Department of Natural Resources
Resource Assessment Service
MARYLAND GEOLOGICAL SURVEY
Emery T. Cleaves, Director

REPORT OF INVESTIGATIONS NO. 70

OCCURRENCE AND DISTRIBUTION OF RADIUM, GROSS ALPHA-PARTICLE ACTIVITY, AND GROSS BETA-PARTICLE ACTIVITY IN GROUND WATER IN THE MAGOTHY FORMATION AND POTOMAC GROUP AQUIFERS, UPPER CHESAPEAKE BAY AREA, MARYLAND

by

David W. Bolton

Prepared in cooperation with the
Maryland Department of the Environment,
Anne Arundel County Health Department,
and the
United States Department of the Interior
Geological Survey

2000

ACRONYMS AND ABBREVIATIONS

AAHD	Anne Arundel County Health Department
ft	feet
ft/d	feet per day
ft/yr	feet per year
GAPA	gross alpha-particle activity
GBPA	gross beta-particle activity
MCL	Maximum Contaminant Level
MDE	Maryland Department of the Environment
mg/L	milligrams per liter
MGS	Maryland Geological Survey
MRL	minimum reporting level
NWQL	National Water Quality Laboratory
pCi/L	picocuries per liter
µg/L	micrograms per liter
USEPA	U.S. Environmental Protection Agency
µS/cm	microsiemens per centimeter at 25 degrees Celsius
TDS	total dissolved solids
USGS	U.S. Geological Survey

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OCCURRENCE AND DISTRIBUTION OF RADIUM, GROSS ALPHA-PARTICLE ACTIVITY, AND GROSS BETA-PARTICLE ACTIVITY IN GROUND WATER IN THE MAGOTHY FORMATION AND POTOMAC GROUP AQUIFERS, UPPER CHESAPEAKE BAY AREA, MARYLAND

by David W. Bolton

KEY RESULTS

A study was conducted of the occurrence and distribution of radium, gross alpha-particle activity, and gross beta-particle activity in ground water in the Magothy Formation and Potomac Group aquifers in the upper Chesapeake Bay area of Maryland. A total of 203 wells were sampled in Prince George's, Anne Arundel, Baltimore, Harford, Cecil, Kent, and Queen Anne's Counties from June through November 1998. This study was a follow-up to a 1997 pilot study of carcinogens in well water in Anne Arundel County, in which radium-226 plus radium-228 concentrations exceeded the U.S. Environmental Protection Agency's Maximum Contaminant Level of 5 picocuries per liter in 15 of the 20 wells sampled in the Magothy and Patapsco Formations. Analysis of the data from this study and the pilot study has resulted in these key findings:

- Radium-226 plus radium-228 concentrations exceeded 5 picocuries per liter in 60 of 122 samples (49 percent) from wells in the Magothy, Patapsco, and Patuxent Formations in central and northern Anne Arundel County. Radium-226 plus radium-228 concentrations ranged from less than 1.1 to 66 picocuries per liter. In 55 of 113 samples (49 percent) from wells in this area, short-term (measured within 72 hours of sampling) gross alpha-particle activity exceeded the Maximum Contaminant Level of 15 picocuries per liter. Short-term gross alpha-particle activity ranged from less than 3 to 919 picocuries per liter. Outside of Anne Arundel County, gross alpha-particle activity exceeded 15 picocuries per liter in only 6 of 96 wells (6 percent), including two wells in Prince George's County and one well each in Baltimore, Harford, Cecil, and Kent Counties.

- Ground-water radium, gross alpha-particle activity, and gross beta-particle activity were highest in the outcrop and updip areas of the Magothy Formation and the Potomac Group, where the aquifers are generally unconfined; radionuclide concentrations tended to be lower in the deeper, confined parts of these aquifers.

- Radium-226, radium-228, gross alpha-particle activity, and gross beta-particle activity tended to increase with decreasing pH. Radium-226 plus radium-228 exceeded 5 picocuries per liter in 65 percent of samples (46 of 71) having pH less than 4.5, while only about 6 percent of samples (3 of 51) with pH 4.5 or more exceeded this concentration.

- Radium-226, radium-228, gross alpha-particle activity, and gross beta-particle activity tended to increase with increasing total-dissolved-solids content (as indicated by specific conductance), and with increasing sodium and chloride concentrations in particular. All samples having more than about 10 milligrams per liter sodium and about 15 milligrams per liter chloride had radium-226 plus radium-228 concentrations greater than 5 picocuries per liter.

- Radionuclide concentrations tended to decrease with increasing depth to the screened interval. Water from wells with screened intervals greater than 300 feet deep were almost always less than the Maximum Contaminant Levels for gross alpha-particle activity and radium-226 plus radium-228. However, wells that are relatively close to one another may have very different radium and gross alpha-particle activity concentrations, even when screened at the same depths but especially when screened at different depths.

- Gross alpha-particle activities measured 30 days after sampling were usually 60 to 90 percent lower than the gross alpha-particle activities in the same samples measured within 72 hours of sampling. This large decrease, along with radium-224 analyses from the pilot study, suggests that radium-224 (which has a half life of 3.64 days) comprises a significant part of the total radium content in ground water in the Magothy, Patapsco, and Patuxent Formations in the upper Chesapeake Bay region.

- Radium can apparently be mobilized to ground water in the Magothy Formation and Potomac Group anywhere in the upper Chesapeake Bay region in Maryland under conditions of high TDS, low pH, or a combination of both.

