 1.0 regardless of the concentration of nitrate. The presence of elevated nitrate concentrations does not affect the occurrence of Ra-224, Ra-226, and Ra-228 if the pH is greater than 5.0. The presence of elevated concentrations of Ra-224, Ra-226 and Ra-228 (greater than 1.0 pCi/L) are found in acidic water (pH less than 5.0), but for these acidic waters, the frequency of occurrence of elevated Ra concentration is the same if nitrate is greater than 3.0 mg/L or less than 3.0 mg/L. This occurrence distribution result is consistent with the initial concern that the concentration of nitrate does not show statistically significant correlation with the concentration of

any Ra isotope in water from the unconfined part of any of the sampled lesser aquifers (tables 4 and 5).

The issue of absence of correspondence between radium concentrations greater than either 1.0 or 2.5 pCi/L and nitrate concentrations greater than 3.0 mg/L is clearly delineated for water from the Vincentown aquifer and the Englishtown aquifer system. Nitrate was not detectable at a concentration level of 0.05 mg/L in water from wells 250717 (Vincentown aquifer) and 051476 (Englishtown aquifer system) both of which had the highest Ra-224 concentrations of 2.7 pCi/L. (Well 250717 also had the highest gross alpha-particle activity of 16 pCi/L and well 051476 had the highest Ra-228 concentration of 4.3 pCi/L.) In fact, of the two samples from the Vincentown aquifer and the four from the Englishtown aquifer system with the highest concentrations of Ra, only one had a nitrate concentration greater than 3 mg/L (well 051478), whereas three did not contain detectable concentrations of nitrate. Also, the concentration of nitrate was detectable but not elevated in one well (well 051500). The sample collected from well 051478 in the Englishtown aquifer system had a nitrate concentration of 11.6 mg/L. The sample collected from well 051500 also in the Englishtown aquifer system had a nitrate concentration of 0.54 mg/L. Only in water samples from the Wenonah-Mount Laurel aquifer did elevated concentrations of Ra and nitrate co-occur. The four samples from the Wenonah-Mount Laurel aquifer with the highest gross alpha-particle activities and Ra-226 radionuclide concentrations also had the highest concentrations of nitrate; three of the four samples had nitrate concentrations greater than 10 mg/L (maximum, 12.46 mg/L from well 330929).

Chemical Classification of Ground Waters and Possible Effects on Radium Occurrence

The chemical compositions of waters in the lesser aquifers of the New Jersey Coastal Plain sampled in this study differ substantially between the unconfined and confined parts of the aquifers (table 6). The median specific conductance (SC) of 236 $\mu\text{S}/\text{cm}$ (microsiemens per centimeter) for water samples from the unconfined parts of the aquifers did not differ significantly from the median value of 199 $\mu\text{S}/\text{cm}$ for water samples from the confined parts of the aquifers on the basis of the population distribution among the samples (table 4), but the relative composition was substantially different. Radium concentrations and pH differ greatly for the confined and unconfined aquifers. Ground waters of the unconfined parts of the lesser aquifers are generally acidic, whereas waters of the confined parts of the lesser aquifers are generally alkaline or neutral. Because waters with pH greater than 5.0 generally do not contain elevated concentrations of radium (greater than 2.5 pCi/L), and those with pH less than 5.0 do, the distribution of pH is critical in terms of radium occurrence. The pH distribution was discussed previously for the unconfined parts of the lesser aquifers.

Radium and nitrate concentrations can be high in the unconfined parts of the aquifers but low or absent in the confined parts as is shown in boxplots in figures 9 and 10. Results of the Wilcoxon rank sum test indicate that significant differences in the concentrations of Ra-224, Ra-226, and Ra-228 occur between water samples on the basis of hydrogeology, specifically confinement status (fig. 9); the mean of the ranked values for each of the Ra constituents was significantly greater in the unconfined parts of the aquifers (table 6).

Table 6. Significance levels (p-values) resulting from the Wilcoxon rank sum statistical test to determine whether concentrations of radionuclides and selected ions, and pH differ in water samples on the basis of aquifer, land-use category, and hydrogeologic status in terms of confinement, Vincentown and Wenonah-Mount Laurel aquifers and Englishtown aquifer system, southwestern and south-central New Jersey, 1999–2001.

[Samples from the Hornerstown and Red Bank Sands are grouped with the Vincentown aquifer for convenience. Comparison for the first two categories is for water samples from the unconfined parts of the aquifers only. Land use aggregated into two categories: developed, greater than or equal to 50 percent agricultural and urban combined; and undeveloped, less than 50 percent with agricultural and urban combined. Confinement indicates unconfined or confined status irrespective of aquifer. Differences significant at the 5-percent confidence level are shown in **bold**; those significant at the 10-percent confidence level are shown in *italics*]

Constituent	Significance level		
	Aquifer	Land use	Confinement
Radium-224	0.8990	<i>0.0627</i>	0.2181
Radium-226	.7144	.5069	.0242
Radium-228	.4329	.3818	.0290
Radium-226 plus radium-228	.4770	.5067	.0243
Alpha-particle activity, gross	.9831	.1343	.2591
Beta-particle activity, gross	.5995	1.0	.1985
Radon-222	.1393	.9369	.8883
pH	.2122	<i>.0839</i>	<.0001
Oxygen, dissolved	.3908	.0294	<.0001
Acid neutralizing capacity	.0717	<i>.0892</i>	<.0001
Dissolved solids	.0167	.0396	.8610
Nitrite plus nitrate	.5858	.0021	<.0001
Calcium	.0092	.0020	.0018
Magnesium	.5767	.0045	.0461
Chloride	.1828	<i>.0771</i>	<.0001
Sulfate	.5056	.2495	<i>0.0617</i>
Iron	.0625	.1084	.0036
Barium	.6730	1.0	.4605
Strontium	.0113	.1469	.0035

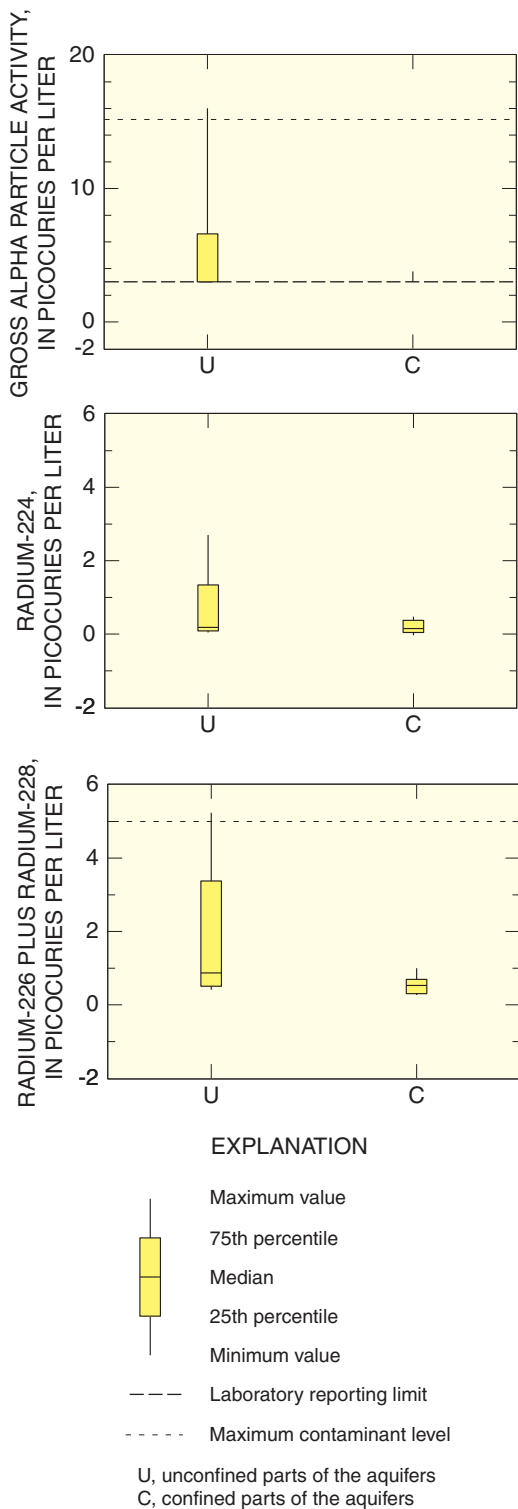


Figure 9. Distribution of gross alpha-particle activity and concentrations of radium-224 and the sum of radium-226 plus radium-228 in water grouped by aquifer confinement status, Vincentown and Wenonah-Mount Laurel aquifers, and Englishtown aquifer system, southwestern and south-central New Jersey, 1999–2001.

Unconfined Parts of the Aquifers

High Ra concentrations (greater than 2.5 pCi/L) were present in water samples from areas where the Vincentown and Wenonah-Mount Laurel aquifers and Englishtown aquifer system are unconfined, or where the confining layer is exposed at land surface and has been substantially weathered. The median pH for the unconfined parts of the sampled aquifers is 4.9, and the maximum is 6.7 (nearly neutral, but still on the acidic side), indicating an acid environment that is favorable for radium mobility.

The overall amount of mineralization of water from the unconfined parts of the lesser aquifers showed appreciable differences among aquifers and by land use (table 6). Both the minimum and maximum values of SC, range 48 to 1,053 $\mu\text{S}/\text{cm}$, occurred in samples from wells in the unconfined parts of the aquifers, reflecting the great compositional variability of water from the unconfined parts of these aquifers. The shallow private well 210574, located in an area without human activity (mostly forested), yielded water with the lowest SC; the shallow observation well 250802, located near a major thoroughfare in a rapidly developing area, yielded water with the highest SC.

In the unconfined parts of the lesser aquifers, not only is the amount of mineralization variable, but the chemical composition of the water is locally variable as well; many constituent concentrations differ on the basis of land use (table 6). Stiff diagrams show the large differences in the composition of the water from unconfined parts of the aquifers (fig. 11, first two columns). Nitrate, is an important anionic component of the water in the unconfined parts, although it is rarely predominant (fig. 11). Nitrate concentrations are highly variable, however. Nitrate concentrations ranged from less than 0.05 to 12.5 mg/L with a median of 2.9 mg/L. Of the 26 samples from unconfined wells analyzed for nitrate, only 5 had concentrations less than the LRL of 0.05 mg/L. Four of these five wells are located in areas that are largely undeveloped; one of the wells, however, is located in an agriculturally developed area. Samples from five other wells, all located in areas with abundant human activity (predominantly agricultural land use), exceeded the MCL of 10 mg/L. Samples of waters from the unconfined parts of the lesser aquifers were generally well oxygenated and ranged in dissolved oxygen (DO) concentration from less than 0.1 to 9.3 mg/L, with a median of 6.3 mg/L. The oxygenated water allows nitrate to persist. Only six wells in the unconfined part of the aquifers yielded water with concentrations less than 1 mg/L. These unconfined wells, intercepting water depleted in DO, either are located near (organic-rich) wetlands (for example, well 250717 in a swamp) or are open to aquifer materials (organic-rich layers) that are reactive and can readily deplete oxygen.

Chloride and nitrate were the dominant anions (fig. 11); sulfate occasionally, though not typically, was present in concentrations nearly equal to that of chloride and nitrate. Concentrations of sodium in the unconfined systems ranged from 1.4 to 164 mg/L with a median of 9.5 mg/L. Concentrations

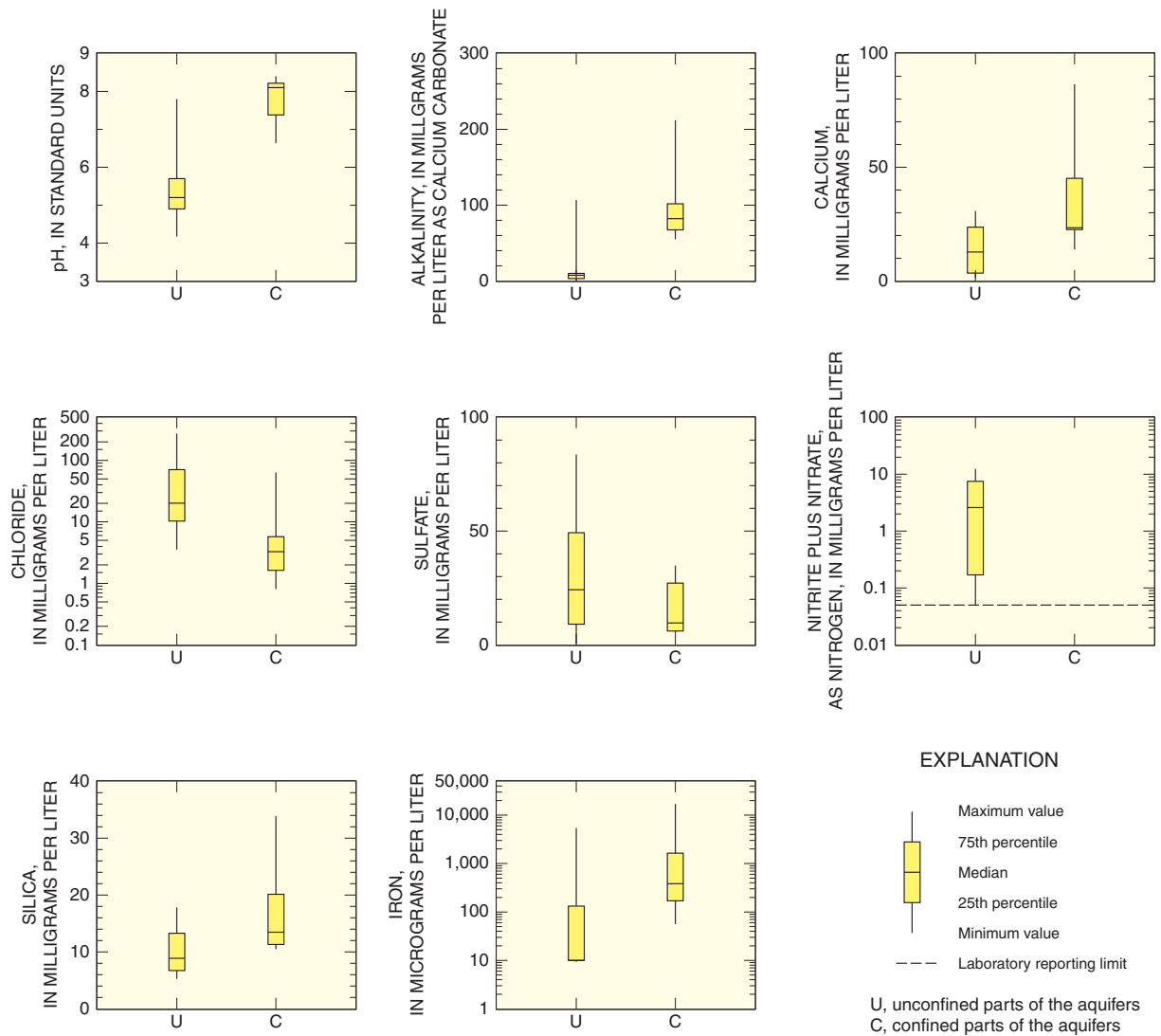


Figure 10. Distributions of concentrations of selected major ions, trace elements, and physical properties, grouped by confinement status, Vincentown and Wenonah-Mount Laurel aquifers, and Englishtown aquifer system, southwestern and central New Jersey, 1999–2001.

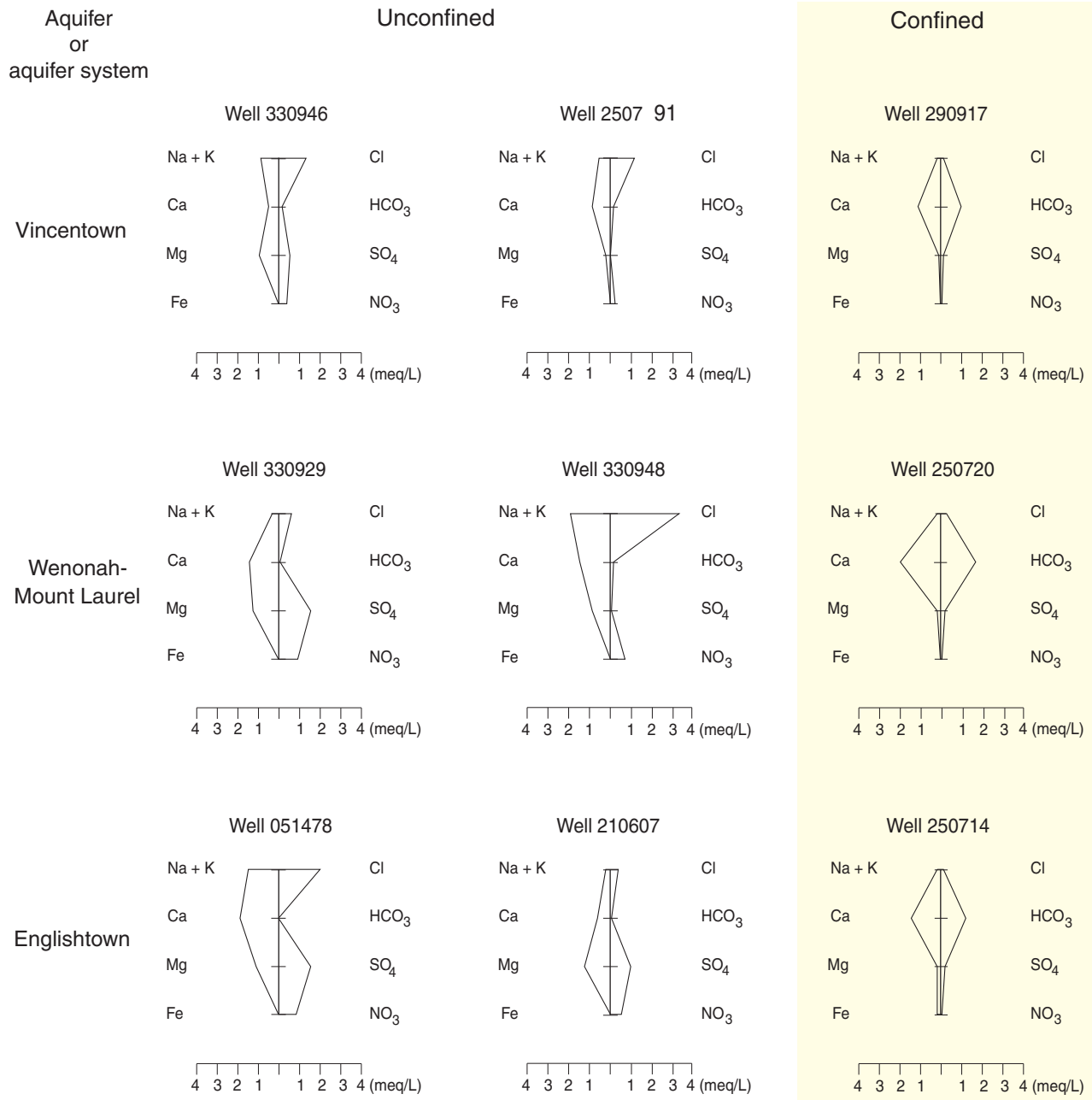


Figure 11. Stiff diagrams representing the composition of water from the confined and unconfined parts of the Vincentown and Wenonah-Mount Laurel aquifers, and Englishtown aquifer system, southwestern and south-central New Jersey, 1999–2001. [meq/L, milliequivalents per liter; Na + K, sodium plus potassium; Ca, calcium; Mg, magnesium; Fe, iron; Cl, chloride; HCO₃, bicarbonate; SO₄, sulfate; NO₃, nitrate]

of chloride in water from wells in the unconfined parts of the aquifers ranged from 3.5 to 272 mg/L, with a median of 21.4 (fig. 10 and table 6). Chloride is present naturally in ground water in the New Jersey Coastal Plain, but concentrations generally are low, especially inland from the shoreline. Yuretic and others (1981) document that chloride concentrations in precipitation and surface waters derived primarily from precipitation typically ranged from about 3 to 5 mg/L with concentrations in samples from central and eastern New Jersey increasing west to east towards the shoreline. Concentrations of chloride greater than 10 mg/L in unconfined aquifers typically are attributed to leaching of surficial materials present as a result of human activity, and concentrations greater than 50 mg/L usually are from percolating leachates of salts from roadway applications. The wells with high concentrations of chloride are shallow (maximum depth 80 feet, median 22 feet) and are located near major roadways in areas where the outcropping aquifer material is thin (80 feet or less). Chloride concentration in a sample from one well (well 250802, depth 35 feet, 272 mg/L) exceeded the secondary MCL of 250 mg/L.

Sodium and calcium were generally the dominant cations (fig. 11); however, in occasional samples, magnesium and iron also were present in concentrations nearly equal to that of sodium and calcium, though typically were not dominant constituents. Samples from four wells, all about 50 feet or less in depth below land surface and all located within Monmouth County, exceeded the Secondary Maximum Contaminant Level (SMCL) of 50 mg/L for sodium established by NJDEP (New Jersey Department Environmental Protection, 2002b). The shallow depth indicates the likely source of the sodium is road salt leachate.

Alkalinity ranged from less than 1.0 mg/L to 24.8 mg/L (figs. 9, 10, and 11), with a median of 5.7 mg/L. Percolating leachates tend to add mineral acids (of nitrate, sulfate, and chloride) and alkalinity is low; hence, waters in the unconfined parts of the lesser aquifers are likely to remain acidic and remain vulnerable to the presence of elevated radium in solution.

Major-ion chemistry of the water in the three aquifer groupings (Vincentown aquifer, Wenonah-Mount Laurel aquifer, Englishtown aquifer system) was similar; results of the Kruskal-Wallis and Wilcoxon rank sum statistical tests indicated significant differences only with respect to concentrations of strontium and calcium (table 6). Because many constituent concentrations were analyzed, yet the concentration distributions of only two (Ca and Sr) differ significantly, the overall chemical difference among the aquifers is considered minor.

Confined Parts of the Aquifers

The maximum gross alpha-particle activity in samples from the confined parts of the aquifers was 3.79 pCi/L in water collected from well 070731 completed in the Englishtown aquifer system in Camden County. The maximum concentrations of Ra-224 and Ra-228 in water from the confined parts

of the aquifers were 0.41 and 0.97 pCi/L from wells 070729 and 290006, respectively, both of which are completed in the Englishtown aquifer system. All concentrations of Ra-226 were less than the respective SSMDCs.

All the samples from the confined parts of the aquifer, where the confining unit had substantial thickness, were circumneutral to neutral to alkaline (range, 6.63–8.4) with a median pH of 8.1. Well 250792, producing water with the lowest pH among the wells in confined parts of the aquifers, is the shallowest, only 50 ft deep, and only this well yielded a sample with pH less than 7 (value, 6.63). This well is located near the updip limit of the confined Wenonah-Mount Laurel aquifer (fig. 5). Water from this well was atypical compared with that from other wells in areas where the aquifers were confined. Iron was the dominant cation with bicarbonate the dominant anion, and sulfate was of importance. Oxidation of pyrite and/or dissolution of siderite nodules might be geochemical mechanisms that result in water with such atypical composition. The driller's log (driller's log on file at the U.S. Geological Survey, New Jersey Water Science Center) does not give an indication of the presence of these minerals, but the shallow depth and presence of nitrate is consistent with penetration of water from land surface that is still somewhat oxic at 50 feet below land surface, resulting in rapid oxidation and dissolution of these mineral phases if they are present.

Almost all the samples from the confined parts of the aquifer are bicarbonate as opposed to chloride or nitrate dominated (figs. 10 and 11). Stiff diagrams show the relative uniformity in the composition of the water from confined parts of the aquifers (fig. 11; third column). Nitrate is not present in waters from the confined parts of the aquifers (fig. 10). Eleven wells in the confined part of the aquifers yielded water with DO concentrations less than 1 mg/L; even if nitrate-bearing water had penetrated beneath the confining units, nitrate is removed by reduction and mineralization in reducing waters.

In the confined parts of the lesser aquifers of the New Jersey Coastal Plain, chemical composition of ground water varies regionally and typically evolves downdip from dilute calcium-bicarbonate-type water to sodium-bicarbonate-type water and ultimately to concentrated sodium-chloride-type water. This evolution of chemical facies downdip has been documented most thoroughly for the Englishtown aquifer system of all the confined aquifers in the New Jersey Coastal Plain (Seaber, 1965). The inorganic composition of water in the confined parts of each of the aquifers sampled in this study was dominated primarily by calcium and bicarbonate, which represents the initial dilute calcium-bicarbonate-type water that undergoes further chemical evolution with increase in residence time and distance from the outcrop (Back, 1966). The water typically is alkaline; pH ranged from 6.63 to 8.4, with median, 8.1. The maximum pH of 8.4 was for water from well 050354 open to the confined Wenonah-Mount Laurel aquifer; the well is located approximately 7 kilometers in the downdip direction from the outcrop area (fig. 5) and is dominated by calcium and bicarbonate. Concentrations of alkalinity were considerably higher in samples from confined parts of the

aquifers than those from unconfined parts and ranged from 55 to 220 mg/L, with a median 82 mg/L. The bicarbonate to chloride ratio increased downdip (fig. 12). Specific conductance in water from the confined parts of the aquifers ranged from 144 to 555 $\mu\text{S}/\text{cm}$, with a median of 199 $\mu\text{S}/\text{cm}$. Dissolved solids ranged from 86 to 320 mg/L, with a median value of 119 mg/L. Typically, under ambient conditions, one can expect that older waters (greater residence time) in the confined systems might have higher dissolved solids content and conductivity than those of younger, unconfined waters. Water from most shallow wells in unconfined parts of aquifers sampled in this study, however, have been affected by anthropogenic contaminants; therefore, dissolved solids content is similar in the unconfined and confined parts of the aquifers.

Downdip along flowpaths within these aquifers, the waters gradually become sodium bicarbonate dominated. With increasing distance downgradient from the outcrop, the bicarbonate to chloride and sodium to chloride ratios increase (fig. 12a and 12b). Furthermore, although calcium is typically the dominant or even the second-most abundant cationic constituent in many confined wells near the aquifer outcrop (fig. 11), calcium concentrations gradually decrease downdip (fig. 12c), as the sodium concentrations increase, providing

evidence of cation exchange. Two wells in the confined group, wells 290006 and 290449, are open to the Englishtown aquifer system, 38 and 25 kilometers from the outcrop, respectively; samples exhibit sodium to chloride molar ratios of 22.3 and 3.5, respectively, evidence of substantial amounts of cation exchange, as opposed to simple dilution of sea water or connate brine. The cation exchange process in dipping confined aquifers is termed “aquifer freshening” by Appelo (1994).

Concentrations of radium were low (less than 1 pCi/L) in water from confined parts of the aquifers (fig. 9). Cation exchange (preferential removal of divalent cations such as Ra) as well as high pH (allowing for sorption, the removal of all cations, in the absence of abundant free acidity) may limit radium mobility. The ion-exchange process has been shown to limit Ra concentrations in water even in uraniumiferous black shale deposits (Szabo and Zapeczka, 1991). The effectiveness of ion exchange as a mechanism to limit Ra concentration in solution decreases with an increase in dissolved solids concentration (Miller, 1992), but the concentrations of dissolved solids are not high enough where the aquifers are used for drinking-water supply to pose concern for mobilizing Ra.

Chloride to borate ratios decrease downdip (fig. 12d). This trend indicates possible input of boron-rich water from

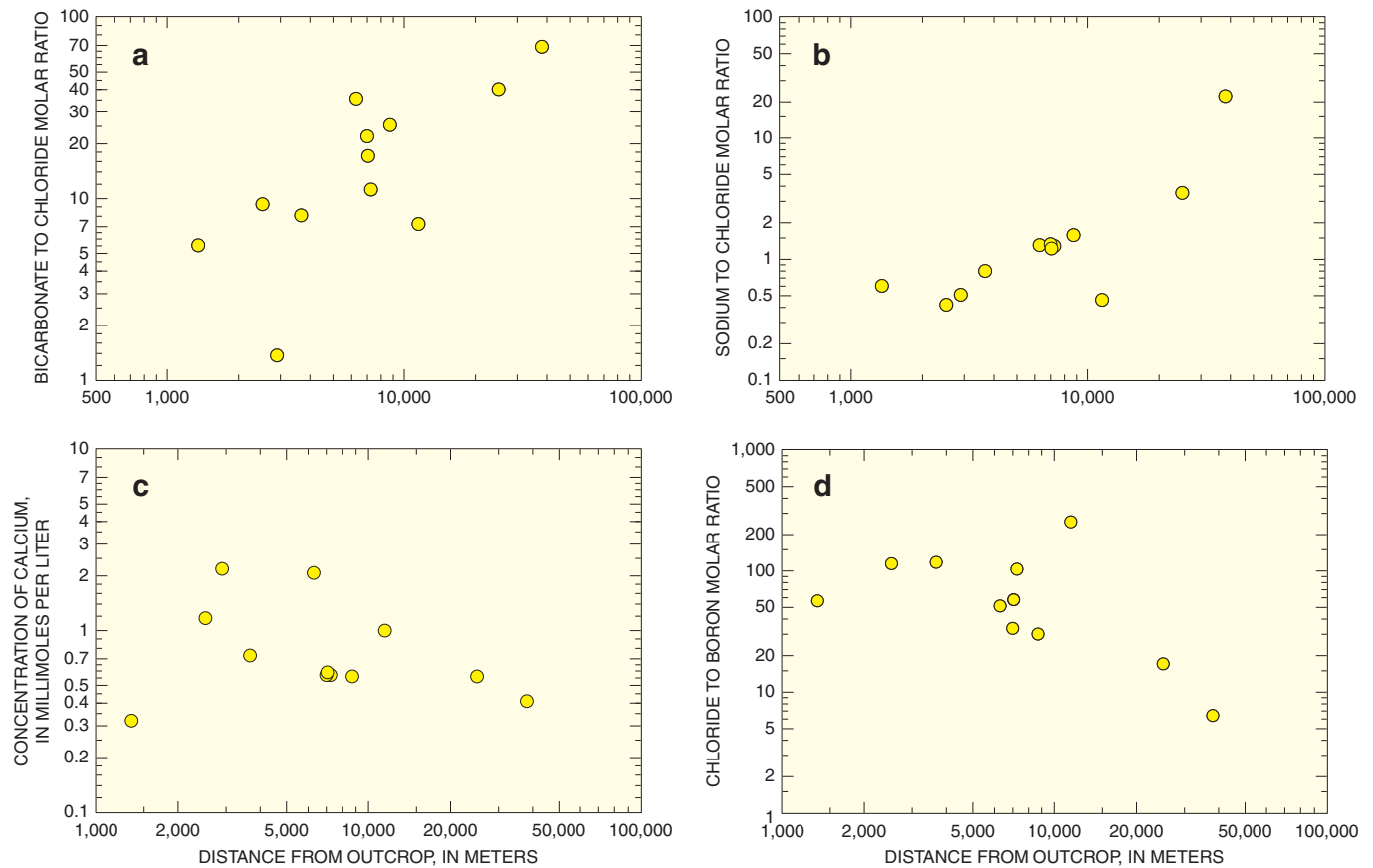


Figure 12. Concentration ratios of (a) bicarbonate to chloride, and (b) sodium to chloride, concentrations of (c) calcium, and concentration ratios of (d) chloride to boron as a function of the distance from the outcrop of the base of the Vincentown and Wenonah-Mount Laurel aquifers and the Englishtown aquifer system, southwestern and south-central New Jersey, 1999–2001.

confining units in New Jersey (Pucci and others, 1997). With the exception of all but one sample, waters from the confined and unconfined parts of the aquifers can be distinguished simply on the basis of the bicarbonate, nitrate plus nitrite, and chloride content (fig. 13). Road salt and fertilizer leachate result in high chloride and nitrate concentrations in the unconfined parts of the lesser aquifers, but have not penetrated the confined parts.

The water quality of samples from several wells shows evidence of effects of pyrite oxidation and dissolution. The dissolution of pyrite leads to high concentrations of sulfur species (often tens of mg/L in contrast to precipitation that typically contains only about 5 mg/L sulfate), of which sulfate is the oxidized end member. Formation of, and dissolution of,

sulfate, coupled with dissolution of iron and trace elements (lead, arsenic, zinc, and copper), results in the generation of hydrogen ions and increases acidity. Water from well 250792 contains atypically high concentrations of iron and sulfate and atypically low pH for a water sample from a confined aquifer and most likely was affected by the dissolution of pyrite. The low pH of waters in New Jersey Coastal Plain aquifers (mostly less than 5.2) usually is associated with unconfined aquifers and acidic recharge that has not yet been buffered by silicate- or carbonate-mineral dissolution reactions. Sulfide mineral oxidation can occur, and can be an appreciable source of acidity in any hydrogeologic environment, however (Gilkeson and others, 1981). The resulting acidic conditions may promote the mobility of radium isotopes in all hydrogeological environments, provided pH is low enough. In the confined parts of the lesser aquifers of the New Jersey Coastal Plain, sulfur appears to have only a minor effect on pH, and Ra solubility remains low.

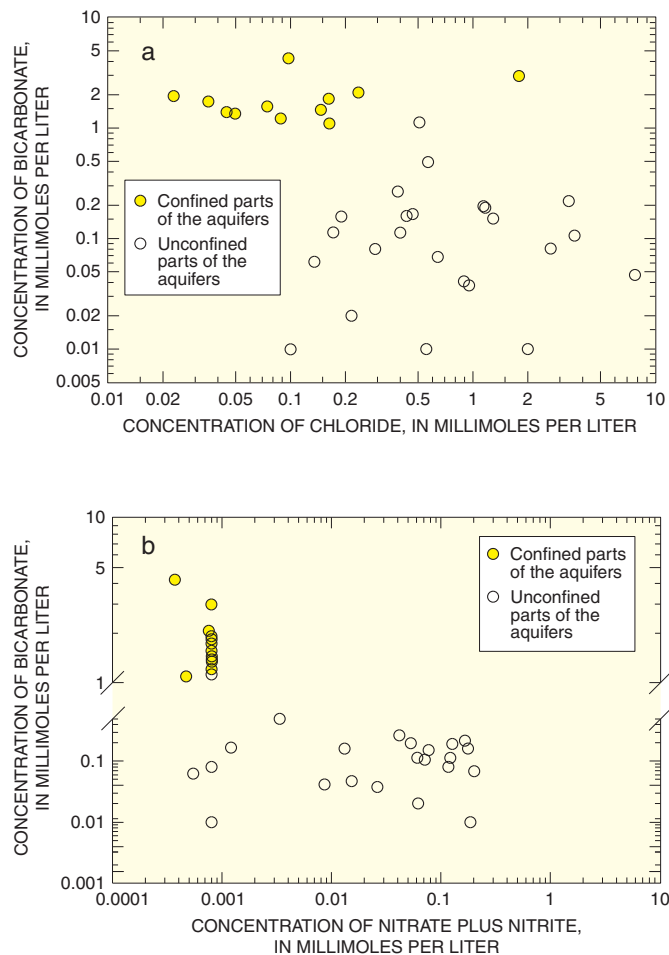


Figure 13. Concentrations of bicarbonate as a function of the concentration of (a) chloride and (b) nitrate plus nitrite in the Vincentown and Wenonah-Mount Laurel aquifers and the Englishtown aquifer system, southwestern and south-central New Jersey, 1999–2001, grouped by whether the sample originated from confined or unconfined parts of the aquifer system.