INTRODUCTION

In 1997, a pilot study of carcinogens in Anne Arundel County well water revealed that high concentrations of radium were present in parts of the Magothy and Patapsco Formations (Bolton and Hayes, 1999). Concentrations of radium-226 plus radium-228 exceeded the Maximum Contaminant Level (MCL) of 5 picocuries per liter (pCi/L) in samples from 15 of 20 wells in these formations. Furthermore, analysis for radium-224 (which has a half-life of 3.64 days) indicated that this isotope comprises a significant proportion of the total radium content of ground water in these aquifers. The high concentrations of radium were associated most closely with acidic (pH less than 5) ground water, and also with high total dissolved solids (TDS). Because ground water in the Magothy and Patapsco Formations is the primary source of drinking water for many residents of the Maryland Coastal Plain, a larger-scale investigation was conducted to determine the extent of the high-radium ground water in these aquifers in the upper Chesapeake Bay area of Maryland.

PURPOSE AND SCOPE

The purpose of this study was to: (1) provide information on the lateral and vertical distribution of radium-226, radium-228, and gross alpha-particle activity (GAPA) and gross beta-particle activity (GBPA) in ground water from the Magothy Formation and Potomac Group aquifers in Anne Arundel County; and (2) identify other areas in Maryland where water in these aquifers may contain high concentrations of radium-226, radium-228, and radium-224. This report presents data on the occurrence and distribution of radium-226, radium-228, GAPA, and GBPA in ground water from the Magothy Formation and Potomac Group (Patapsco and Patuxent Formations) in the upper Chesapeake Bay area of Maryland. Factors associated with high concentrations of radium in ground water are discussed, including water quality and depth to the screened interval. Several areas of investigation are recommended that will provide more information about the specific aspects of radium occurrence in ground water. A glossary of terms used in this report is included at the end of the report.

RADIOACTIVITY: PRINCIPLES AND HEALTH EFFECTS

Radium is formed from the spontaneous radioactive decay of uranium and thorium, small amounts of which occur naturally in most aquifer materials (fig. 1; tab. 1). Three of the four known isotopes of radium have been identified in ground water in the Magothy and Patapsco Formations in Anne Arundel County: radium-226, radium-228, and radium-224 (Bolton and Hayes, 1999). (The fourth isotope, radium-223, is limited by the scarcity of uranium-235 in crustal rocks.) Radium-226 is an intermediate decay product in the uranium-238 series (fig. 1). Radium-228 and radium-224 are in the thorium-232 decay series. Radium-226 and radium-228 are long-lived isotopes with half-lives of 1,622 years and 5.75 years, respectively. (A half-life is defined as the time required for any amount of a radioisotope to be reduced to one-half the initial amount.) Radium-224 has a half-life of 3.64 days. During the spontaneous radioactive decay of radium-226 and radium-224, an alpha particle (consisting of two protons and two neutrons) is emitted from the nucleus (Brownlow, 1979). Radium-228 emits a beta particle, which consists of an electron derived from the transformation of a neutron to a proton. The chemical properties of radium are similar to the other alkaline-earth ions such as barium and calcium, and trace amounts of radium can substitute for these cations in crystal lattices (a process known as coprecipitation) (Wanty and Nordstrom, 1993). Radium has only one oxidation state (Ra^{2+}), and, therefore, is not directly affected by redox conditions.

The geochemistry of uranium and thorium differ greatly; this difference affects their distribution in aquifers, which in turn will affect radium distribution. Uranium has three oxidation states (U^{4+}, U^{5+}, and U^{6+}). Under oxidizing conditions, uranium is quite mobile as dissolved U^{6+}. Under oxidizing conditions, U^{6+} is in the form of the uranyl ion (UO_2^{2+}), which can form soluble complexes with carbonate, biphosphate, and humic acid (Wanty and Nordstrom, 1993). Uranyl is strongly sorbed onto ferric oxides and other secondary minerals (Ames, McGarrah, Walker, and Salter, 1983; Hsi and Langmuir, 1985). Uranium concentrations are low in reducing ground-water conditions as a result of