Radium Isotopes in, and Land Use Overlying, the Unconfined Parts of the Lesser Aquifers

Statistically significant differences (significance level, 0.05) were not determined for the concentrations of Ra-224, Ra-226, and Ra-228 when compared by land use (table 6), though concentrations of Ra-224 were marginally greater in areas of human activity (developed land) (significance level, 0.06). Concentrations of Ra-224, Ra-226, and Ra-228 in water samples collected from the 27 wells completed in the unconfined parts of the Vincentown and Wenonah-Mount Laurel aquifers, and Englishtown aquifer system were compared using only the two land-use categories: developed (agricultural, urban, suburban and undeveloped (forested, wetland, barren). The median concentrations of Ra-224, Ra-226, and Ra-228 in samples from wells in developed areas were less than 0.5, less than 0.5, and 0.65 pCi/L, respectively, and those from wells in undeveloped areas were less than 0.5, less than 0.5, and 0.63 pCi/L, respectively. Similarly, no significant differences were determined among radionuclides when using two categories based only on the predominance of agriculture. Much residential development in these outcrop areas is on land formerly used for agriculture; therefore, it is difficult to differentiate the effects of either land use on water quality. At depth in residential areas, with increasing residence time of the ground water, the water chemistry likely retains an agricultural imprint from the leaching of soil additives such as fertilizers (Szabo and others, 1997; Rice and Szabo, 1997). The effects of agricultural land use on water quality in these mixed land-use areas, therefore, probably is underestimated when considering the chemical data in view of the recent land use. The absence of statistically significant differences in gross alpha-particle activity and radium isotope concentration is the result of typically low concentrations, as well as the small number of samples in each category. The distribution of concentrations of radium between the two groups, developed and undeveloped,

can be distinguished statistically, however, with respect to other inorganic constituents such as nitrate, calcium, magnesium, and dissolved solids, all of which are present in greater concentrations in the developed group than the undeveloped group (table 6).

Leachates from agricultural land or residential land with well-drained soils are readily intercepted by the wells in the unconfined parts of these lesser aquifers because the aquifers are thin, and unconfined wells typically are shallow, often 60 feet in depth or less. The effects of agriculture on water quality, therefore, are great when evaluated by the presence of nitrate in concentrations greater than 3 mg/L. Of the 27 wells completed in unconfined parts of the lesser aquifers, 5 (19 percent) contained nitrate in concentrations greater than the 10-mg/L MCL, and the maximum concentration was 12.46 mg/L (well 330929, completed in the Wenonah-Mount Laurel aquifer). All five of the wells producing water with the highest nitrate concentrations are located in areas of predominantly agricultural land. The maximum concentration of nitrate in water in an area developed primarily as residential land was 7.92 mg/L for well 250793 which is completed in the Vincentown aquifer. Because of the thinness of the aquifers and the shallow nature of the wells, even a small parcel of agricultural or residential land near the well can affect the quality of the ground water.

Undeveloped land overlying these aquifers often encompasses poorly drained clayey soil in low-lying wetlands areas. Nitrate was not present in concentrations greater than 0.5 mg/L in samples from wells completed in unconfined parts of the aquifers in the undeveloped areas; dissolved oxygen (DO) was not detected in samples from some, although not all, of these wells. For example, well 330947 is adjacent to a wetland; samples of water from this well contained less than 0.1 mg/L of DO and 0.08 mg/L nitrate.

Concentrations of divalent cations, such as calcium and magnesium, and the anions chloride, nitrate, and sulfate, are higher in samples of water from unconfined parts of the aquifers in developed areas, especially agricultural areas, than in water samples from the unconfined parts of aquifers in undeveloped areas (table 6). The ranges of concentrations of the divalent cations, such as calcium and magnesium, in water samples from unconfined parts of the aquifers in developed areas were 2.25 to 41 mg/L and 1.1 to 15.6 mg/L, respectively, and for the anions chloride, nitrate, and sulfate, 6.7 to 273 mg/L, 0.05 to 12.46 mg/L, and 0.3 to 83.7 mg/L, respectively. The ranges of concentrations of calcium and magnesium in samples of water from unconfined parts of the aquifers in undeveloped areas were 1.36 to 12.25 mg/L and 2.76 to 3.06 mg/L, respectively, and for the anions chloride, nitrate, and sulfate, 4.7 to 31.6 mg/L, 0.03 to 0.54 mg/L, and 10.61 to 19.91 mg/L, respectively. Solute composition in the unconfined aquifers in developed areas differed from that in the unconfined aquifers in undeveloped areas, and from that in the confined parts of the aquifers, probably as a result of the leaching of soil additives, road salts, and other compounds dispersed by human activity.

The potential for increased acidification of water by nitrification is present in these developed areas and has been documented for the Kirkwood-Cohansey aquifer system (see Szabo and others, 1997, for detail). Nitrate concentrations greater than 3 mg/L do not appear to have resulted in a corresponding decrease in pH for water from the lesser aquifers sampled for this study. Montmorillinite clay, carbonate concretions, and shell material provide greater acid neutralizing capacity and sorption/ion-exchange capacity to sediments that form the lesser aquifers than the marginal marine (beach and barrier island) quartz-rich sand deposits provide to the Kirkwood-Cohansey aquifer system. If development and the associated land application of salts that form dissolved ions continue, along with the ongoing input of hydrogen ions from nitrification, the pH of the water in the lesser aquifers might be decreased and subsequently reduce the available sorption/ion-exchange capacity. This sequence of chemical changes might provide an environment favorable for Ra mobilization (Szabo and others, 1997) and result in a greater frequency of occurrence of Ra isotopes in waters in the lesser aquifers than is documented in this study.

Knowledge of the geochemical mass balance of nitrification and mineral dissolution, especially in agricultural areas, might be useful in understanding the relative importance of nitrification and acidification on the chemistry of water in the aquifers. By analyzing for effects of added fertilizers in sediment cores collected from the various aquifers, one might determine the amount that leads to increased Ra leaching. Experiments similar to those conducted by Yin and others (1996) and Barringer and McLeod (2001) to evaluate trace-element (mercury) leaching could be useful. The frequency of Ra occurrence in conjunction with changes in land use in areas that overlie the aquifers could be determined by targeted sampling along a land-use or geochemical gradient.

Hydrogeological Factors

The strong correlation among concentrations of Ra and geochemical characteristics of the waters from the lesser aquifers indicate aquifer geochemistry is important in determining radium mobility. The aquifer geochemistry is likely affected by the composition of the aquifer materials and surficial inputs as they relate to land use. Because the depositional environments of these lesser aquifers differed substantially, variability in sediment composition, water chemistry, and radium occurrence among the aquifers is likely.

Occurrence of Radium Isotopes Among the Aquifers

For the sake of comparison, the radium isotope concentration and gross alpha-particle activity in samples from the lesser aquifers do not differ significantly among aquifers (table 6). The absence of a statistically significant difference in either gross alpha-particle activity or radium isotope concen-

tration in water from the lesser aquifers in the New Jersey Coastal Plain (table 6) is the result of the typically low concentrations. The concentration of the sum of the Ra isotopes (combined Ra) is greater than 2.5 pCi/L in only four samples. The median gross alpha-particle activity was 4.1 pCi/L with only one sample (4 percent) exceeding the 15-pCi/L MCL (table 4). Each aquifer has a nearly equal percentage of water samples that contain gross alpha-particle activity and radium isotope concentrations high enough to be of concern. The highest gross alpha-particle activities in water from each aquifer overlap or nearly overlap within the analytical PE. On the basis of this limited occurrence data set, water from the Englishtown aquifer system contains slightly more Ra-228 than Ra-226 or Ra-224, whereas water from the Vincentown and Wenonah-Mount Laurel aquifers contains slightly more Ra-226 than Ra-228 or Ra-224.

Researchers have documented the presence of U-rich beds and minerals in the geologic materials that compose most of these aquifers (Gundersen and Peake, 1992; Sugarman, 1999). The maximum concentration of Ra-226 in water from these lesser aquifers, as well as the maximum ratio of Ra-226 to Ra-224 and Ra-226 to Ra-228, was measured in samples from the Wenonah-Mount Laurel aquifer and could indicate that in this aquifer, the U-rich strata may be an appreciable source of Ra in the water. (It is not known at this time why the concentrations of Ra-226 in the water samples from the Vincentown aquifer and Englishtown aquifer system are considerably lower than that from the Wenonah-Mount Laurel aquifer, especially since U-enriched zones are known to be present in the basal units of the sedimentary strata composing these two aquifers.) The maximum concentration of Ra-226 (3.21 pCi/L) in water from the Wenonah-Mount Laurel aquifer is slightly greater than the median concentration value for the Kirkwood-Cohansey aquifer system, 2 pCi/L, despite the fact that the sediments composing that aquifer are not U rich (Szabo and others, 1997). The maximum concentration of U at the Mount Laurel Formation contact (46.5 ppm) is about two orders of magnitude greater than typical concentration results for the sediment materials that compose the Kirkwood-Cohansey aquifer system (typically much less than 0.5 ppm; Szabo and others, 1997). The lower concentrations of Ra-226 in water from the Wenonah-Mount Laurel aquifer when compared to those from the Kirkwood-Cohansey aquifer system illustrate the importance of other factors (such as aquifer geochemistry) in understanding the occurrence of Ra in water; therefore, reliance solely on the presence of radionuclides in the aquifer materials may be misleading when trying to determine radionuclide occurrence in water.

Relations of Radium and pH to the Geologic Composition of Aquifer Materials

Water from the Vincentown and Wenonah-Mount Laurel aquifers, the Englishtown aquifer system, and the Hornerstown and Red Bank sands is slightly less acidic than water

from the Kirkwood-Cohansey aquifer system. This difference in pH probably is the result of the offshore marine environment in which the strata that form the lesser aquifers were deposited. Abundant calcium carbonate bearing shell material, iron carbonate (siderite) concretions, and clay minerals bearing calcium and magnesium (montmorillinite) were available during the formation of, and post-depositional alteration of, the sediments composing the aquifers. The presence of the montmorillinite clay, the concretions, and the shells provides additional acid-neutralizing capacity to the aquifer materials in addition to that provided by the few weatherable silicate minerals (feldspars). Montmorillinite clay commonly contains substantial amounts of calcium and magnesium as part of its internal structure or exchanged onto cation-exchange sites on its surface (Keller, 1970). The aquifer materials are still primarily quartzose, but are micaceous and feldspathic in places, and contain appreciable amounts of marine shell material, especially in the Vincentown Formation. The Red Bank Sand and Englishtown Formation contain siderite (iron carbonate) concretions as well. The sandy sediments of the Englishtown Formation (that compose the Englishtown aquifer system) were deposited primarily in the non-marine delta that inundated the region in late Cretaceous time; consequently the Englishtown aquifer system does have the lowest median pH (5.2) of all the lesser aquifers. Even the sandy deltaic sediments of the Englishtown Formation, however, contain minor amounts of shell materials and siderite concretions, as well as interbedded clayey strata that contain montmorillinite clay (Owens and others, 1961). The delta facies change downdip towards the east-southeast and the south becoming more marine with more shell beds and interbedded montmorillinite clayey strata. The shell minerals and siderite concretions are highly reactive in the presence of infiltrating acidic water and provide minimal, moderate, or substantial acid neutralizing and acid buffering capacity, depending upon the general concentration of carbonate materials and the degree of exposure and weathering. Thus in these lesser aquifers, even where they are unconfined, the hydrogen ions (acidity) in infiltrating water may be consumed by shell mineral dissolution. Also, pH less than 5.0 is not readily maintained, as is the case for the water percolating into the marginal marine (Carter, 1978) but extremely quartzose sand of the upper Kirkwood Formation and the Cohansey Sand (composing the Kirkwood-Cohansey aquifer system) where shells and montmorillinite clay are absent. The sandy sediments of the Englishtown Formation are quartzose but also contain feldspar, mica, carbonate shells, and montmorillinite; therefore, the sediments are not exactly like the extremely quartzose sand sediments of the Kirkwood Formation and Cohansey Sand. The slightly greater median pH of the Englishtown aquifer system than that of the Kirkwood-Cohansey aquifer system (4.8, Szabo and others, 2005) indicates the water-rock interactions (geochemical processes in aquifers along water flow paths) between the two aquifers differ slightly (because of differing depositional setting resulting in differing mineralogy).

The distribution of Ra concentrations in the water in these lesser aquifers is primarily dependent upon the local pH. The local pH within each aquifer sampled in this study may, in part, be a function of the amount and distribution of shells and clay present in the aquifer material, the orientation of flow paths, and the residence time of the water. It is assumed that the weathering of feldspar, mica, montmorillonite clay (which can release calcium and magnesium), and carbonate shells along flow paths in the aquifers will result in an increase in pH, even for water with short (5–10 years) residence times.

Geographic Distribution of Radium Isotopes within the Lesser Aquifers

The Ra-224, Ra-226, Ra-228 concentrations, and gross alpha-particle activity differ geographically; values of these constituents typically were greater in the water from the northeastern part of the study (aquifer outcrop) area than the southwestern part (figs. 2 and 5). (Burlington County and north is considered the northeastern part; Camden County and south is considered the southwestern part.) Three samples from the northeastern part of the study area (Vincentown aquifer and Englishtown aquifer system outcrop area) contained concentrations of Ra-224 greater than 2.5 pCi/L, and four samples contained combined Ra concentrations of greater than 3.5 pCi/L; two samples contained combined Ra greater than 5 pCi/L. These samples were collected in Burlington and Monmouth Counties. The only sample containing gross alpha-particle activity greater than the 15-pCi/L MCL was collected from a well in Monmouth County (well 250717; fig. 5) completed in the Vincentown aquifer.

In the southwestern part of the study (aquifer outcrop) area, the maximum concentration of Ra-224, 0.42 pCi/L, was present in a sample from well 330902, and the maximum concentration of Ra-226, 1.31 pCi/L, was present in a sample from well 330929. Both wells were completed in the Wenonah-Mount Laurel aquifer in Salem County. The maximum gross alpha-particle activity was 4.91 pCi/L in the sample from well 071005 completed in the Englishtown aquifer system in Camden County. The concentration of Ra-228 was less than the SSMDC in all but one sample, which was from well 330948 completed in the Wenonah-Mount Laurel aquifer in the southwestern part of the study (aquifer outcrop) area.

The lesser aquifers in the southwestern and northeastern parts of the study area contain predominantly acidic waters in the unconfined parts (outcrop area) of each of the aquifers; typical pH ranged from 4.2 to 6.7. The pH was slightly but significantly lower statistically in the northeastern part (median, 5.15) than the southwestern part (median, 5.4) of the study (aquifer outcrop) area, however. In the northeastern part of the study area (aquifer outcrop), eight samples had pH less than 5.0, whereas no sample had pH less than 5.0 in the southwestern part of the study area (aquifer outcrop). The minimum pH in the southwestern part of the study area (aquifer outcrop) was 5.2.

The southwestern part of the study (aquifer outcrop) area differs from the northeastern part in that the environment of deposition in the southwestern area tends to be further offshore (more distal) for each of the sedimentary units forming the aquifers than is the case for the northeastern area. The sand is somewhat thinner and somewhat more shelly and clayey in the southwest than the northeast. Each of the described factors would tend to buffer pH at somewhat more circumneutral (less acidic) values. The pH does reflect this minor difference in composition, as does the occurrence pattern of Ra isotopes, which are highest in concentration in the most acidic waters. In contrast, the geographic distribution of elevated (greater than 3 pCi/L) Ra occurrence is the reverse for the Kirkwood-Cohansey aquifer system, where agricultural land, high nitrate, and low pH are more likely to be found in the southwestern part of that aquifer outcrop area than in the northeastern part (Szabo and others, 2005).

The geographic distribution of the naturally occurring radioactive materials in the surficial gravels of the Bridgeton Formation, which caps local ridges in southwestern New Jersey, was considered, but it overlaps only a very minor region of the outcrops of these lesser aquifers in the southwestern part of the State. The Bridgeton Formation is known to contain substantial amounts of radionuclides based on areal gamma ray surveys (Duval, 1991), elevated radon concentrations in soil gas (Gundersen and Peake, 1992), and elevated concentrations of Ra in water (Zapeczka and Szabo, 1989). Radium contamination of water from the lesser aquifers is minimal in the southwestern part of the State, however, and the presence of the Bridgeton Formation is so slight that it is not a major factor. Concentrations of all isotopes of Ra are typically low (less than 1 pCi/L) in the southwestern part of the aquifer outcrop area. This result is due to the general tendency for the ground-water pH to be greater than 5.0 in the area; the pH of each of the 10 samples from the southwestern part of the aquifer outcrop area was greater than 5.2. On the other hand, the Bridgeton Formation caps the Cohansey sand primarily in areas of intense agriculture in southwestern New Jersey where the median pH of ground water is about 4.8 (Kozinski and others, 1995).

This study of the water quality in the lesser aquifers, Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and the Hornerstown and Red Bank Sands, has provided a considerable amount of new information showing that the elevated Ra-224 concentrations (greater than 2.5 pCi/L) are present in water from aquifers underlying a few townships or drainage basins, primarily in, but not restricted to, the central, north-central, and northeastern Coastal Plain of New Jersey from southwestern Burlington County to southern Monmouth County (fig. 5). The highest concentrations of Ra in water in the lesser aquifers typically are not found in the southwestern part of the State. The determination of the concentration of Ra-224 and measurement of gross alpha-particle activity within 48 hours of sample collection in east-central New Jersey more accurately characterizes the amount of radiation exposure from drinking water than was the case before

this sampling program was conducted. Because the lesser aquifers in the outcrop areas in central and east-central New Jersey contain acidic water (pH less than 5.0) and because use of these lesser aquifers for drinking water is greatest in these areas, this finding that concentrations of combined radium and Ra-224 are most likely to be elevated above 2.5 pCi/L in acidic water is of substantial importance to water managers and private citizens (water consumers). Educational outreach documents regarding the issues concerning radioactivity in water have been prepared by NJDEP (New Jersey Department Environmental Protection, 1997) but had been distributed mostly in the southwestern part of the State where radionuclide occurrence had previously been documented by Szabo and dePaul (1998).