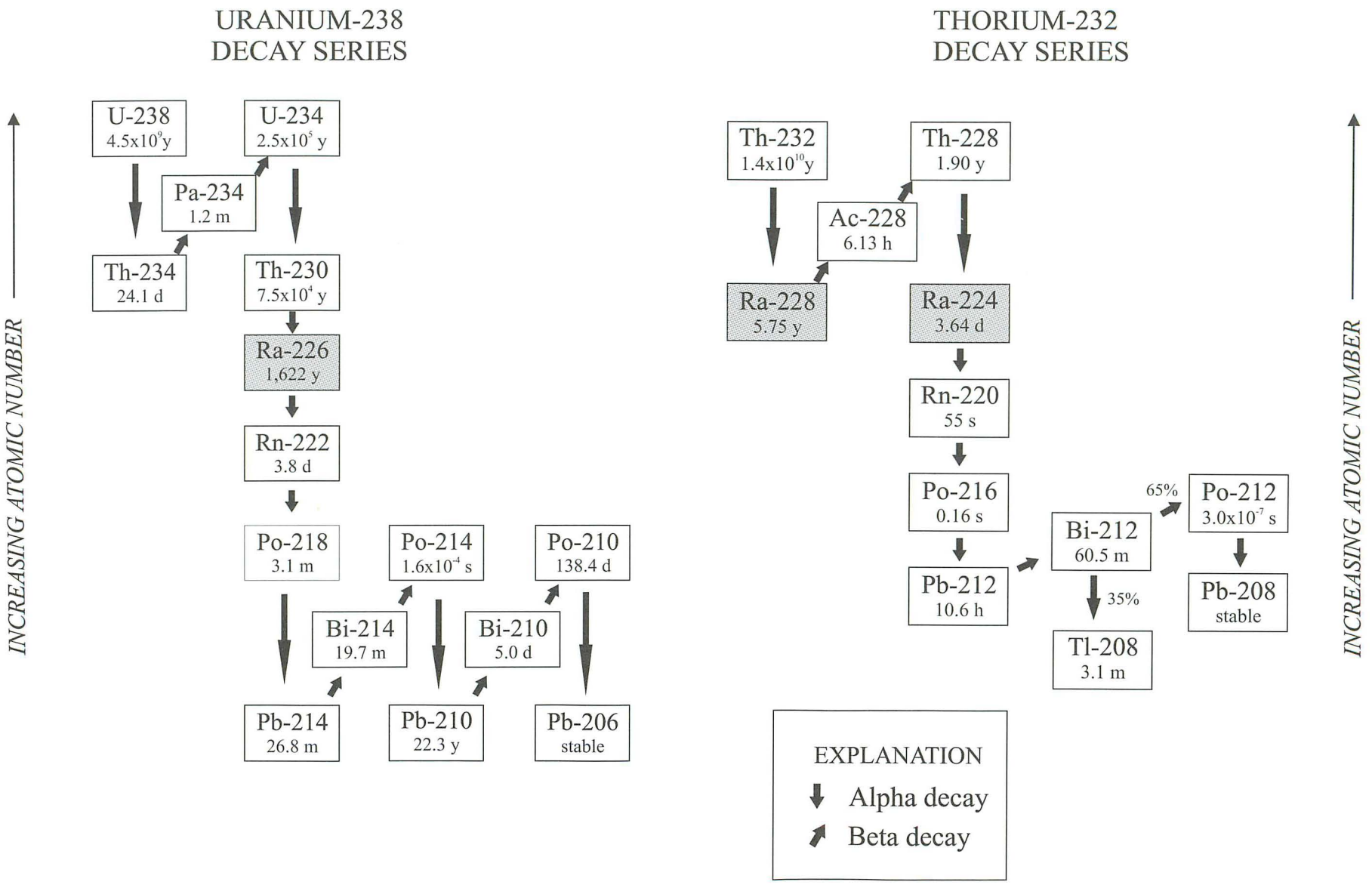

Figure 1. Uranium-238 and thorium-232 radioactive decay series. Isotope half-lives are given in years (y), days (d), hours (h), minutes (m), and seconds (s). Radium isotopes are shaded. Modified from Aieta and others (1987).

Table 1. Concentrations of uranium and thorium in selected rocks, sediments, and minerals

[Concentrations are in parts per million. Sources: Mahdavi (1964); Brownlow (1979); Hoffman and Buttleman (1994)]

Rock or mineral	Uranium	Thorium
Granite	4.4	16
Shale	3.8	12
Biotite	20	25
Muscovite	20	25
K-feldspar	1.5	5.0
Plagioclase	2.5	1.5
Zircon	2,500	2,000
Beach sands, North Carolina coast	0.5-2.1	1.2-5
Stream sediments, Anne Arundel County	1.4-16.4	3-58

the insolubility of uranium(IV) minerals (Wanty and Nordstrom, 1993). The extremely long half lives of uranium-238 and uranium-234 (4.5×10^9 years and 2.5×10^5 years, respectively) in conjunction with its mobility under oxidizing conditions give uranium the potential to be transported significant distances in ground water.

Thorium has one oxidation state (Th^{4+}) and is very insoluble in most ground water; concentrations are rarely more than 1 µg/L in natural waters in the pH range of 5 to 9 (Langmuir and Herman, 1980). Calculations based on critically assessed thermodynamic data, however, indicate that thorium solubility is greatly enhanced in low-pH waters due to the formation of inorganic and organic complexes, including $Th(SO_4)_2^o$, ThF_2^{2+}, and $Th(HPO_4)_2^o$; desorption also increases greatly with decreasing pH between pH 2 and 6.5 (Langmuir and Herman, 1980). Low levels of thorium have been detected in Anne Arundel County ground water (M. Focazio, U.S. Geological Survey, written commun., 2000). There is currently no Federal drinking-water standard for thorium.

Radium-226 and radium-228 are human carcinogens (Cancer Group A) (U.S. Environmental Protection Agency, 1996). Most radium ingested through drinking water is eliminated in urine or feces. However, radium that is not eliminated can accumulate in the bone tissue, where the alpha and beta particles produced from the decay of radium can damage cell tissue and may induce cancer (National Research Council, 1988). Much of the knowledge of the health effects of radium is derived from studies of watch-dial painters in the early part of the twentieth century. These workers painted watch dials with radium, and would routinely shape the tips of their brushes with their tongues and lips. In the 1920s and 1930s, many workers developed head sarcomas and bone carcinomas (Milvy and Cothern, 1990). A full discussion of the health effects of radium is beyond the scope of this report; information on this subject may be found in the BEIR IV report of the National Research Council (1988). The USEPA established a MCL of 5 picocuries per liter (pCi/L) for combined radium-226 plus radium-228 in public drinking-water supplies (Federal Register, 1976). However, under the 1976 regulations, water samples were required to be analyzed for radium-226 only if GAPA exceeded 5 pCi/L, and radium-228 analysis was required only if radium-226 exceeded 3 pCi/L (Federal Register, 1976). Furthermore, testing for GAPA was permitted by analyzing an annual composite sample consisting of four consecutive quarterly samples, which has likely resulted in the non-detection of short-lived alpha-emitting isotopes such as radium-224. In light of the recent studies that have detected such isotopes in ground water (Szabo and others, 1998; Bolton and Hayes, 1999; Focazio and others, in press), the USEPA is currently reviewing the Federal Drinking Water Standards for radionuclides (D. Huber, U.S. Environmental Protection Agency, 1998, oral commun.).

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HYDROGEOLOGIC SETTING

The Maryland Coastal Plain physiographic province consists of a wedge of predominantly unconsolidated sands, silts, clays, and gravels that ranges in thickness from zero on the northwestern boundary near Interstate 95 to about 7,700 feet (ft) at Ocean City (Hansen and Edwards, 1986). The sediments range in age from early Cretaceous to Holocene. A stratigraphic section of the Coastal Plain sediments in the upper Chesapeake Bay area in Maryland is shown in table 2.

The aquifers in the Potomac Group and Magothy Formation are recharged from precipitation that falls in the outcrop areas and then flows downgradient in the direction of decreasing potentiometric head. The water is ultimately discharged to the major water bodies in the area, usually the Chesapeake Bay or the major rivers; discharge also occurs to wells. In Anne Arundel County, groundwater flow in the Magothy Formation and the Potomac Group is generally to the southeast, although heavy pumping at the Arnold and Severndale wellfields have created cones of depression in the potentiometric surface on the Broadneck Peninsula (Curtin and others, 1999a; 1999b; 1999c).

POTOMAC GROUP

The Potomac Group includes the Patuxent and Patapsco Formations. The Potomac Group aquifers outcrop in a broad band extending from Prince George's County northeast to Cecil County. They are an important source of water both in the outcrop areas and where they are confined elsewhere in the study area, in southern Maryland, and on the Eastern Shore. In Prince George's, Anne Arundel, and Baltimore County and parts of Queen Anne's Counties, the Patuxent Formation is mapped separately because it is separated from the Patapsco Formation by a marker bed, the Arundel Clay. However, in Harford, Cecil, and Kent Counties, the Potomac Group is undivided because the formations are difficult to differentiate (Higgins and Conant, 1990; Cleaves, 1968).

Patuxent Formation

The Patuxent Formation is the oldest Cretaceous unit outcropping in Maryland, and forms an irregular belt immediately adjacent to the crystalline Piedmont rocks. The Patuxent Formation is composed of discontinuous and interconnected lenses of quartz and feldspathic sands and tough, variegated clays (Mack and Andreasen, 1991). The Patuxent Formation was deposited in a fluvial environment, and consists of a complex series of channel and point-bar sands and gravels interstratified with flood plain (or swamp) silts and clays. It is a multiple-layer aquifer system with individual sand beds that are difficult to correlate between wells. Kaolinized feldspar, pyrite, and lignite are common; iron stains and siderite granules are also found. Occasional to rare occurrences of hematite granules, pyrite, and lignite were noted in samples from a test well drilled at Sandy Point (Mack and Andreasen, 1991). The Patuxent Formation is a significant aquifer in northwestern Anne Arundel and

Table 2. Generalized description of geologic formations in Anne Arundel County

[ft, feet. Modified from Fleck and others (1996)]

System	Series	Group	Formation	Average thickness (ft)	General lithology	Hydrologic character
QUATERNARY	Holocene and Pleistocene		Alluvium and terrace deposits	20	Sand, gravel, silt, and clay.	Confining bed in most places; limited aquifer in some places
	Pleistocene		Talbot Formation	20	Clay, silt, brown to gray, with some glauconite and pebbles.	Confining unit
TERTIARY	Pliocene (?) or Miocene (?)		Brandywine Formation	30	Sand, pebbly sand, and gravel; extremely limited distribution.	Aquifer
	Miocene	Chesapeake	Calvert Formation	75	Sandy clay and fine sand, fossiliferous, diatomaceous earth.	Limited aquifer
	Eocene	Pamunkey	Nanjemoy Formation	50	Glauconitic sand, silt, and clay.	Confining unit
	Paleocene		Marlboro Clay	15	Clay, silvery gray to pink.	Confining unit
			Aquia Formation	130	Glauconitic, greenish to brown sand with thin indurated or "rock" layers, and silt layers.	Aquifer
			Brightseat Formation	15	Silt and clay, olive-gray to black, glauconitic.	Leaky confining unit
CRETACEOUS	Upper Cretaceous		Severn Formation	45	Sand, silty to fine, with some glauconite.	Limited aquifer, equivalent to Monmouth aquifer
			Matawan Formation	60	Silt and fine sand, clayey, dark-green to black, glauconitic.	Confining unit
			Magothy Formation	120	Sand, light-gray to white, with interbedded thin layers of organic black clay; pyrite common.	Aquifer
	Lower Cretaceous	Potomac Group	Patapsco Formation	800	Sand, fine to coarse, brown, and tough variegated clay.	Multiple layered aquifer
			Arundel Clay	250(?)	Clay, red, brown, and gray; contains some ironstone nodules, plant remains, and thin sandy layers.	Confining unit
			Patuxent Formation	300(?)	Sand, gray and yellow, with interbedded clay; kaolinized feldspar, pyrite, and lignite common; locally clay layers predominate.	Aquifer
Triassic (?) and Lower Paleozoic (?) or Precambrian (?)			Basement Complex	Unknown	Shale, sandstone, gneiss, or granite.	Confining unit

northern Prince George's Counties. Groundwater flow in the Patuxent Formation in these areas is generally to the east or east-southeast, although it is influenced locally by cones of depression surrounding public-supply wells (Grufon Achmad, Maryland Geological Survey, written commun., 1999).