Regional Significance of Ra-224 Concentrations and Gross Alpha-Particle Activity

The analytical capability to detect and quantify the presence of short-lived radioisotopes (such as Ra-224) (Szabo and others, 1998) and the reduction in sample holding time before measuring gross alpha-particle activity (Parsa, 1998) has led to identification of ground waters that contain more radioactivity than had been known previously. This improvement in understanding radionuclide occurrence is especially notable in some areas in southern New Jersey underlain by acidic sand-and-gravel aquifers. In many areas of southwestern New Jersey where samples had been collected before 1997, the MCL for combined radium or gross alpha-particle activity was known to be exceeded in water from the Kirkwood-Cohansey aquifer system in some locales (Szabo and dePaul, 1998); with the 48-hour gross alpha-particle measurement technique, the gross alpha-particle activity was found to exceed the MCL far more frequently (Szabo and others, 2005). This increased detection capability is thus expected to continue to make a considerable difference in our understanding of the distribution of radioactivity in drinking-water supplies throughout the Atlantic Coastal Plain of the United States as the measurement techniques with short holding times gain widespread acceptance.

This study of the generalized geohydrology and geochemistry of Ra occurrence in the lesser aquifers of the New Jersey Coastal Plain, as well as the studies of the Kirkwood-Cohansey aquifer system (Szabo and dePaul, 1998; Szabo and others, 2005) provides data to evaluate the occurrence of Ra in a regional sense in the New Jersey Coastal Plain. To gain understanding, the gross alpha-particle activities and Ra concentrations in the samples from the lesser aquifers are compared with those in samples from the Kirkwood-Cohansey aquifer system, collected by the USGS since 1997 (when the 48–72 hour holding time came into use). In the following sections, the results for the New Jersey Coastal Plain also are

compared to similar results available for the Mid-Atlantic region (Delaware and Maryland) of the Atlantic Coastal Plain of the United States.

Comparison of the Occurrence of Ra-224, Ra-226, Ra-228 and Gross Alpha-Particle Activity in the Lesser Aquifers with that in the Kirkwood-Cohansey Aquifer System

Water samples from the Kirkwood-Cohansey aquifer system collected by the USGS since 1997 had a median gross alpha-particle activity of 14.9 pCi/L with 49 percent exceeding the 15-pCi/L MCL (Szabo and others, 2005). In contrast, water samples collected by the USGS from the sampled (lesser) aquifers in this study had a median gross alpha-particle activity of 4.1 pCi/L with only 4 percent exceeding the 15-pCi/L MCL. The highest gross alpha-particle activity for the post-1997 sampling of the Kirkwood-Cohansey aquifer system was 77.3 pCi/L, an activity about five times greater than the 16 pCi/L maximum gross alpha-particle activity in water from the sampled (lesser) aquifers. The concentration of Ra isotopes was greater than 2.5 pCi/L in only a handful (about 10 percent) of samples from the lesser aquifers (app. 3), whereas this result was commonplace (about 50 percent) in samples from the slightly more acidic Kirkwood-Cohansey aquifer system. The large difference between typical gross alpha-particle activity in water from the Kirkwood-Cohansey aquifer system and that in water from the lesser Coastal Plain aquifers is proportional to, and represents, the difference in concentrations of alpha-particle emitting radioisotopes, primarily Ra-224 and Ra-226.

The median pH of water from the Vincentown and Wenonah-Mount Laurel aquifers, the Englishtown aquifer system, and the Hornerstown and Red Bank Sands, 5.2, is only about one-half a pH unit greater than for water from the Kirkwood-Cohansey aquifer system (4.8 in Kozinski and others, 1995; 4.7 in Szabo and others, 2005); this minor difference results in an appreciable difference in the frequency of occurrence of elevated concentrations of Ra. Also, the pH at the 25th percentile of the water-pH data from the unconfined parts of these lesser aquifers is 4.9, whereas the pH at the 75th percentile of the water-pH data from the unconfined Kirkwood-Cohansey aquifer system is 4.9 (Szabo and others, 2005). Therefore, about 75 percent of the water in the Kirkwood-Cohansey aquifer system is acidic enough to contain elevated concentrations of Ra, but only 25 percent of the water in the unconfined part of the lesser aquifers is acidic enough to contain elevated concentrations of Ra. Concentrations of Ra isotopes typically did not exceed 2.5 pCi/L in the Kirkwood-Cohansey aquifer system where pH was greater than 5.2 (Szabo and others, 2005); the pH typically must be less than 5.0 for Ra isotopes to exceed 3 pCi/L in that aquifer, indicating Ra occurrence is similar for the lesser aquifers and the Kirkwood-Cohansey aquifer system when the distribution of pH is considered. Concentrations of a Ra isotope greater than

3.0 pCi/L have been measured on occasion in water samples from the Kirkwood-Cohansey aquifer system with pH slightly greater than 5.0 (5.1 in Szabo and others, 2005; 5.4 in Kozinski and others, 1995). It is not readily evident whether there is a physical or chemical reason for the absence of elevated concentrations of Ra in water with pH greater than 5.0 from the lesser aquifers or whether the sampling density simply has not been great enough to intercept and thus identify such water.

The occurrence of low pH with Ra is consistent with Ra geochemistry as previously reported by Kozinski and others (1995) and Szabo and dePaul (1998). The lack of correspondence between nitrate concentrations and elevated Ra concentrations in water samples from the Vincentown aquifer and Englishtown aquifer system is not consistent, however, with the results for the Kirkwood-Cohansey aquifer system as reported by Kozinski and others (1995) and Szabo and others (2005). In water samples from the Kirkwood-Cohansey aquifer system, concentrations of Ra typically were greater than 3 pCi/L when nitrate concentrations were greater than 3 mg/L, and pH ranged from about 4.8 to 5.2 (Szabo and others, 2005).

The importance of nitrate as a fraction of the dissolved mineral matter in water and its role in Ra mobilization is not as great for water from the unconfined part of the Vincentown and Wenonah-Mount Laurel aquifers and the Englishtown aquifer system as for water from the Kirkwood-Cohansey aquifer system. Because nitrate typically is the predominant anion and the quartzose mineral matter contributes little dissolved mineral matter, nitrate-bearing leachate dominates the chemistry and often enhances acidity in the dilute waters of the Kirkwood-Cohansey aquifer system (Kozinski and others, 1995; Szabo and others, 1997; Szabo and dePaul, 1998). Szabo and others (1997) propose that the water-quality degradation (increase in dissolved salts and decrease in pH) associated with nitrate-bearing leachate is likely to mobilize Ra in the poorly buffered acidic environments in the dilute waters of the Kirkwood-Cohansey aquifer system.

A likely reason for the smaller effect of nitrate on the mobilization of Ra in the lesser aquifers relative to the effect in the Kirkwood-Cohansey aquifer system is the complex aqueous chemistry of the lesser aquifers. Alkalinity ranged from less than 1.0 mg/L to 24.8 mg/L in water from the unconfined parts of the lesser aquifers (figs. 9, 10, and 11), with a median of 5.7 mg/L. In contrast, the median alkalinity of samples from the unconfined Kirkwood-Cohansey aquifer is reported as 2.0 mg/L (Kozinski and others, 1995). The difference in alkalinity is indicative of the slightly higher pH values of the unconfined lesser Coastal Plain aquifers than of the Kirkwood-Cohansey aquifer system. Water from the unconfined parts of the lesser aquifers typically contain a greater amount of dissolved mineral matter and greater buffering capacity than is present in the Kirkwood-Cohansey aquifer system. These geochemical characteristics result, in part, from the complex mineralogy of the moderate-depth marine deposits of the Vincentown and Wenonah Formations, and of the Mount Laurel Sand and the partially submerged sandy deltaic deposits of the Englishtown Formation. Because of the mod-

erate-depth marine depositional environment for the former, abundant shell material bearing calcium carbonate and clay minerals bearing calcium and magnesium (montmorillinite) are present. The presence of carbonate shell material and other soluble silicate minerals, such as feldspars, and clay minerals with high calcium and magnesium content, such as montmorillinite and glauconite, leads to higher dissolved mineral matter, specific conductivity, and acid neutralizing capacity in the lesser aquifers than is the case in the Kirkwood-Cohansey aquifer system. The predominantly quartzose marginal marine sediments of Kirkwood-Cohansey aquifer system provide little dissolved mineral matter or buffering capacity.

Radium-224 was the alpha-particle emitting radionuclide that most often had the highest concentration of any radioisotope in water from the Kirkwood-Cohansey aquifer system; thus, Ra-224 accounts for the greatest amount of alpha radioactivity in water from that aquifer (Szabo and others, 2005). In the absence of previously measured concentration data, the same trend in concentrations was considered possible for water from the lesser aquifers of the Coastal Plain. Concentrations of Ra-224 and progeny were on occasion dominant in the water samples from the Englishtown aquifer system. For water from the either the Vincentown or Wenonah-Mount Laurel aquifers, however, the concentration of Ra-224 accounts for an appreciable, but not an overwhelming part of the gross alpha-particle activity, and the concentration of Ra-226 is dominant among the Ra isotopes on many occasions. The geologic materials composing the lesser aquifers, especially the Vincentown Formation, Wenonah Formation, Mount Laurel Sand, and the Hornerstown Sand, have been reported previously to contain radioactive (uranium enriched) phosphatic strata common in some moderate depth marine depositional environments. The geologic materials composing the Kirkwood-Cohansey aquifer system are not known to contain uranium-rich phosphate beds. The difference in geology in this respect could be one of the reasons that Ra-224 is not predominant among the Ra isotopes in these lesser aquifers, as it is in the Kirkwood-Cohansey aquifer system.

Comparison of the Occurrence of Ra-224, Ra-226, Ra-228 and Gross Alpha-Particle Activity in the Lesser Aquifers with that in Other Aquifers in the Mid-Atlantic Coastal Plain

The occurrence of Ra in water from the Vincentown and Wenonah-Mount Laurel aquifers, the Englishtown aquifer system, and the Hornerstown and Red Bank Sands appears to be consistent with previous conclusions drawn regarding the generalized geohydrology and geochemistry of Ra occurrence in the New Jersey Coastal Plain (Szabo and dePaul, 1998), making the occurrence predictable, at least in a regional sense. The presence of elevated Ra is likely in the unconfined part of the lesser aquifer systems where the water is acidic with pH less than 5.0. The occurrence of such acidic waters is not commonplace in the lesser aquifer systems and may be controlled

locally as much by mineralogy of the geologic strata, such as the abundance of pyrite or shell beds or the type of clay mineral, as by leachate associated with various human activities at the overlying land surface.

Large values for gross alpha-particle activity also have been reported in water where pH was typically less than 5.0 for the Kirkwood-Cohansey aquifer system in southern New Jersey, as well as at least two Coastal Plain aquifers in Maryland (Bolton, 2000). In contrast, gross alpha-particle activity was reported to be typically low in water with pH greater than 5.0, the typical condition encountered in the initial sampling efforts for the lesser aquifers in the Coastal Plain of New Jersey and in the Coastal Plain aquifers of Delaware (Ferrari, 2002). Geochemical processes appear to be a critical factor in mobilizing Ra in aquifers in large parts of the Mid-Atlantic region of the Atlantic Coastal Plain, a region that has been documented to contain abundant gross alpha-particle activity and Ra in ground water (Bolton, 2000; Focazio and others, 2001).

Summary and Conclusions

This study of naturally occurring radioactivity in water from the lesser aquifers in southwestern and east-central New Jersey—Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and the Hornerstown and Red Bank Sands—was conducted by the U.S. Geological Survey, in cooperation with the New Jersey Department Environmental Protection, as part of a series of studies of natural radioactivity in water in the southern and central New Jersey Coastal Plain. The occurrence of alpha radioactivity and three isotopes of radium—radium-224, radium-226, and radium-228—was investigated in the first regionally focused study of the presence of natural radioactivity in water in these thin, local sand aquifers.

The geologic materials composing the lesser aquifers, especially the Vincentown Formation, Wenonah Formation, Mount Laurel Sand, and the Hornerstown Sand, previously had been reported to contain radioactive (uranium enriched) phosphatic strata common in some moderate depth marine depositional environments. The decay of uranium (and thorium) gives rise to the presence of natural radioactivity and of numerous radioactive progeny, including isotopes of radium. The presence of natural radioactive isotopes in water used for drinking, especially isotopes of radium, is of concern because radium is a known human carcinogen and ingestion may increase the health risk. Determining the distribution of the isotopes of radium in water from the lesser aquifers of southwestern and south-central New Jersey is of considerable interest because the widespread presence of concentrations of radium-226 and radium-228 greater than the U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL) previously has been demonstrated in other aquifers in the New Jersey Coastal Plain.

A regional network in southwestern and east- and south-central New Jersey of 39 wells completed in the lesser aquifers was sampled for determination of gross alpha-particle activity and concentrations of radium, major ions, and selected trace elements. Concentrations of radium-224, radium-226, and radium-228 were determined for water samples from 28 of the 39 wells, whereas gross alpha-particle activity was determined for all 39. The alpha spectroscopic technique was used to determine concentrations of radium-224, which ranged from less than 0.5 to 2.7 pCi/L with a median concentration of less than 0.5 pCi/L, and of radium-226, which ranged from less than 0.5 to 3.2 pCi/L with a median concentration of less than 0.5 pCi/L. The beta-counting technique was used to determine concentrations of radium-228, which ranged from less than 0.5 to 4.3 pCi/L with median concentration also less than 0.5 pCi/L. Radium-228 had the greatest concentration among the three radium radioisotopes in 9 of the 12 samples (75 percent) for which radium concentrations were quantifiable. The concentration of radium-224 exceeded that of radium-226 in five of six samples (83 percent) in which concentrations of both were quantifiable. Radium radionuclide distribution differs by aquifer, the highest concentrations of Ra-228 were present in the Englishtown aquifer system, and the highest Ra-226 concentrations were present in the Wenonah-Mount Laurel aquifer. Water containing radium radionuclides at levels of concern in the regions underlain by these lesser aquifers are located primarily in, but are not restricted to, the central, north-central, and northeastern Coastal Plain of New Jersey. Radium-224 contributes a considerable amount of gross alpha-particle activity to drinking water withdrawn from all the aquifers but is not consistently the dominant radionuclide as it is in water from the Kirkwood-Cohansey aquifer system also in the New Jersey Coastal Plain.

Gross alpha-particle activities were found to exceed the MCL of 15 pCi/L for this measure of radioactivity in one sample (activity, 16 pCi/L) collected from the Vincentown aquifer. Concentrations of gross alpha-particle activity were measured within 48 hours after sample collection to ensure that the alpha-particle radiation from radium-224 also was determined. A greater part of the gross alpha-particle activity in water from the Wenonah-Mount Laurel aquifer is attributable to the decay of Ra-226 than is the case for the other aquifers; this result is consistent with the distribution of the Ra-226.

Concentrations of radium-224 correlate strongly with those of radium-226 and radium-228 (Spearman correlation coefficients, r , +0.86 and +0.66, respectively). The greatest concentrations of radium-224, radium-226, and radium-228 were present in the most acidic ground water. All radium-224, radium-226, and radium-228 concentrations greater than 2.5 pCi/L were present in samples of ground water with pH less than 5.0.

The presence of gross alpha-particle activities greater than 15 pCi/L and combined radium-226 and radium-228 concentrations greater than 5 pCi/L in the lesser aquifers was not nearly as common as in samples from the Kirkwood-Cohansey aquifer system, probably because the pH of water

from these lesser aquifers is slightly greater than the pH in the Kirkwood-Cohansey aquifer system. Only about 25 percent of the samples from wells in the unconfined parts of the lesser aquifers contained water with pH less than 5.0, whereas about 75 percent of the samples from wells in the Kirkwood-Cohansey aquifer system had a pH less than 5.0. The moderate depth marine depositional environment and the resultant abundance of shell beds and calcium- and magnesium-bearing clays provide slightly greater acid neutralizing capacity than is typical for the marginal marine quartzose Kirkwood-Cohansey aquifer system.

Much of the drinking water obtained from these lesser aquifers is from private self-supply wells that likely are not routinely tested for the presence of alpha-particle radioactivity or radium isotopes, except perhaps at the time of real estate transfer as required by the State of New Jersey. The low pH (less than 5.0) associated with all the elevated concentrations of radium-224, radium-226, and radium-228, and gross alpha-particle activities that might exceed the respective MCLs could be used as an initial screen that could indicate relative vulnerability of drinking water to elevated concentrations of radium radionuclides and alpha-particle activity, which present an increased health risk.