Patapsco Formation

The Patapsco Formation outcrops over a wide area of north-central Anne Arundel County and northern Prince George's County. It is a fluvio-deltaic deposit consisting of interbedded gray, brown, and red silt and clay and argillaceous quartzose sand (Hansen, 1972). In Anne Arundel County, the thickness of individual sand, silt, and clay layers is generally less than 20 ft thick, but can vary greatly. In general, the sands are discontinuous and correlation of individual layers is difficult, even on a local scale. The formation contains thin beds of gravel and siderite-cemented sandstone (Fleck and others, 1996). In the upper Chesapeake Bay area, the sediments are mainly composed of white to gray quartz sand interbedded with variegated clay (red, brown, purple, gray, white, and yellow). Some of the sand beds are reported to be feldspathic, and may contain siderite, hematite, or limonite. Lignite and pyrite are commonly found in medium to dark gray clays (Otton and Mandle, 1984). Groundwater flow is generally to the southeast, although a cone of depression in the potentiometric surface is found near the Severndale and Arnold wellfields on the Broadneck Peninsula (Curtin and others, 1999a; 1999c).

MAGOTHY FORMATION

The Magothy Formation is an important aquifer in Prince George's, Anne Arundel, Cecil, Kent, and Queen Anne's Counties (Wheeler and Wilde, 1989). It outcrops in a narrow band across northern Anne Arundel County, but is present only in the subsurface in Prince George's County. It subcrops beneath the Chesapeake Bay and is found in outcrop in isolated exposures in northern Kent and eastern Cecil County on the Eastern Shore (Cleaves and others, 1968). The Magothy Formation is a fluviomarine deposit consisting of light gray to white, sugary, medium-to coarse-grained quartzose sand and fine gravel interbedded with dark gray silts and clays and containing lignite and pyrite (Hansen, 1972). Although the Magothy and Patapsco Formations are separated by a regional unconformity, it is often difficult to identify the contact between the two formations using well logs and drill cuttings. In some areas (for example, the Mountain Road peninsula), the Magothy and Patapsco Formations are hydraulically connected across a sand-on-sand contact and locally may function as a single aquifer. Groundwater flow in the Magothy Formation is generally toward the southeast (Curtin and others, 1999b).

AQUIA FORMATION

The Aquia Formation outcrops over a wide area in central Anne Arundel County and is an important aquifer in southern Maryland. It is a fine- to coarse-grained green to brown sand containing 20 to 70 percent glauconite and goethite (Hansen, 1972). In the outcrop area near Annapolis, it is weathered to a depth of 70 ft, and there is no carbonate material in the aquifer. It contains weathered quartzose and glauconitic sands interbedded with thin layers of iron-stained silt and iron-oxide cemented sandstone (Mack and Andreasen, 1991). In the confined part of the Aquia Formation, carbonate material and fossils are abundant.

METHODS OF INVESTIGATION

WELL-NUMBERING SYSTEM

Wells in this report are identified by an alphanumeric system. The first two letters (both uppercase) indicate the county where the well is located. The next two letters (the first uppercase, the second lowercase) correspond to a 5-minute by 5-minute block of a grid superimposed over the county: the first letter corresponds to the row and the second letter corresponds to the column within the grid.

Wells within each block are numbered sequentially as they were inventoried. Thus, well CE Be 22 refers to the twenty-second well inventoried in the block located at the intersection of row "B" and column "e" in Cecil County. Well locations are shown for Anne Arundel County in plate 1 and for the rest of the study area in plate 2.

WELL SELECTION

Water samples were collected from 203 wells in the upper Chesapeake Bay area of Maryland, of which 104 wells were located in Anne Arundel County. Twenty of the Anne Arundel County wells were located along three southeastward-trending sections in order to construct geochemical transects. Seventeen other wells in Anne Arundel County were selected to construct a transect across the Mountain Road peninsula. The remaining 67 wells in the county were located in areas that had not been sampled during the pilot study, or where radionuclide data from relatively deep (greater than about 100 ft) wells were absent. Water samples were collected from 99 wells in Prince George's, Baltimore, Harford, Cecil, Kent, and Queen Anne's Counties; these wells are referred to in this report as the regional wells. These wells were selected to evaluate ground-water radium concentrations throughout the Magothy Formation and Potomac Group aquifers, rather than to achieve a population-density-weighted selection of wells. A variety of resources were used to identify wells for sampling, including USGS, MGS, MDE, and county-level personnel and databases. In areas where no data were available, well owners were interviewed to determine whether their well had suitable construction documentation to be included in the study. Well-construction data and site characteristics are given in appendix A.

The density of sampled wells was greater in Anne Arundel County than in the rest of the study area because of the need to define the lateral and vertical distribution of radium in the county, and because of the number of people in Anne Arundel County who rely on ground water from the Magothy and Potomac Group aquifers compared to the rest of the study area. Because of the different methods of well selection and the greater density of sampled wells in Anne Arundel County than the rest of the study area, the data set may be biased.

Eighty percent (163 of 203) of the sampled wells were domestic water-supply wells, 15 percent were public water-supply wells, and the remainder were either institutional, industrial, commercial, recreational water-supply wells or observation wells. Two wells (AA Df 124 and QA Db 27) were sampled to evaluate the relation between elevated TDS and radium concentrations in the Aquia Formation. In the pilot study, high TDS was associated with high concentrations of radium in the Patapsco and Magothy Formations. Radium concentrations from pilot-study wells in the Aquia Formation were low; however, no high-TDS Aquia wells had been sampled. The two Aquia wells sampled during this study were selected because chloride concentrations from previous samples from the wells were relatively high (more than 80 milligrams per liter [mg/L]). Two other wells (CE Df 42 and CE Df 43), whose screened intervals were believed at the time of sampling to have been in the Magothy Formation, were subsequently determined to be in the Monmouth Formation.

SAMPLE COLLECTION AND ANALYSIS

All water samples were collected from spigots or other outlets that were identified by the owners as sources of untreated water. Samples from approximately 75 percent of private water wells were collected from outside spigots; the rest were collected from the tap at the pressure tank. Samples from public water-supply wells were collected from spigots drawing water from points located before the treatment systems. Observation wells were sampled with submersible pumps or bailers. A YSI 600XL datasonde[1] was used to measure pH, specific conductance, dissolved oxygen, and water temperature as the well water was purged. The datasonde was calibrated at the start of each day with a two-buffer pH calibration and a one-standard specific conductance calibration. Buffers for the pH calibration were selected to bracket the anticipated pH of the samples; the specific conductance standard that was selected was close to the anticipated specific conductance of the sample. For samples collected from spigots, the flow rate was adjusted to a rate of two to four gallons per minute. Specific conductance, pH, dissolved oxygen, and temperature were recorded at five-minute intervals. The water was run and readings were taken at 5-minute intervals until the water was clear and

[1] The use of trade names in this report is for identification purposes only, and does not constitute endorsement by the Maryland Geological Survey or the other cooperating agencies.

three consecutive readings fell within the following ranges of tolerance: specific conductance, ±5 percent (if specific conductance was more than 100 µS/cm) or ±5 µS/cm (if specific conductance was less than 100 µS/cm); pH, ±0.1 pH unit; temperature, ±0.5 degree Celsius. Six samples did not meet purge criteria for temperature but were collected nevertheless; the temperature fluctuation or change at these sites was attributed to surface effects such as the discharge hose being located in direct sunlight.

Samples were collected once the stabilization criteria had been met. The radionuclide sample bottles were filled directly from the spigot and were immediately acidified with nitric acid to pH less than 2. Unfiltered, rather than filtered, samples were analyzed for radionuclides. For the purposes of this study, unfiltered samples were more representative of well water available for consumption. Although turbidity was not monitored during purging, samples were not collected until the purge water was flowing clear. It has been shown that concentrations of barium (whose chemical behavior is similar to radium) are little affected by particulate matter in ground water (Gibs and others, in press). Samples that were analyzed for major ions were collected in a 5L amber glass bottle and filtered through a 0.45-micron Gelman[1] capsule filter using a peristaltic pump. After sample collection and processing had been completed, the 5L glass amber bottles and the peristaltic pump tubes were cleaned with a liquinox detergent and rinsed with deionized water, rinsed with hydrochloric acid, and re-rinsed with deionized water. Samples analyzed by NWQL and Quanterra Analytical Services, including radionuclide and major-ion samples, were shipped by overnight courier. Samples analyzed by the Maryland Department of Health and Mental Hygiene laboratory were delivered to the laboratory at the end of each sampling day.

All wells in the study were analyzed for short-term (measured approximately 72 hours after sampling) and long-term (measured approximately 30 days after sampling) GAPA and GBPA, specific conductance, pH, and dissolved oxygen. GAPA and GBPA were used as an inexpensive indicator of radium. Short-term GAPA was measured in order to more accurately assess GAPA as it exists in water withdrawn from the aquifer. The difference between the short-term and long-term GAPA was associated with direct measurements of radium-224 concentrations in the pilot study, and was used in the present study as an indicator of radium-224. Long-term and short-term GBPA were also measured to check for the possible presence of short-lived beta-particle emitting isotopes. Concentrations of radium-226 and radium-228 were determined for well water in Anne Arundel County; additionally, concentrations of major cations and anions were determined for the wells comprising the three geochemical transects. Chloride and nitrate concentrations were analyzed in another 51 samples in Anne Arundel County. Chemical constituents, minimum reporting levels (MRLs), sample containers, treatment, preservatives, and analytical methods for the chemical constituents are given in Appendix B.

In this report, radium-226, radium-228, GAPA, and GBPA are collectively referred to as "radionuclides" as a matter of convenience; this is not meant to imply that there are no other radionuclides present. Analysis for the presence of other radionuclides were not conducted in the study.

DATA ANALYSIS

The radionuclide data were evaluated with respect to pH, specific conductance, ion concentrations, and depth to the middle of the screened interval. Nonparametric rather than parametric statistical tests were used to determine whether the water-quality variables were correlated because none of the water-quality or well-construction data were normally distributed (Kolmogorov-Smirnov test, $P<0.01$). The Spearman rank order correlation test was used to measure the strength of the association between two variables. The Spearman rank order correlation coefficient r_s was determined for pairs of variables based on ranks rather than measured values, and can range from +1 to -1. An r_s value near +1 indicates a strong positive correlation between the variables; an r_s value near -1 indicates a strong negative correlation. An r_s value of zero means that there is no correlation between the ranks of the variables. The Mann-Whitney rank-sum test was used to test for statistically significant differences between two groups of data; the Kruskal-Wallis rank sum test was used to test for differences between three or more groups. A significance level of $\alpha=0.05$ was used; that is, the association between variables was considered statistically significant if there was less than a 5 percent chance of incorrectly concluding that there was a true association between the variables. The P value is the calculated value that is compared to the α value to determine significance. In addition to the data from the 203 wells sampled for this project, data from the 20 Magothy and Patapsco wells sampled

during the Anne Arundel County pilot study (Bolton and Hayes, 1999) were also utilized in the data-evaluation phase of the project. The statistical tests are described in Conover (1999). Test statistics were calculated using SigmaStat[1] 2.0 (SPSS, Inc., Chicago, Illinois).