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References Cited

- American Society for Testing and Materials, 1999, Measurement of radioactivity, *in* American Society for Testing and Materials Standards, Philadelphia, Pa., v. 11.02, p. 240.
- Anderson, J.R., Hardy, E.E., Roach, J.T., and Witmer, R.E., 1976, A land use and land cover classification system for use with remote sensor data: U.S. Geological Survey Professional Paper 964, 28 p.
- Apello, C.A.J., 1994, Cation and proton exchange, pH variations, and carbonate reactions in a freshening aquifer: *Water Resources Research* 30, p. 2793–2805.
- Back, William, 1966, Hydrochemical facies and ground-water flow patterns in northern part of Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 498-A, 64 p.
- Barringer, J.L., and MacLeod, C.L., 2001, Relation of mercury to other chemical constituents in ground water in the Kirkwood-Cohansey aquifer system, New Jersey Coastal Plain, and mechanisms for mobilization of mercury from sediments to ground water: US Geological Survey Open-File Report 00-4230, 154 p.
- Bolton, D.W., 2000, Occurrence and distribution of radium, gross alpha-particle activity and gross beta-particle activity in ground water in the Magothy Formation and the Potomac Group aquifers, upper Chesapeake Bay area, Maryland: Maryland Geological Survey Report of Investigations 70, 143 p.
- Carter, C.H., 1978, A regressive barrier and barrier-protected deposit: depositional environments and geographic setting of the Late Tertiary Cohansey Sand: *Journal of Sedimentary Petrology*, v. 48, no. 3, p. 933–950.
- Cauller, S.J., Carleton, G.B., and Storck, M.J., 1999, Hydrogeology of, water withdrawal from, and water levels and chloride concentrations in the major Coastal Plain aquifers of Gloucester and Salem Counties, New Jersey: U.S. Geological Survey Water-Resources Investigations Report 98-4136, 123 p.
- Cohn, Perry, Skinner, Ric, Burger, Stasia, Fegliano, Jerald, and Klotz, Judith, 2003, Radium in drinking water and the incidence of osteosarcoma: Trenton, N.J., New Jersey Department of Health, unpublished report, 23 p. [Online at <http://www.nj.gov/health/eoh/radium.pdf>]
- dePaul, V.T., Gardner, P.L., Kopera, A.J., Roy, H.C., and Szabo, Zoltan, 2000, Use of ground-water radon-222 occurrence data in combination with indoor-air radon potential to maximize benefits of the “Multimedia” Radon-Mitigation Program in New Jersey: Proceedings, National Groundwater Association Emerging Issues Conference, Minneapolis, Minn., June 7–8, 2000, p. 34–35.

- Durrance, E.M., 1986, Radioactivity in geology: Principles and applications: Chichester, UK, Ellis Horwood Limited, 441 p.
- Duval, J.S., 1991, Use of aerial gamma-ray data to estimate relative amounts of radon in soil gas: U.S. Geological Survey Bulletin 1971, p. 155–162.
- Ellis, W.H., Jr., and Price, C.V., 1995, Development of a 14-digit hydrologic coding scheme and boundary data set for New Jersey: U.S. Geological Survey Water-Resources Investigations Report 95-4134, 1 pl.
- Faires, L.M., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory-Determination of metals in water by inductively coupled plasma-mass spectrometry: U.S. Geological Survey Open-File Report 92-634, 28 p. [Available online at <http://pubs.er.usgs.gov/pubs/ofr/ofr92634>]
- Ferrari, M.J., 2002, Occurrence and distribution of selected contaminants in public drinking-water supplies in the surficial aquifer in Delaware: U.S. Geological Survey Open-File Report 01-327, 62 p.
- Fishman, M.J., and Friedman, L.C., 1989, Methods for determination of inorganic substances in water and fluvial sediments: Techniques of Water Resources Investigations of the U.S. Geological Survey, book 5, chap. A1, 545 p.
- Fleischer, R.L., 1980, Isotopic disequilibrium of uranium: Alpha-recoil damage and preferential solution effects: Science, v. 207, p. 979–981.
- Focazio, M.J., Szabo, Zoltan, Kraemer, T.F., Mullin, A.H., Barringer, T.H. and dePaul, V.T., 2001, Occurrence of selected radionuclides in ground water used for drinking water in the United States: A reconnaissance Survey, 1998: U.S. Geological Survey Water-Resources Investigations Report 00-4273, 35 p. [Available online at <http://water.usgs.gov/pubs/wri/wri004273/pdf/wri004273.pdf>]
- Gilkeson, R.H., Perry, E.C., Jr., and Cartwright, Keros, 1981, Isotopic and geologic studies to identify the sources of sulfate in groundwater containing high barium concentrations: Illinois State Geological Survey Report 1981-4, 39 p.
- Gundersen, L.C.S., and Peake, R.T., 1992, Radon in the Coastal Plain of Texas, Alabama, and New Jersey: Geological Society of America Special Paper 271, p. 53–64.
- Hall, F.R., Donahue, P.M., and Eldridge, A.L., 1985, Radon gas in ground water in New Hampshire: National Water Well Association Proceedings, Second Annual Eastern Regional Ground Water Conference, Worthington, Ohio, p. 86–100.
- Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: New York, N.Y., Elsevier, 522 p.
- Hess, C. T., Michel, J., Horton, T. R., Prichard, H. M. and Coniglio, W. A., 1985, The occurrence of radioactivity in public water supplies in the United States: Health Physics, v. 48, no 4, p. 553–586.
- Ivahnenco, Tamara, Szabo, Zoltan and Hall, G.S., 1996, Use of an ultra-clean sampling technique with inductively coupled plasma-mass spectrometry to determine trace-element concentrations in water from the Kirkwood-Cohansey aquifer system, Coastal Plain, New Jersey: U.S. Geological Survey Open-File Report 96-142, 37 p. [Available online at <http://pubs.er.usgs.gov/pubs/ofr/ofr96142>]
- Ivahnenco, Tamara, Szabo, Zoltan and Gibs, Jacob, 2001, Changes in sample-collection and analytical techniques and effects on retrospective comparability of low-level concentration of trace elements in ground water: Water Research, v. 35, no. 15, p. 3611–3624.
- Janzer, V. J., 1980, Discordant gross radioactivity measurements of natural and treated waters, in Kelly, J.J., ed., Effluent and environmental radiation surveillances: Philadelphia, Pa., American Society Testing Materials Special Technical Publication 698, p. 327–341.
- Jeter, H.W., 1998, An extended-range method for gross alpha-beta-particle measurements in water samples: Radiochemistry Radioactivity, v. 9, no. 1, p. 16–25.
- Kauffman, L.J., Baehr, A.L., Ayers, M.A., and Stackelberg, P.E., 2001, Effects of land use and travel time on the distribution of nitrate in the Kirkwood-Cohansey aquifer system in southern New Jersey: U.S. Geological Survey Water-Resources Investigations Report 01-4117, 49 p.
- Keller, W.D., 1970, Environmental aspects of clay minerals: Journal Sedimentary Petrology, v. 40, p. 788–813.
- Knoll, G.F., 1989, Radiation detection and measurement: New York, Wiley & Sons, 754 p.
- Koterba, M.T., Wilde, F.D. and Lapham, W.W., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment Program: Collection and documentation of water-quality samples and related data: U.S. Geological Survey Open-File Report 95-399, 113 p.
- Kozinski, Jane, Szabo, Zoltan, Zapacza, O.S., and Barringer, T.H., 1995, Natural radioactivity in, and inorganic chemistry of, ground water in the Kirkwood-Cohansey aquifer system, southern New Jersey 1983–89: U.S. Geological Survey Water-Resources Investigations Report 92-4144, 130 p. [Available online at <http://pubs.er.usgs.gov/pubs/wri/wri924144>]
- Krieger, H.L., and Whittaker, E.L., 1980, Prescribed procedures for measurement of radioactivity in drinking water: U.S. Environmental Protection Agency Manual EPA-600/4-80-032, 111 p.

- Lacombe, P.J., and Rosman, Robert, 2001, Water levels in, extent of freshwater in, and water withdrawals from ten confined aquifers, New Jersey and Delaware Coastal Plain, 1998: U.S. Geological Survey Water-Resources Investigations Report 00-4143, 10 pl. [Available online at <http://pubs.er.usgs.gov/pubs/wri/wri004143>]
- Langmuir, Donald, and Herman, J.S., 1980, The mobility of thorium in natural waters at low temperatures: *Geochimica Cosmochimica Acta*, v. 44, p. 1753–1766.
- Leahy, P.P., and Martin, Mary, 1993, Geohydrology and simulation of ground-water flow in the northern Atlantic Coastal Plain aquifer system: U.S. Geological Survey Professional Paper 1404-K, 81 p. [Available online at <http://pubs.er.usgs.gov/pubs/pp/pp1404K>]
- Leydecker, Al, Sickman, J.O., and Melack, J.M., 1999, Episodic lake acidification in the Sierra Nevada, California: *Water Resources Research*, v. 35, no. 9, p. 2793–2804.
- Martin, Mary, 1998, Ground-water flow in the New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1404-H, 146 p. [Available online at <http://pubs.er.usgs.gov/pubs/pp/pp1404H>]
- 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.
- Miller, K.G., Mountain, G.S., Browning, J.V., Kominz, M., Sugarman, P.J., Christie-Blick, N., Katz, M.E., and Wright, J.D., 1998a, Cenezoic global sea-level, sequences, and the New Jersey Transect: Results from coastal plain and slope drilling: *Reviews of Geophysics*, v. 36, p. 569–601.
- Miller, K.G., Sugarman, P.J., Browning, J.V., Olsson, R.K., Pekar, S.F., Reilly, T.J., Cramer, B.S., Aubry, M.P., Lawrence, R.P., Curran, J., Stewart, M., Metzger, K.T., Uptegrove, Jane, Bukry, D., Burckle, L.H., Wright, J.D., Feigenson, M.D., Brenner, G.J., and Dalton, R.F., 1998b, Bass River site, *in* Miller, K.G., Sugarman, P.J., and Browning, J.V., eds., *Proceedings Ocean Drilling Program Initial Reports 174AX*, p. 5–43 [Online at http://www.odp.tamu.edu/publications/174AXSR/VOLUME/CHAPTERS/174AXS_1.PDF]
- Miller, K.G., Sugarman, P.J., Browning, J.V., Cramer, B.S., Olsson, R.K., deRomero, Linda, Aubry, M.P., Pekar, S.F., Georgescu, M.D., Metzger, K.T., Monteverde, D.H., Skinner, E.S., Uptegrove, Jane, Mullikin, L.G., Muller, F.L., Feigenson, M.D., Reilly, T.J., Brenner, G.J., and Queen, Don, 1999, Ancora site, *in* Miller, K.G., Sugarman, P.J., and Browning, J.V., eds., *Proceedings Ocean Drilling Program Initial Reports 174AX Supplement*, p. 1–65 [Online at http://www.odp.tamu.edu/publications/174AXSR/VOLUME/CHAPTERS/174AXS_2.PDF]
- Miller, K.G., Sugarman, P.J., Browning, J.V., Kominz, M.A., Hernandez, J.C., Olsson, R.K., Wright, J.D., Feigenson, M.D., and Van Sickle, William, 2003, Late Cretaceous chronology of large, rapid sea-level changes: Glacioeustasy during the greenhouse world: *Geology*, v. 31, no. 7, p. 585–588.
- Miller, R.L., 1992, Ion-exchange control of radium-226 activities in ground water of Sarasota County, Florida, *in* Gohn, G.S., ed., *Proceedings of the 1988 U.S. Geological Survey workshop on the geology and geohydrology of the Atlantic Coastal Plain*: U.S. Geological Survey Circular 1059, p. 149–151.
- Minard, J.P., and Owens, J.P., 1960, Differential subsidence of the southern part of New Jersey Coastal Plain since early Late Cretaceous time: U.S. Geological Survey Professional Paper 400-B, p. B184–B186.
- Minard, J.P., Owens, J.P., and Todd, Ruth, 1961, Redefinition of the Mount Laurel Sand (Upper Cretaceous) in New Jersey: U.S. Geological Survey Professional Paper 424-C, p. C64–C67.
- Muessig, Karl, Houghton, Hugh, Monteverde, Donald, and Volkert, Richard, 1992, Field guide to the geology of radon hazard areas in New Jersey: New Jersey Geological Survey Open-File Report OFR 92-2, 17 p.
- Nawyn, J.P., 1997, Withdrawals of ground water and surface water in New Jersey, 1994: U.S. Geological Survey Fact Sheet FS-120-97, 4 p.
- New Jersey Administrative Code, 2002a, Private Well Testing Act; Regulations governing the certification of laboratories and environmental measurements; N.J. Administrative Code, Amendment 7:18: New Jersey Register, v. 34, 16 p.
- New Jersey Administrative Code, 2002b, Revision 7: 10-1 N.J. Safe Drinking Water Regulations, Secondary Standards, Chemical characteristics: Trenton, N.J. State of New Jersey.
- New Jersey Department Environmental Protection, 1997, A homeowner's guide to radioactivity in drinking water: Trenton, N.J., New Jersey Department Environmental Protection, 4 p.
- Nichols, W.D., 1977, Geohydrology of the Englishtown Formation in the northern Coastal Plain of New Jersey: U.S. Geological Survey Water-Resources Investigations Report 76-123, 62 p.
- Olsson, R.K., 1991, Cretaceous to Eocene sea-level fluctuations on the New Jersey margin: *Sedimentary Geology*, v. 70, p. 195–208.

- Olsson, R.K., Gibson, T.G., Hansen, H.J. and Owens, J.P., 1988, geology of the northern Atlantic coastal plain: Long Island to Virginia, *in* Sheridan, R.E., and Grow, J.A., eds., *The Atlantic continental margin: U.S.*, Geology of North America: Boulder, Colo., Geological Society of America, v. 1-2, p. 87–105.
- Owens, J.P., and Minard, J.P., 1960, Some characteristics of glauconite from the Coastal Plain formations of New Jersey: U.S. Geological Survey Professional Paper 400-B, p. B430–B432.
- Owens, J.P., and Minard, J.P., 1979, Upper Cenozoic sediments of the Lower Delaware Valley and the northern Delmarva Peninsula, New Jersey, Pennsylvania, Delaware, and Maryland: U.S. Geological Survey Professional Paper 1067-D, 47 p.
- Owens, J.P., and Sohl, N.F., 1969, Shelf and deltaic paleoenvironments in the Cretaceous-Tertiary formations of the New Jersey Coastal Plain, *in* Subitzky, Seymour, ed., *Geology of selected areas of New Jersey and Pennsylvania*: New Brunswick, N.J., Rutgers University Press, p. 235–278.
- Owens, J.P., Minard, J.P., and Blackmon, P.D., 1961, Distribution of clay-sized sediments in the Coastal Plain formations near Trenton, New Jersey: U.S. Geological Survey Professional Paper 424-C, p. C317–C319.
- Owens, J.P., Minard, J.P., Sohl, N.F., and Mello, J.F., 1970, Stratigraphy of the outcropping Post-Magothy Upper Cretaceous formations in southern New Jersey and northern Delmarva Peninsula, Delaware, and Maryland: U.S. Geological Survey Professional Paper 674, 60 p. [Available online at <http://pubs.er.usgs.gov/pubs/pp/pp674>]
- Owens, J.P., Sugarman, P.J., Sohl, N.F., Parker, R.A., Houghton, H.F., Volkert, R.A., Drake, A.A., Jr., and Orndorff, R.C., 1998, Bedrock geologic map of central and southern New Jersey: U.S. Geological Survey Miscellaneous Investigations Series Map I-2540-B, 3 pl.
- Parsa, Bahman, 1998, Contribution of short-lived radionuclides to alpha-particle radioactivity in drinking water and their impact on the Safe Drinking Water Act regulations: *Radioactivity Radiochemistry*, v. 9, no. 4, p. 41–50.
- Pritchard, H.M., and Gesell, T.F., 1977, Rapid measurements of Rn-222 concentrations in water with a commercial liquid scintillation counter: *Health Physics*, v. 33, p. 577.
- Pucci, A.A., Jr., Szabo, Zoltan, and Owens, J.P., 1997, Variations in pore-water quality, mineralogy, and sedimentary texture of clay-silts in the lower Miocene Kirkwood Formation, Atlantic City, New Jersey, *in* Miller, K.G. and Snyder, S.W., eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, v. 150X, p. 317–341. [Available online at http://www-odp.tamu.edu/publications/150X_SR/24X_CHP.PDF]
- Rice, D.E., and Szabo, Zoltan, 1997, Relation of ground-water flowpaths and travel time to the distribution of radium and nitrate in current and former agricultural areas of the Kirkwood-Cohansey aquifer system, New Jersey Coastal Plain: U.S. Geological Survey Water-Resources Investigations Report 96-4165B, 48 p. [Available online at <http://pubs.er.usgs.gov/pubs/wri/wri964165B>]
- Rosenau, J.C., Lang, S.M., Hilton, G.S., and Rooney, J.G., 1969, *Geology and ground-water resources of Salem County, New Jersey*: New Jersey Dept. Conservation and Economic Development Special Report 33, 142 p.
- Schlein, B., 1992, *The health physics and radiological health handbook*, revised 1992: Silver Spring, Md., Scinta Corp., 734 p.
- Seaber, P.R., 1965, Variations in chemical character of water in the Englishtown Formation, New Jersey: U.S. Geological Survey Professional Paper 498-B, p. 35.
- Sill, C.W., Hindman, F.D., and Anderson, J.I., 1979, Simultaneous determination of alpha-emitting radionuclides of radium through californium in large environmental and biological samples: *Analytical Chemistry*, v. 51, no. 8, p. 1307–1314.
- Sill, C.W., and Williams, R.L., 1981, Preparation of actinides for alpha-spectrometry without electrodeposition: *Analytical Chemistry*, v. 53, p. 412–415.
- Sill, C.W., 1987, Determination of Ra-226 in ores, nuclear waste and environmental samples by high-resolution alpha-spectrometry: *Nuclear Chemistry Waste Management*, v. 226, p. 67–74.
- Sugarman, P.J., 1992, Geologic controls on aquifer distribution in the Coastal Plain of New Jersey, *in* Gohn, G.S., ed., *Proceedings of the 1988 U.S. Geological Survey workshop on the geology and geohydrology of the Atlantic Coastal Plain*: U.S. Geological Survey Circular 1059, p. 35–38.
- Sugarman, P.J., 1999, Radon potential of New Jersey Coastal Plain formations: New Jersey Geological Survey Open-File Map OFM 25, 1 pl.
- Sugarman, P.J., Miller, K.G., Owens, J.P., and Feigenson, M.D., 1993, Strontium-isotope and sequence stratigraphy of the Miocene Kirkwood Formation, southern New Jersey: *Geological Society of America Bulletin*, v. 105, p. 423–436.
- Sugarman, P.J., Miller, K.G., Bukry, D., and Feigenson, M.D., 1995, Uppermost Campanian-Maastrichtian strontium isotopic, biostratigraphic, and sequence stratigraphic framework of the New Jersey Coastal Plain: *Geological Society America Bulletin*, v. 107, p. 19–37.
- Sugarman, P.J., and Miller, K.G., 1997, Correlation of Miocene sequences and hydrogeologic units, New Jersey Coastal Plain: *Sedimentary Geology*, v. 108, p. 3–18.

- Sugarman, P.J., 2001, Hydrostratigraphy of the Kirkwood and Cohansey Formations of Miocene Age in Atlantic County and Vicinity, New Jersey: N.J. Geological Survey Geological Survey Report 40, 26 p.
- Szabo, Zoltan, and Zapecza, O.S., 1991, Geologic and geochemical factors controlling natural radioactivity in ground water, Newark basin, New Jersey, *in* Gundersen, L.C.S., and Wanty, R.B., eds., Field studies of radon in rocks, soils, and water: U.S. Geological Survey Bulletin 1971, p. 243–266.
- Szabo, Zoltan, Rice, D.E., Plummer, L.N., Busenberg, Eurybades, Drenkard, Stefan, and Schlosser, Peter, 1996, Age dating of shallow groundwater with chlorofluorocarbons, tritium/helium-3, and flow path analysis, southern New Jersey coastal plain: *Water Resources Research*, v. 32, no. 4, p. 1023–1038.
- Szabo, Zoltan, Rice, D.E., McLeod, C.L., and Barringer, T.H., 1997, Relation of distribution of radium, nitrate, and pesticides to agricultural land use and depth, Kirkwood-Cohansey aquifer system, New Jersey Coastal Plain, 1990–91: U.S. Geological Survey Water-Resources Investigations Report 96-4165A, 107 p. [Available online at <http://pubs.er.usgs.gov/pubs/wri/wri964165A>]
- Szabo, Zoltan, and dePaul, V.T., 1998, Radium-226 and radium-228 in shallow ground water, southern New Jersey: U.S. Geological Survey Fact Sheet FS-062-98, 6 p. [Available online at <http://nj.usgs.gov/publications/FS/FS-062-98.pdf>]
- Szabo, Zoltan, dePaul, V.T., and Parsa, Bahman, 1998, Decrease in gross alpha-particle activity in water samples with time after collection from the Kirkwood-Cohansey aquifer system in southern New Jersey [abs.]: Implications for drinking water regulations: 63rd annual meeting, American Water Works Association New Jersey section, Atlantic City, N.J.
- 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, 84 p. [Available online at <http://pubs.er.usgs.gov/pubs/sir/sir20045224>]
- U.S. Environmental Protection Agency, 1976, National interim primary drinking-water regulations: Washington, D.C., Office of Water Supply, U.S. Environmental Protection Agency Report EPA-570/9-76-003.
- U.S. Environmental Protection Agency, 1997, National primary drinking water regulations: Analytical methods for radionuclides: Federal Register, v. 62, no. 43, p. 10168–10175.
- U.S. Environmental Protection Agency, 1999, Environmental Radiation Guidance Document No. 13: Washington, D.C., Office of Water Supply, U.S. Environmental Protection Agency Report EPA-2501/10-99-013.
- U.S. Environmental Protection Agency, 2000a, National Primary Drinking Water Regulations; Radionuclides; Final rule, 40CFR parts 141 and 142: Washington, D.C., Federal Register, v. 65, no. 236.
- U.S. Environmental Protection Agency, 2000b, 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.
- Watt, M.K., 2000, A hydrologic primer for New Jersey watershed management: U.S. Geological Survey Water-Resources Investigations Report 00-4140, 108 p. [Available online at <http://pubs.er.usgs.gov/pubs/wri/wri004140>]
- Wilde, F.D., and Radtke, D.B., 1999, Field measurements, U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A6, 68 p. [Available online at <http://water.usgs.gov/owq/FieldManual/Chapter6>]
- Yin, Y., Allen, H.E., Huang, C.P., and Sanders, P.F., 1996, Adsorption of mercury (II) by soil—Effects of pH, chloride, and organic matter: *Journal Environmental Quality*, v. 25, p. 837–844.
- Yuretich, R.F., Crerar, D.A., Kinsman, D.J.J., Means, J.L., and Borcsik, M.P., 1981, Hydrogeochemistry of the New Jersey Coastal Plain: 1. Major-element cycles in precipitation and river waters: *Chemical Geology*, v. 33, p. 1–21.
- Zapecza, O.S., 1989, Hydrogeologic framework of the New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1404-B, 49 p. [Available online at <http://pubs.er.usgs.gov/pubs/pp/pp1404B>]
- Zapecza, O.S., and Szabo, Zoltan, 1988, Natural radioactivity in ground water—A review, in *National Water Summary 1986—Ground water quality: Hydrologic conditions and events*: U.S. Geological Survey Water-Supply Paper 2325, p. 50–57.
- Zapecza, O.S., and Szabo, Zoltan, 1989, Source of natural radioactivity in ground water in the Kirkwood-Cohansey aquifer system, southwestern Coastal Plain, New Jersey: *Geological Society America, Abstracts with Programs*, v. 21, no. 2, p. 78.

Glossary

A

Acidification An increase in the concentration of anions associated with the production of acids, the presence of which may decrease the acid neutralizing capacity of the water body (see Leydecker and others, 1999 for further discussion).

Activity The amount of radioactivity in a given volume of material such as water or air. For water, activity is generally expressed in units of picocuries per liter.

Alpha radiation Alpha radiation is composed of a particle, consisting of two protons and two neutrons, spontaneously emitted from the nucleus of a subset of radioactive elements (mostly the heaviest elements) during radioactive decay. Alpha radiation is ionizing radiation, meaning that it strips electrons from adjacent atoms as it passes. Alpha radiation cannot penetrate skin; thus, an alpha-particle emitting radionuclide must be ingested in order to contact internal tissue. Because of the large size, alpha particles are likely to collide with cell tissue, causing tissue damage. An accumulation of tissue damage in the cell nucleus may lead to cell mutation and potential cancer formation (risk).

Alpha radioactivity, gross A laboratory measurement of total alpha radioactivity emitted by a sample. This measurement includes alpha particle radioactivity emitted by isotopes of naturally occurring uranium, thorium, radium, and progeny such as polonium, as well as alpha particles emitted from isotopes of plutonium, which is manmade (not naturally occurring). Long-term measurement, usually conducted 20 to 30 days after sample collection, measures only the amount of alpha radiation present from long-lived radionuclides, such as naturally occurring uranium-238, radium-226 (half-life, 1,602 years), or the long-lived isotopes of plutonium. Short-term measurements, usually made within 24, 48, or 72 hours after sample collection indicate the alpha-particle decay of radionuclides with short half-lives.

Alpha radioactivity count An analytical technique that specifies alpha radioactivity emitted by a chemically purified sample that contains only one radionuclide of interest. The alpha-particle activity is counted in a low-background gas proportional counter.

Alpha spectrometry An analytical technique that specifies the amount of alpha radiation emitted at specified energy levels, thus allowing determination of individual radionuclide concentrations (from known energy levels of alpha particles unique to each radionuclide). The gridded-pulse-ionization chamber is the most sensitive and most commonly used instrument.

B

Beta radioactivity Beta radiation is composed of a particle, consisting of an electron, spontaneously emitted from the nucleus of a subset of radioactive elements during radioactive decay. Beta radiation, like alpha radiation, is ionizing radiation — it strips electrons from adjacent atoms as it passes. Beta radiation can only penetrate the surface layer of skin; thus, a beta-particle emitting radionuclide must be ingested in order to contact internal organs or tissues. An accumulation of tissue damage in the cell nucleus may lead to cell mutation and potential cancer formation.

Beta radioactivity, gross A laboratory measurement of total beta radioactivity emitted by a sample. This measurement includes radioactivity emitted by naturally occurring progeny of uranium and thorium, such as radium-228 and lead-210, and numerous other naturally occurring beta-particle-emitting radioactive isotopes.

Beta radioactivity count An analytical technique that specifies total beta radioactivity emitted by a chemically purified sample that contains only one radionuclide of interest. The beta-particle activity is counted in a low-background gas proportional counter.

C

Contaminant As defined in the Safe Drinking Water Act, any physical, chemical, biological, or radiological substance or matter in water.

D

Decay product of radiation The isotope remaining after a radioactive decay event.

G

Gamma radioactivity Gamma radiation is composed of a packet of energy, also known as a photon or photon particle, spontaneously emitted from the nucleus of most radioactive elements during radioactive decay. Gamma radiation is ionizing radiation meaning that it strips electrons from adjacent atoms as it passes. Gamma radiation can penetrate through skin into internal tissues as opposed to alpha and beta radiation, which cannot. An accumulation of tissue damage in the cell nucleus from gamma radiation may lead to cell mutation and potential cancer formation.

Glauconite A green mineral, essentially a hydrous potassium iron silicate, which is closely related to mica. Sands rich in glauconite are typically called greensands.

H

Histogram A vertical bar graph representing population frequency distribution. The height of the bars is proportional to the frequency of occurrence within each class interval.

I

Isotope Various forms of a single element differing in the number of neutrons in the nucleus. Unstable isotopes of an element decay through the emission of a form of radioactivity.

L

Laboratory reporting level (LRL) The laboratory reporting level (LRL) is a minimum concentration pre-determined by the laboratory personnel before the project begins, generally based on typical counting results under routine operating conditions in a given sample matrix using known standards (American Society of Testing and Materials, 1999), which the laboratory personnel define as a level of detection they can routinely achieve. It is generally defined by the requirement that

the counted radioactivity must differ from the background count by three times the standard deviation of the background count. The LRL was targeted as 0.5 to 1 pCi/L for the individual radionuclide concentrations determined in this study.

M

Maximum contaminant level (MCL) The maximum permissible level of a contaminant in water that is delivered to the free flowing outlet of the ultimate user of a public water-supply system (except in the case of turbidity). The MCL is an expression of the acceptable health risk of developing or dying from cancer per unit of ingested water containing a harmful substance entering the body (exposure). The MCL for Ra-226, Ra-228, uranium, and gross alpha-particle activity in community water systems follows:

- Sum of Ra-226 and Ra-228, 5 pCi/L;
- Uranium, 30 $\mu\text{g/L}$; and
- Gross alpha-particle activity (including Ra-226 but excluding radon and uranium), 15 pCi/L.

Minimum detectable concentration, sample-specific (SSMDC) The minimum quantity of a specific radionuclide detectable by the counting instrument for any given sample for a given analysis defined by instrument operating conditions and variation in background radiation at the time of analysis. This value is computed individually for each radionuclide analysis based on instrument operating conditions at the time. The computation is repeated for each individual sample analysis because of the variability in background radioactivity over time. The laboratory reporting level (LRL), is a contractually determined minimum concentration determined by the laboratory personnel before the project begins that can be achieved routinely; it is generally based on typical results under routine operating conditions in a given matrix using known standards (American Society Testing Materials, 1999). In many cases, the SSMDC is less than the LRL. In some cases, such as in a complex sample matrix, the SSMDC may exceed the LRL. For purposes of this report, because many of the analytical techniques are still considered to be in the research phase of development, the LRL will generally be

referred to when evaluating a sample result unless otherwise specified.

Montmorillinite A clay mineral that has slight replacement of trivalent aluminum with divalent cations, primarily magnesium, and possibly calcium.

N

Negative result A result from a radiation measurement (count) of a sample over a fixed interval of time where the measured radioactivity from the sample is less than the long-term average background radiation reported routinely by the instrument. In practical terms, the result is below the sample-specific minimum detectable concentration and the laboratory reporting level and thus indicates that radioactivity was not detected.

P

Picocurie per liter The measurement unit that expresses the amount of radioactivity in water. One picocurie per liter (pCi/L) equals 2.2 radioactive disintegrations per minute per liter of water.

Precision estimate (PE) or combined standard uncertainty (csu) A calculated measure of uncertainty of the laboratory analysis. Determination of the precision estimate for radionuclides evaluates many sources of error, some that are unique to radionuclides. Because radioactive elements decay randomly at any given instant of time, any measurement of radioactivity has an associated uncertainty (also called “counting error”) independent of, and in addition to, laboratory sources of analytical uncertainty. Uncertainty can be reported in a variety of ways; the most common include (1) the sum of the laboratory and counting uncertainty, known as the “precision estimate” or the “combined standard uncertainty (CSU)” (or less frequently as the “total propagated uncertainty”), and (2) a counting error or counting uncertainty only. There is a 67 percent or 95 percent probability (based on one or two standard deviations, respectively, of the radioactivity count) that the true value of the radionuclide concentration is within the range of the reported measured value plus or minus the precision estimate or uncertainty. The precision estimate or uncertainty terms are generally smaller than the measured value except when the measured values are low concentrations (near the LRL). The precision estimates associated with the various

radionuclide concentrations determined by the alpha spectrometry measurement technique and presented in this report are given as the two standard deviation propagated precision estimates.

R

Radionuclide An isotope of an element that emits radiation.

S

Siderite Iron carbonate mineral, brown in color, typically formed as mineral cement in iron-rich sand or clay.

Appendixes 1-3

52 Occurrence of Radium in Water, Southwestern and South-Central New Jersey

Appendix 1. Construction information for wells sampled for radioactive constituents in water or natural gamma-ray activity in sediment from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and the Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999-2001.

[NA, data not available; BLS, below land surface; Twp, Township; *, natural gamma-ray log only; latitude and longitude relative to North American Datum of 1983. Use of site: W, withdrawal; O, observation. Use of water: H, domestic; I, irrigation; P, production; U, unused. Aquifer: VNCN, Vincentown aquifer; HRRS, Hornerstown Sand; RDBK, Red Bank Sand; MLRW, Wenonah-Mt.Laurel aquifer; EGLS, Englishtown aquifer system; MRPAU, Upper Potomac-Raritan-Magothy aquifer system]

U.S. Geographical Survey well number (C5)	New Jersey permit number (C213)	Municipality (C13)	Well depth (feet BLS) (C28)	Depth to top of open interval (feet BLS) (C83)	Depth to bottom of open interval (feet BLS) (C84)	Primary use of site (C23)	Primary use of water (C24)	Aquifer (C714)	Latitude (C9)	Longitude (C10)
050354	32-00103	Pemberton Twp	198	178	198	W	P	211MLRW	395813.5	743948.2
050752*	NA	Evesham Twp	515	473.33	513.67	T	U	211MRPAU	395247	745156
051189	31-31317	Medford Twp	127.58	87.58	127.58	W	P	211MLRW	395441	744959
051403	32-22227	Southampton Twp	13	8	13	O	U	125HRRS	395815	744420
051476	31-55694	Hainesport Twp	14	9	14	O	U	211EGLS	395928	745026
051478	31-55695	Moorestown Twp	22.5	17.5	22.5	O	U	211EGLS	395836	745426
051481	27-15113	Springfield Twp	12	7	12	O	U	211EGLS	400202	744612
051486	31-55697	Medford Twp	12.5	7.5	12.5	O	U	125HRRS	395532	745046
051500	31-58773	Mount Laurel Twp	19.5	14.5	19.5	O	U	211EGLS	395806	745404
070729	31-29318	Laurel Springs Boro	227	204	224	W	P	211EGLS	394925	750020
070731	31-29319	Gibbsboro Boro	239	216	236	W	P	211EGLS	394951.2	745856
071005	31-58441	Belmawr Boro	13.62	8.62	13.62	O	U	211EGLS	395143	750440
150422*	31-17805	Harrison Twp	573	498	568	W	I	211MRPAU	394259	750852
210574	28-13330	East Windsor Twp	56	51	56	W	H	211EGLS	401406.92	743128.91
210607	28-47503	East Windsor Twp	65	51	62	W	H	211EGLS	401356.87	743032
250037*	29-4068	Colts Neck Twp	706	686	706	W	I	211MRPAU	401608	741206.1
250714	29-25383	Atlantic Highlands Boro	251	198	248	W	P	211EGLS	402424.5	740142.9
250717	29-28188	Freehold Twp	48	38	43	O	U	125VNCN	401046	742001
250720	29-16821	Howell Twp	255	235	255	W	P	211MLRW	401053	741557
250766	NA	Upper Freehold Twp	22.1	NA	NA	W	H	211MLRW	401200	743052
250785	28-43877	Upper Freehold Twp	24	19	24	O	U	125VNCN	400525	743140
250790	28-46966	Upper Freehold Twp	14.17	9.17	14.17	O	U	211MLRL	400954	743019
250791	29-09661	Eatontown Boro	40	36	40	W	I	125VNCN	401753.16	740314.28
250792	NA	Upper Freehold Twp	50	30	45	W	H	211MLRW	400850.68	743122.18
250793	29-24333	Long Branch City	80	70	80	W	H	125VNCN	401722.1	735920.9
250796	29-15771-4	Colts Neck Twp	20	5	20	O	U	125VNCN	401611.4	740855.2
250797	29-44945	Eatontown Boro	38.5	33.5	38.5	O	U	125VNCN	401732	740219
250798	29-45122	Freehold Twp	22	17	22	O	U	211RDBK	401531	741727
250800	28-48499	Upper Freehold Twp	18.5	13.5	18.5	O	U	211MLRW	401229	742859
250801	28-48675	Upper Freehold Twp	26	21	26	O	U	211EGLS	401233	743203
250802	29-37697	Manalapan Twp	35.08	30.08	35.08	O	U	211RDBK	401508	741934
250803	NA	Upper Freehold Twp	16.8	NA	NA	W	H	211MLRW	401054.8	743134.5
290006	29-00087	Bay Head Boro	818	778	818	W	P	211EGLS	400405	740242
290238*	28-8229	Jackson Twp	652	584	648	W	P	211MRPAU	400820	742632.9
290449	29-05496	Lakewood Twp	698	569	698	W	P	211EGLS	400614.7	741155.7
290917	29-16962	Jackson Twp	195	126	186	W	P	125VNCN	400850	741514.7
330249	50-00042	Salem City	157	110	150	W	P	211MLRW	393342.8	752717
330384*	30-1356	Quinton Twp	320	NA	NA	W	I	211MLRW	393138	752459.9
330902	30-09510	Woodstown Boro	149	100	143	W	P	211MLRW	393845.3	751903.6
330927	30-13272	Mannington Twp	25	20	25	O	U	125VNCN	393610	752459
330929	30-12179	Pilesgrove Twp	17	12	17	O	U	211MLRW	394024	752346
330946	30-04782	Mannington Twp	28	NA	NA	W	H	125VNCN	393549	752622
330947	30-06154	Mannington Twp	45	35	45	W	H	211EGLS	393943	752727
330948	30-05052	Pilesgrove Twp	60	50	60	W	H	211MLRW	394141	752204