QUALITY ASSURANCE

Quality assurance methods included verification of water-quality and well-construction data. Blank and duplicate samples were collected to document the lack of contamination and precision, respectively. Radium-226, radium-228, short-term and long-term GAPA and GBPA from four field blank samples were all less than MRLs. Radionuclide concentrations from duplicate samples collected from four wells were all within the range of total propagated error of the measurements. For the duplicate samples, short-term GAPA was always higher in the sample that was analyzed first (usually there was a three- to six-hour lag time between analyses), which likely reflects radium-224 decay.

Charge-balance errors were calculated for samples from the 20 wells analyzed for major ions in this study and for 19 wells sampled during the pilot study. Charge-balance errors were less than ±10 percent for 29 of 39 wells. In most of the other 10 wells, TDS was less than 80 mg/L, where apparently large charge-balance errors can result from small differences in ionic concentrations. The charge-balance error from well AA Bf 70 (-27 percent) was considered unacceptably large; the major-ion concentrations from this well were not included in the data analysis, with the exception of chloride. The chloride analysis was retained because the specific conductance/chloride ratio (30) seemed reasonable compared to analyses from other wells with similar specific conductances and well depths.

RADIUM AND RADIOACTIVITY IN GROUND WATER

DISTRIBUTION OF RADIONUCLIDES IN GROUND WATER IN SELECTED AQUIFERS OF THE UPPER CHESAPEAKE BAY AREA

Radionuclide data from water samples from the Magothy, Patapsco, and Patuxent Formations are presented in this section. The discussion focuses on radium-226 plus radium-228, and short-term GAPA, since these are the constituents for which MCLs have been established; however, all radionuclides were highly correlated (tab. 3). Unless otherwise specified, in this report, "high" concentrations of radium are defined as those which exceed the MCL of 5 pCi/L for radium-226 plus radium-228, and "high" GAPA are those which exceed the MCL of 15 pCi/L. Water-quality data are given in appendix C.

Radium, Gross Alpha-Particle Activity and Gross Beta-Particle Activity in Anne Arundel County

Magothy Formation

Radium-226 plus radium-228 concentrations in well water from the Magothy Formation in Anne Arundel County ranged from less than 1.1 to 66 pCi/L. Samples from 12 of the 35 wells in the Magothy Formation exceeded 5 pCi/L. Short-term gross alpha-particle activity ranged from less than 3 to 919 pCi/L; samples from 12 of 34 wells exceeded 15 pCi/L. Short-term gross beta-particle activity ranged from less than 4 to 188 pCi/L. Ground-water radium and GAPA concentrations exceeding their respective MCLs were all located within a three- to four-mile-wide zone extending from the Mountain Road peninsula southwest to Crofton; this area is in or near the outcrop area of the Magothy Formation (figs. 2, 3, and 4). Radionuclide concentrations from Magothy Formation wells located more than about two to four miles downdip of the outcrop area were all less than MCLs (figs. 2 and 3). The boundary between the areas of high and low ground-water radionuclide concentrations is fairly distinct. Radionuclide concentration data are summarized in tables 4 and 5.

Patapsco Formation

Radium-226 plus radium-228 concentrations in well water from the Patapsco Formation in Anne Arundel County ranged from less than 1.1 to 64 pCi/L.

Table 3. Spearman correlation coefficients for radionuclides

[The first (upper) number in each cell is the Spearman correlation coefficient r_s, which quantifies the strength of the association between the variables. Values of r_s near +1 indicate a strong positive correlation, while values near -1 indicate a strong negative correlation. A correlation of 0 means that no correlation exists between the variables. The second (middle) number is the *P* value, which is the probability of incorrectly concluding that a correlation exists between the variables. The third (lower) number is the number of samples. GAPA, gross alpha-particle activity; GBPA, gross beta-particle activity.]

Constituent	Long-term GAPA	Short-term GBPA	Long-term GBPA	Radium-226	Radium-228	Radium-226 plus radium-228
Short-term GAPA	0.82 <0.01 209	0.88 <0.01 199	0.82 <0.01 209	0.94 <0.01 112	0.96 <0.01 112	0.96 <0.01 112
Long-term GAPA		0.79 <0.01 199	0.80 <0.01 219	0.92 <0.01 122	0.89 <0.01 122	0.91 <0.01 122
Short-term GBPA			0.83 <0.01 199	0.91 <0.01 102	0.94 <0.01 102	0.94 <0.01 102
Long-term GBPA				0.92 <0.01 122	0.95 <0.01 122	0.95 <0.01 122
Radium-226					0.94 <0.01 122	0.97 <0.01 122
Radium-228						0.99 <0.01 122

Samples from 45 of 79 wells exceeded 5 pCi/L. Short-term gross alpha-particle activity ranged from less than 3 to 351 pCi/L; samples from 40 of 71 wells exceeded 15 pCi/L. Short-term gross beta-particle activity ranged from less than 4 to 180 pCi/L. Radionuclide concentrations exceeding MCLs do not exhibit as strong a geographical trend as those from wells in the Magothy Formation (figs. 5, 6, and 7). Wells with samples exceeding 15 pCi/L for short-term GAPA are either in or within three miles downdip of the Patapsco Formation outcrop area. The highest radionuclide concentrations were from wells in the Lake Shore area on the Mountain Road peninsula. The four wells located the greatest distance from the outcrop area of the Patapsco Formation (AA Cf 119, AA Cf 142, AA Dg 19, and AA De 139) all had short-term GAPA less than 15 pCi/L.