Appendix 2. Concentrations of radionuclides, major ions, and selected trace elements in equipment blank samples for radionuclide sampling, New Jersey, 1999-2001

[mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; SSMDC, sample specific minimum detectable concentration; 2X, twice; 2 S, 2 sigma; E, estimated; <, less than; --, not analyzed; SiO₂, silica; N, nitrogen; P, phosphorus; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS)]

Station number	Date of sampling (mm/dd/yyyy)	Sample number	Calcium, filtered (mg/L)	Magnesium, filtered (mg/L)	Sodium, filtered (mg/L)	Silica, filtered (mg/L as SiO ₂)	Nitrogen, ammonia, filtered (mg/L as N)	Nitrite plus nitrate, filtered (mg/L as N)	Nitrogen, nitrite, filtered (mg/L as N)	Phosphorus, orthophosphate, filtered (mg/L as P)	Aluminum, filtered (µg/L)	Antimony, filtered (µg/L)
			(P00915)	(P00925)	(P00930)	(P00955)	(P00608)	(P00631)	(P00613)	(P00671)	(P01106)	(P01095)
392254074343201	8/9/2000	00000175	0.003	<0.001	<0.03	<0.02	0.005	<0.005	<0.001	<0.001	<0.3	<0.2
394931075144901	5/17/2000	00000203	<0.02	<0.01	<0.03	<0.02	0.009	<0.005	<0.001	0.014	<.3	<.2
395356074570805	8/4/1999	99900104	0.003	0.001	0.03	<0.02	<0.002	<0.005	<0.001	0.001	<.3	<.2
395815074442101	8/31/1999	99900142	<0.02	<0.01	<0.03	<0.02	--	--	--	--	<.3	<.2
395906075000601	8/23/2000	00000181	<0.02	<0.01	<0.03	<0.02	<0.002	<0.005	<0.001	<0.001	<.3	<.2
400000074000097	8/22/2001	00100184	<.01	<0.008	<0.06	<0.09	0.002	<0.005	<0.001	<0.007	<.1	--
400000074000097	9/6/2001	00100190	E.01	<0.008	<0.06	<0.09	<0.002	E.007	<0.001	<0.007	<.1	--
400000074000097	6/21/1999	99900062	0.006	0.001	<0.03	<0.02	0.003	0.006	<0.001	0.005	<.3	<.2
401611074085501	6/12/2001	00100303	<.01	<0.008	<0.06	E.05	--	--	--	--	<.1	<.05
401722073592201	5/29/2001	00100304	<.01	<0.008	<0.06	<0.09	--	--	--	--	<.1	<.05
402022074285301	8/2/2000	00000206	0.004	<0.001	<0.03	<0.02	<0.002	<0.005	<0.001	0.002	<.3	<.2

Appendix 2. Concentrations of radionuclides, major ions, and selected trace elements in equipment blank samples for radionuclide sampling, New Jersey, 1999-2001.—Continued

[mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; SSMDC, sample specific minimum detectable concentration; 2X, twice; 2 S, 2 sigma; E, estimated; <, less than; --, not analyzed; SiO₂, silica; N, nitrogen; P, phosphorus; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS)]

Station number	(P01000)	Arsenic, filtered (µg/L)	(P01005)	Barium, filtered (µg/L)	Beryllium, filtered (µg/L)	(P01010)	Boron, filtered (µg/L)	(P01020)	Cadmium, filtered (µg/L)	(P01025)	Chromium, filtered (µg/L)	(P01030)	Cobalt, filtered (µg/L)	(P01035)	Copper, filtered (µg/L)	(P01040)	Iron, filtered (µg/L)	(P01046)	Lead, filtered (µg/L)	(P01049)	Lithium, filtered (µg/L)	(P01130)	Manganese, filtered (µg/L)	(P01056)
392254074343201	--	<0.2	<0.2	<0.2	<0.2	<0.2	<2	<0.3	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<3	<0.3	<0.3	<0.3	--	--	<0.1	<0.1	
394931075144901	--	<2	<2	<2	<2	<2	<2	<3	<2	<2	<2	<2	<2	<2	0.8	<3	<3	<3	<3	--	--	<1	<1	
395356074570805	--	<2	<2	<2	<2	<2	<2	<3	<3	<2	<2	<2	<2	<2	<2	<3	<3	<3	<3	--	--	<1	<1	
395815074442101	<9	<2	<2	<2	<2	<2	<2	<3	<3	<2	<2	<2	<2	<2	<2	<3	<3	<3	<3	--	--	<1	<1	
395906075000601	--	<2	<2	<2	<2	<2	<2	<3	<3	<2	<2	<2	<2	<2	<2	<3	<3	<3	<3	--	--	<1	<1	
400000074000097	<2	<1	<1	<06	<06	<06	<7	<04	<04	<8	<8	<8	<02	<02	<2	<10	<10	<08	<08	--	--	<1	<1	
400000074000097	<2	<1	<1	<06	<06	<06	<7	<04	<04	<8	<8	<8	<02	<02	<2	<10	<10	<08	<08	--	--	<1	<1	
400000074000097	--	<2	<2	<2	<2	<2	<2	<3	<3	<2	<2	<2	<2	<2	<2	<3	<3	<3	<3	--	--	<1	<1	
401611074085501	<2	<1	<1	<06	<06	<06	E4	<04	<04	<8	<8	<8	<02	<02	<2	<10	<10	<08	<08	<0.3	<0.3	<1	<1	
401722073592201	<2	<1	<1	<06	<06	<06	<7	<04	<04	<8	<8	<8	<02	<02	<2	<10	<10	<08	<08	E.3	E.3	<1	<1	
402022074285301	--	<2	<2	<2	<2	<2	<2	<3	<3	<2	<2	<2	<2	<2	<2	<3	<3	<3	<3	--	--	<1	<1	

Appendix 2. Concentrations of radionuclides, major ions, and selected trace elements in equipment blank samples for radionuclide sampling, New Jersey, 1999-2001.—Continued

[mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; SSMDc, sample specific minimum detectable concentration; 2X, twice; 2 S, 2 sigma; E, estimated; <, less than; --, not analyzed; SiO₂, silica; N, nitrogen; P, phosphorus; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS)]

Station number	(P71890)	(P01060)	(P01065)	(P01145)	(P01075)	(P01080)	(P01057)	(P01090)	(P75995)	(P17503)	(P75998)	(P19503)
	Mercury, filtered (µg/L)	Molybdenum, filtered (µg/L)	Nickel, filtered (µg/L)	Selenium, filtered (µg/L)	Silver, filtered (µg/L)	Strontium, filtered (µg/L)	Thallium, filtered (µg/L)	Zinc, filtered (µg/L)	Lead-210, 2 S precision estimate, filtered (pCi/L)	Lead-210, filtered (pCi/L)	Polonium-210, 2 S precision estimate, filtered (pCi/L)	Polonium-210, filtered (pCi/L)
392254074343201	--	<0.2	<0.5	--	<0.2	<0.1	<0.1	<0.5	0.4	0.166	0.02	<1
394931075144901	--	<2	<5	--	<2	<1	<1	<5	0.27	0.227	--	--
395356074570805	<0.1	<2	<5	--	<2	<1	<1	<5	0.35	0.215	0.03	<1
395815074442101	<1	<2	<5	<0.7	<2	<1	<1	<5	--	--	--	--
395906075000601	--	<2	<5	--	<2	<1	<1	<5	0.59	0.72	0.022	<1
400000074000097	--	<2	<06	--	<1	<08	--	<1	0.47	1.1	0.1	0.05
400000074000097	--	<2	<06	--	<1	<08	--	<1	0.39	0.62	0.14	0.05
400000074000097	<1	<2	<5	--	<2	<1	<1	0.7	0.3	0.4	0.02	<1
401611074085501	--	<2	<06	<.3	<1	<08	<04	<1	0.34	0.05	--	--
401722073592201	--	<2	<06	<.3	<1	<08	<04	<1	0.33	0.51	--	--
402022074285301	--	<2	<5	--	<2	<1	<1	<.5	0.33	0.05	0.01	<1

Appendix 2. Concentrations of radionuclides, major ions, and selected trace elements in equipment blank samples for radionuclide sampling, New Jersey, 1999-2001.—Continued

[mg/L, milligrams per liter; $\mu\text{g/L}$, micrograms per liter; pCi/L, picocuries per liter; SSMDC, sample specific minimum detectable concentration; 2X, twice; 2 S, 2 sigma; E, estimated; <, less than; --, not analyzed; SiO_2 , silica; N, nitrogen; P, phosphorus; number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS)]

Station number	Radium-224, 2 S precision estimate, filtered (pCi/L) (P50834)	Radium-224, 2X critical level (SSMDC), filtered (pCi/L) (P99324)	Radium-224, alpha spectroscopy, filtered (pCi/L) (P50833)	Radium-226, 2 S precision estimate, filtered (pCi/L) (P76001)	Radium-226, alpha copy, filtered (pCi/L) (P09503)	Radium-226, radon method, filtered (pCi/L) (P09511)	Radium-226, gamma count, filtered (pCi/L) (P50837)	Radium-226, 2 S precision estimate, gamma count, filtered (pCi/L) (P50911)	Radium-226, 2X critical level (SSMDC), filtered (pCi/L) (P99325)	Radium-228, 2 S precision estimate, filtered (pCi/L) (P76000)	Radium-228, 2X critical level (SSMDC), filtered (pCi/L) (P99326)	Radium-228, filtered (pCi/L) (P81366)	Uranium, natural, filtered ($\mu\text{g/L}$) (P22703)
39225407433201	0.02	0.051	-0.008	0.09	0.03	0.023	--	--	0.019	0.29	0.483	0.42	<0.2
394931075144901	0.03	0.063	-0.003	0.004	-0.003	--	--	--	0.025	--	--	--	<.2
395356074570805	0.05	0.083	0.018	0.014	0.002	<.02	--	--	0.026	--	--	--	<.2
395815074442101	--	--	--	--	--	--	--	--	--	--	--	--	<.2
395906075000601	0	0.04	0	0.024	0.017	0.021	--	--	0.023	0.93	1.78	0.98	<.2
400000074000097	0	0.023	0	0.015	-0.003	0.046	--	--	0.028	0.4	0.697	0.62	<.02
400000074000097	0.09	0.14	0.048	0.012	0.008	0.022	--	--	0.04	0.4	0.613	0.86	<.02
400000074000097	0.29	--	0.193	0.08	--	<.02	<1	0.08	0.161	--	--	--	<.2
401611074085501	--	--	--	0.01	--	0.021	--	--	--	0.31	0.515	0.45	<.02
401722073592201	--	--	--	0.01	--	0.01	--	--	--	0.32	0.482	0.55	<.02
402022074285301	0.07	0.128	0.04	0.02	0.006	--	--	--	0.039	0.32	0.559	0.41	<.2

Appendix 3. Concentrations of radionuclides, major ions, selected trace elements in, and physical properties of, water from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and the Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999-2001.

[mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; µS/cm, microsiemens per centimeter; NTU, Nephelometric Turbidity Units, SSMDC, sample specific minimum detectable concentration; 2X, twice; 2S, 2-sigma; CaCO₃, calcium carbonate; <, less than; N, nitrogen; P, phosphorus; E, estimated. Aquifers: VNCN, Vincentown aquifer; HRRS, Hornerstown Sand; RDBK, Red Bank Sand; MLRW, Wenonah-Mount Laurel aquifer; EGLS, Englishtown aquifer system. Number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS)]

U.S. Geological Survey well number	Aquifer	Date of sampling (mm/dd/yyyy)	Station number	Sample number	Turbidity, field, unfiltered, (NTU)	Oxygen, dissolved (mg/L)	pH, field, unfiltered (Standard units)	Specific conductance (µS/cm at 25 degrees Celsius)	Temperature, water (degrees Celsius)	Calcium, filtered (mg/L)	Magnesium, filtered (mg/L)	Potassium, filtered (mg/L)
050354	211MLRW	9/26/2000	395813074395001	00001006	0.1	0.1	8.4	175	13.5	23.8	4.27	5.5
051189	211MLRW	5/8/2000	395441074500001	00000474	0.48	0.4	7.7	250	14.1	46.8	0.919	2.06
051403	125HRRS	8/31/1999	395815074442101	99901035	0.3	8.1	5.7	116	16	12.7	2.91	0.73
051476	211EGLS	8/19/1999	395928074502701	99901202	0.35	1.3	4.4	64	16	E.72	E.55	E.90
051478	211EGLS	8/19/1999	395836074542701	99901201	13.5	7	4.6	518	18	38.1	13.8	3.24
051481	211EGLS	9/2/1999	400202074461301	99901130	0.3	6.2	4.9	204	17.5	3.39	2.53	4.17
051486	125HRRS	9/21/1999	395532074504701	99901172	0.6	6.7	5.1	289	13.5	E21.1	E16.2	E3.60
051500	211EGLS	9/14/2000	395806074540501	00001030	3.1	2.1	4.4	182	19.5	12.2	2.72	2.9
070729	211EGLS	8/22/2000	394925075002101	00000845	0.1	0.1	8.2	152	14.6	22.6	2.7	2.67
070731	211EGLS	8/2/1999	394945074585502	99900791	0.1	0.2	8.3	149	14.5	22.9	2.09	2.36
071005	211EGLS	8/16/2000	395143075044101	00001037	0.7	0.5	5.5	507	15.5	12.3	3.8	6.07
210574	211EGLS	5/8/2001	401407074312901	00100431	0.31	9.3	5.8	48	13	2.25	1.1	1.12
210607	211EGLS	5/2/2001	401357074303201	00100409	0.68	6.7	5.5	237	13.1	12.9	14.6	1.61
250714	211EGLS	6/5/2001	402424074014401	00100578	0.1	<1	7.1	195	13.8	29.4	1.95	2.03
250717	125VNCN	8/18/1999	401046074200201	99900985	1.8	<1	4.2	174	13.8	0.79	2	4.53
250720	211MLRW	11/14/2000	401053074155801	00100072	1.7	0.2	8.1	252	12.5	39.9	2.45	3.44
250766	211MLRW	5/30/2001	401200074305301	00100543	--	2.1	6.7	230	11.8	23.6	4.4	4.16
250785	125VNCN	9/15/1999	400525074314101	99901149	4.8	2	6.5	297	14	28.2	2.8	4.28
250790	211MLRL	9/28/2000	400954074302001	00001027	1.1	0.3	5.7	506	20	23	7.27	1.65
250791	125VNCN	5/15/2001	401756074031701	00100549	0.2	3.1	5.5	199	13.5	17.6	2.4	2.31
250792	211MLRW	5/23/2001	400851074312201	00100542	1.5	0.1	6.6	203	13.2	12.7	1.42	4.77
250793	125VNCN	5/29/2001	401722073592201	00100544	<1	6.4	5.5	235	13.9	10.4	2.62	2.51
250796	125VNCN	6/12/2001	401611074085501	00101478	3.4	6.9	5.16	56	11.6	1.36	0.76	2.45
250797	125VNCN	8/7/2001	401732074022101	00101439	3.3	3.6	7.8	245	15.5	41	2.26	1.5
250798	211RDBK	8/22/2001	401531074172801	00101437	0.5	0.6	4.9	499	15	5.79	8.85	3.15
250800	211MLRW	8/8/2001	401229074290001	00101440	0.5	5.2	4.3	173	12.5	9.16	7.43	2.59
250801	211EGLS	9/6/2001	401233074320401	00101441	5.1	9	5.2	165	12.5	16.7	3.2	4.81
250802	211RDBK	9/26/2001	401508074193501	00101436	3.9	4.2	4.9	1050	13.5	3.42	15.6	3.69
250803	211MLRW	7/5/2000	401054074313601	00002265	0.89	7.7	4.6	719	15	16.2	10.9	6.94
290006	211EGLS	8/10/1999	400405074024401	99900872	0.1	0.1	8.2	209	20.5	16.4	5.91	9.54
290449	211EGLS	8/10/1999	400614074115701	99900873	0.2	0.1	8.1	171	16.5	22.6	4.43	4.92
290917	125VNCN	7/12/2000	400850074151601	00000710	0.11	<1	8.2	144	13.1	22.9	1.39	2.4
330249	211MLRW	7/19/2000	393342075271801	00002258	<1	<1	7.5	555	14.3	87.6	3.04	2.81
330902	211MLRW	6/6/2001	393847075191001	00100577	0.2	0.1	7.3	458	13.9	83.5	4.64	3.7
330927	125VNCN	9/28/1999	393610075250001	99901160	0.6	8.7	5.4	281	12	26.1	10.7	1.74
330929	211MLRW	9/9/1999	394024075234701	99901140	0.7	9.2	5.2	369	16	28.8	15.2	8.75
330946	125VNCN	5/1/2001	393549075262201	00100408	0.1	7.4	5.7	271	14.6	9.88	11.5	2.86
330947	211EGLS	5/1/2001	393943075272701	00100579	0.26	<1	5.7	113	15.2	3.35	3.06	1.12
330948	211MLRW	6/13/2001	394141075220401	00101433	0.1	7.44	5.6	534	15.2	28.9	10.4	3.67

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U.S. Geological Survey well number	Aquifer	Date of sampling (mm/dd/yyyy)	Sodium, filtered (mg/L) (P00930)	Acid neutralizing capacity, laboratory, unfiltered (mg/L as CaCO ₃) (P90410)	Chloride, filtered (mg/L) (P00940)	Silica, filtered (mg/L as SiO ₂) (P00955)	Sulfate, filtered (mg/L as SO ₄) (P00945)	Solids, sum, filtered (mg/L) (P70301)	Nitrogen, ammonia, filtered (mg/L as N) (P00608)	Nitrogen, ammonia plus organic, filtered (mg/L as N) (P00623)	Nitrogen, nitrite plus nitrate, filtered (mg/L as N) (P00631)	Nitrogen, nitrate, filtered (mg/L as N) (P00613)	Phosphorus, orthophosphate, filtered (mg/L as P) (P00671)
050354	211MLRW	9/26/2000	2.09	78	2.63	11.1	6	102	0.12	0.14	<.05	<.010	0.04
051189	211MLRW	5/8/2000	1.56	92	5.71	21	24.1	158	0.04	<.10	<.05	<.010	0.11
051403	125HRRS	8/31/1999	1.88	13	13.7	3.3	9.1	64	<.02	0.19	2.58	<.010	<.01
051476	211EGLS	8/19/1999	E1.40	--	E3.5	E6.75	E17.2	--	<.02	<.10	<.05	<.010	<.01
051478	211EGLS	8/19/1999	32.8	--	70.8	6.64	74.3	--	<.02	E.09	11.6	<.010	<.01
051481	211EGLS	9/2/1999	26.5	2	33.8	5.7	22.1	107	<.02	0.13	1.64	<.010	<.01
051486	125HRRS	9/21/1999	E2.70	--	10.3	10.8	83.7	--	<.02	E.07	7.24	<.010	0.04
051500	211EGLS	9/14/2000	11.2	2	31.6	7.6	19.9	92	<.02	<.10	0.54	<.010	<.01
070729	211EGLS	8/22/2000	1.62	69	1.58	11.8	5.8	88	0.03	<.10	<.05	<.010	<.01
070731	211EGLS	8/2/1999	1.52	67	1.76	12.2	6.3	88	<.02	<.10	<.05	<.010	0.08
071005	211EGLS	8/16/2000	49.5	--	94.4	6.6	35.3	241	0.95	1.1	<.05	<.010	0.01
210574	211EGLS	5/8/2001	3.62	8	6.73	14.4	0.3	38	<.04	<.10	0.82	<.006	<.02
210607	211EGLS	5/2/2001	4.36	6	14.2	13.6	49.3	148	<.04	E.05	7.51	<.006	<.02
250714	211EGLS	6/5/2001	2.7	72	5.2	16.1	10.5	117	<.04	<.10	<.05	E.005	0.03
250717	125VNCN	8/18/1999	9.41	--	19.6	8.4	34.1	--	0.48	0.43	<.05	<.010	<.01
250720	211MLRW	11/14/2000	2.49	104	8.31	14	10.2	146	E.03	<.10	<.05	<.006	0.05
250766	211MLRW	5/30/2001	8.12	25	20.2	16.7	40.3	134	<.04	<.10	0.21	<.006	<.02
250785	125VNCN	9/15/1999	6.23	--	18	45	50.7	213	0.03	0.12	<.05	<.010	<.01
250790	211MLRL	9/28/2000	58.7	--	82.6	10.1	46.8	263	<.02	0.25	0.17	<.010	0.1
250791	125VNCN	5/15/2001	10.5	10	40.5	13.3	2.3	109	<.04	<.10	3.28	<.006	0.02
250792	211MLRW	5/23/2001	2.26	9	5.77	34.7	29.3	126	0.06	<.10	E.03	0.028	E.01
250793	125VNCN	5/29/2001	26.1	10	41.3	10.7	3.1	138	E.03	<.10	7.92	<.006	<.02
250796	125VNCN	6/12/2001	4.95	3	4.79	3.3	10.6	30	0.003	<.10	0.005	<.001	<.007
250797	125VNCN	8/7/2001	3.27	107	8.17	11.8	1.9	130	<.04	<.10	1.17	<.006	E.01
250798	211RDBK	8/22/2001	61.8	5	127	13.8	3.1	250	2.7	2.9	4.41	E.003	<.02
250800	211MLRW	8/8/2001	1.51	<1	7.63	7.3	46.2	--	E.03	<.10	3.86	E.003	E.01
250801	211EGLS	9/6/2001	1.69	6	6.07	6.3	2.6	68	E.01	E.05	E3.78	E.001	E.01
250802	211RDBK	9/26/2001	164	2	273	8.9	53.8	528	<.04	<.10	0.95	<.006	<.02
250803	211MLRW	7/5/2000	87.6	--	171	8.26	21.7	--	<.02	E.08	11.7	<.010	<.01
290006	211EGLS	8/10/1999	11.7	96	0.81	11.1	9	121	0.37	0.4	<.05	<.010	0.03
290449	211EGLS	8/10/1999	2.85	86	1.25	10.2	6.9	106	0.11	0.21	<.05	<.010	0.05
290917	125VNCN	7/12/2000	2.6	60	3.12	13	4.9	86	<.02	<.10	<.05	<.010	0.09
330249	211MLRW	7/19/2000	20.9	149	63.3	17.5	34.8	321	0.05	E.07	<.05	<.010	0.02
330902	211MLRW	6/6/2001	2.93	212	3.45	31.9	28.2	288	0.11	0.12	E.02	<.006	<.02
330927	125VNCN	9/28/1999	4.3	8	15.4	6.7	51.1	169	<.02	E.06	11	<.010	0.03
330929	211MLRW	9/9/1999	2.92	3	22.7	12	73.9	221	<.02	0.13	12.5	<.010	<.01
330946	125VNCN	5/1/2001	17.9	8	45.6	8.08	24.2	146	<.04	0.1	4.77	<.006	<.02
330947	211EGLS	5/1/2001	9.55	8	16.5	22.4	11.1	76	<.04	E.07	0.07	<.006	<.02
330948	211MLRW	6/13/2001	41.7	11	118	10.1	5.3	272	<.04	<.10	10.4	E.003	<.02

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U.S. Geological Survey well	Date of sampling (mm/dd/yyyy)	Aquifer	Carbon, organic, filtered (mg/L)	Aluminum, filtered (µg/L)	Arsenic, filtered (µg/L)	Barium, filtered (µg/L)	Boron, filtered (µg/L)	Chromium, filtered (µg/L)	Copper, filtered (µg/L)	Iron, filtered (µg/L)	Lead, filtered (µg/L)	Manganese, filtered (µg/L)
050354	211MLRW	9/26/2000	0.5	<20	--	33.4	E14	--	--	181	--	13.7
051189	211MLRW	5/8/2000	E.3	E10	--	97.3	E15	--	--	754	--	67.5
051403	125HRRS	8/31/1999	1	E10	<1	8.1	--	<1.0	2.5	<10	<1	4.5
051476	211EGLS	8/19/1999	1	E1780	E1.0	E147	--	M	M	E3750	M	E170
051478	211EGLS	8/19/1999	0.9	929	<1	51	81	1.3	<1.0	E7	<1.00	64.8
051481	211EGLS	9/2/1999	0.7	90	<1	18.4	--	<1.0	18	26	<1	51.4
051486	125HRRS	9/21/1999	0.8	E150	<1	E66.6	--	E3.6	E2.9	E26	<1	E320
051500	211EGLS	9/14/2000	E.2	56	<9	40	22	<8	<1.0	46	<1.00	102
070729	211EGLS	8/22/2000	0.6	<20	--	65.5	<16	--	--	197	--	11.4
070731	211EGLS	8/2/1999	0.5	<20	--	55	<16	--	--	166	--	11.7
071005	211EGLS	8/16/2000	4.4	65	112	53	105	1.3	<1.0	29400	<1.00	70.7
210574	211EGLS	5/8/2001	<1	<20	--	43.2	<13	--	--	<10	--	E2.2
210607	211EGLS	5/2/2001	E.3	50	--	101	E7.3	--	--	344	--	56.9
250714	211EGLS	6/5/2001	E.3	<20	0.3	54.8	13	--	--	4910	--	81.1
250717	125VNCN	8/18/1999	0.4	3440	1.4	142	E13	2	<1.0	2280	<1.00	36.8
250720	211MLRW	11/14/2000	0.4	<20	--	38.4	E9.9	--	--	1120	--	126
250766	211MLRW	5/30/2001	0.7	<20	<2	38.7	21	--	--	76	--	135
250785	125VNCN	9/15/1999	1.1	<20	2	29.9	--	<1.0	<1.0	24000	<1	94.4
250790	211MLRL	9/28/2000	4.1	6	1	7	73	<8	<1.0	132	<1.00	54
250791	125VNCN	5/15/2001	<.3	30	<2	27.1	23	--	--	<10	--	13.7
250792	211MLRW	5/23/2001	--	<20	1.6	28.1	31	--	--	29100	--	258
250793	125VNCN	5/29/2001	0.4	<20	<2	47.4	E11	--	--	<10	--	10
250796	125VNCN	6/12/2001	1.7	173	E.2	20	E8.9	2	0.3	<10	0.24	5.6
250797	125VNCN	8/7/2001	E.2	<1	<2	1	17	5.5	E.2	<10	<.08	0.3
250798	211RDBK	8/22/2001	0.3	54	<2	35	24	0.9	1	<10	<.08	224
250800	211MLRW	8/8/2001	0.4	1140	<2	51	20	0.9	36.8	<10	3.76	52.6
250801	211EGLS	9/6/2001	0.4	32	<2	111	19	<8	1.4	<10	5.04	63.7
250802	211RDBK	9/26/2001	<.3	87	<2	70	22	E.7	0.8	<10	E.07	115
250803	211MLRW	7/5/2000	0.6	2050	--	153	17	--	--	E7	--	75.1
290006	211EGLS	8/10/1999	0.3	<20	--	26.2	38	--	--	46	--	49.6
290449	211EGLS	8/10/1999	0.4	M	--	57.3	22	--	--	185	--	38.6
290917	125VNCN	7/12/2000	0.3	<20	--	6.2	E9.2	--	--	86	--	7.3
330249	211MLRW	7/19/2000	0.7	<20	--	18.9	17	--	--	769	--	6.2
330902	211MLRW	6/6/2001	0.7	<20	E.1	79.8	20	--	--	1860	--	34.5
330927	125VNCN	9/28/1999	0.7	80	<2	57.1	--	E.5	E.9	<10	<1	51.3
330929	211MLRW	9/9/1999	0.6	20	<1	53.6	--	<1.0	<1.0	<10	<1	18.7
330946	125VNCN	5/1/2001	0.5	30	--	92.6	E6.8	--	--	35	--	23.2
330947	211EGLS	5/1/2001	0.3	<20	--	28.6	E6.4	--	--	2870	--	141
330948	211MLRW	6/13/2001	<.3	220	<2	184	E12	--	--	114	--	154

Appendix 3. Concentrations of radionuclides, major ions, selected trace elements in, and physical properties of, water from the Vincentown and Wenonah-Mount Laurel aquifers, Englishtown aquifer system, and the Hornerstown and Red Bank Sands, southwestern and south-central New Jersey, 1999-2001.—Continued

[mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picocuries per liter; µS/cm, microsiemens per centimeter; NTU, Nephelometric Turbidity Units. SSMDC, sample specific minimum detectable concentration; 2X, twice; 2S, 2-sigma; CaCO₃, calcium carbonate; <, less than; N, nitrogen; P, phosphorus; E, estimated. Aquifers: VNCN, Vincentown aquifer; HRRS, Hornerstown Sand; RDBK, Red Bank Sand; MLRW, Wenonah-Mount Laurel aquifer; EGLS, Englishtown aquifer system. Number in parentheses is parameter code used to identify the constituent, property, or characteristic in the U.S. Geological Survey water-quality database (NWIS)]

U.S. Geological Survey well	Date of sampling (mm/dd/yyyy)	Aquifer	Uranium, filtered (mg/L)		Radium-226, 2 S precision estimate, filtered (pCi/L)		Radium-226, alpha spectrometry, filtered (pCi/L)		Radium-228, 2X critical level estimate, filtered (pCi/L)		Radium-228, alpha spectrometry, filtered (pCi/L)		Radium-224, 2 S precision estimate, filtered (pCi/L)		Radium-224, 2X critical level estimate, filtered (pCi/L)	
			(P22703)	(P76001)	(P99325)	(P09503)	(P76000)	(P99326)	(P81366)	(P50833)	(P50834)	(P99324)				
050354	211MLRW	9/26/2000	--	0.043	0.056	0.036	0.338	0.662	0.293	0.073	0.098					
051189	211MLRW	5/8/2000	--	0.016	0.014	0.026	0.342	0.644	0.373	0.037	0.02					
051403	125HRRS	8/31/1999	--	--	--	--	--	--	--	--	--					
051476	211EGLS	8/19/1999	E1	0.154	--	0.93	1.08	--	4.3	2.7	0.344					
051478	211EGLS	8/19/1999	<1	0.248	0.076	1.02	1.01	1.07	3.25	2.56	0.476					
051481	211EGLS	9/2/1999	--	--	--	--	--	--	--	--	--					
051486	125HRRS	9/21/1999	--	--	--	--	--	--	--	--	--					
051500	211EGLS	9/14/2000	--	--	--	--	--	--	--	--	--					
070729	211EGLS	8/22/2000	--	0.069	0.032	0.19	0.47	0.876	0.531	0.411	0.067					
070731	211EGLS	8/2/1999	--	0.254	0.328	0.198	0.446	0.866	0.4	-0.046	0.77					
071005	211EGLS	8/16/2000	--	--	--	--	--	--	--	--	--					
210574	211EGLS	5/8/2001	--	0.022	0.036	0.014	0.406	0.737	0.495	0.042	0.12					
210607	211EGLS	5/2/2001	--	0.017	0.022	0.013	0.361	0.714	0.313	0.043	0.039					
250714	211EGLS	6/5/2001	--	0.078	0.05	0.229	0.314	0.578	0.39	0.235	0.032					
250717	125VNCN	8/18/1999	<1	0.242	0.04	1.75	0.655	0.712	2.02	2.702	0.301					
250720	211MLRW	11/14/2000	--	0.065	0.068	0.076	0.245	0.467	0.2	0.07	0.107					
250766	211MLRW	5/30/2001	--	0.044	0.021	0.113	0.312	0.591	0.341	0.14	0.057					
250785	125VNCN	9/15/1999	--	--	--	--	--	--	--	--	--					
250790	211MLRL	9/28/2000	--	--	--	--	--	--	--	--	--					
250791	125VNCN	5/15/2001	--	0.14	0.078	0.271	0.381	0.708	--	--	--					
250792	211MLRW	5/23/2001	--	0.182	0.18	0.154	0.404	0.762	0.477	0.13	0.17					
250793	125VNCN	5/29/2001	--	0.028	0.010	0.054	0.343	0.622	0.456	0.079	0.29					
250796	125VNCN	6/12/2001	0.027	0.07	0.13	0.227	0.383	0.589	0.462	0.042	0.019					
250797	125VNCN	8/7/2001	--	--	--	--	--	--	0.758	0.51	0.19					
250798	211RDBK	8/22/2001	--	0.058	0.023	0.163	0.415	0.562	0.842	0.079	0.056					
250800	211MLRW	8/8/2001	--	0.32	0.06	1.04	0.477	0.692	1.11	0.39	0.5					
250801	211EGLS	9/6/2001	--	--	--	--	--	--	--	--	--					
250802	211RDBK	9/26/2001	--	0.102	0.028	0.328	0.369	0.725	0.304	0.221	0.15					
250803	211MLRW	7/5/2000	--	0.545	0.092	3.209	0.647	0.723	2	1.621	0.534					
290006	211EGLS	8/10/1999	--	0.047	0.046	0.085	0.424	0.685	0.972	0.219	0.139					
290449	211EGLS	8/10/1999	--	0.058	0.049	0.123	0.402	0.725	0.726	0.258	0.111					
290917	125VNCN	7/12/2000	--	0.048	0.059	0.043	0.358	0.734	0.216	0	0.146					
330249	211MLRW	7/19/2000	--	0.066	0.087	0.085	0.354	0.677	0.369	0.047	0.136					
330902	211MLRW	6/6/2001	--	0.108	0.26	0.014	0.339	0.672	0.29	0.42	0.28					
330927	125VNCN	9/28/1999	--	--	--	--	--	--	--	--	--					
330929	211MLRW	9/9/1999	--	--	--	--	--	--	--	--	--					
330946	125VNCN	5/1/2001	--	0.034	0.021	0.137	0.362	0.675	0.443	0.114	0.051					
330947	211EGLS	5/1/2001	--	0.06	0.039	0.146	0.315	0.597	0.329	0.134	0.073					
330948	211MLRW	6/13/2001	--	0.44	0.085	1.31	0.453	0.727	0.897	0.4	0.45					

For additional information, write to:
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