Patuxent Formation

Radium-226 plus radium-228 concentrations in samples from eight wells in the Patuxent Formation ranged from less than 1.1 to 23 pCi/L. Short-term GAPA ranged from less than 3 to 70 pCi/L. Samples from three of the eight wells exceeded both 5 pCi/L radium-226 plus radium-228 and 15 pCi/L short-term GAPA. Short-term GBPA ranged from less than 4 to 39 pCi/L. Short-term GAPA and radium-226 plus radium-228 exceeded their respective MCLs in samples from three of the eight wells (figs. 8 and 9). The highest short-term GBPA values were from the same three wells (fig. 10), two of which (AA Bb 22; AA Bb 89) are located in the outcrop area of the Patuxent Formation. Well AA Bb 22 had the highest short-term GAPA (70 pCi/L) of all Patuxent

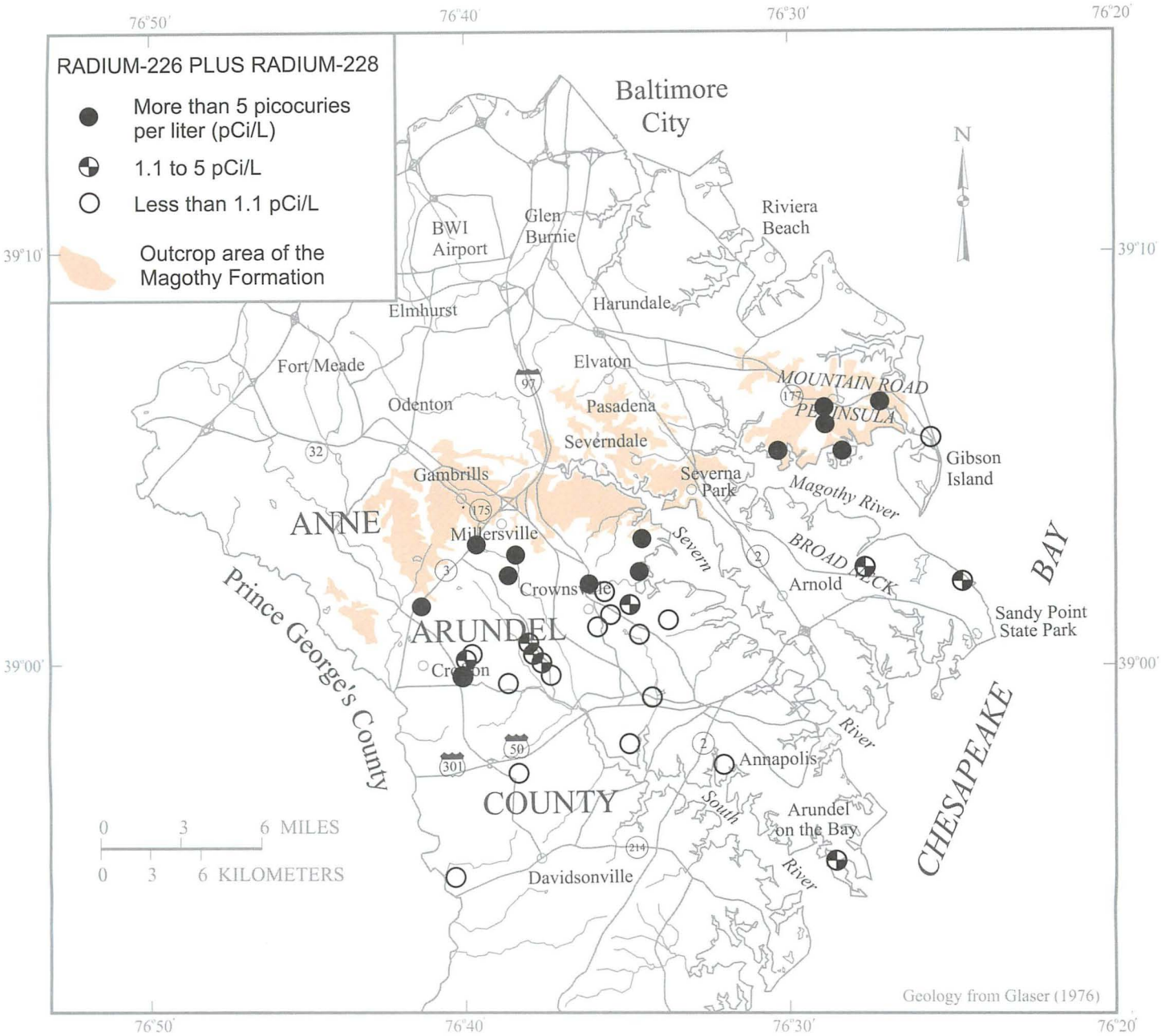


Figure 2. Map showing the distribution of radium-226 plus radium-228 in ground water from the Magothy Formation in Anne Arundel County.

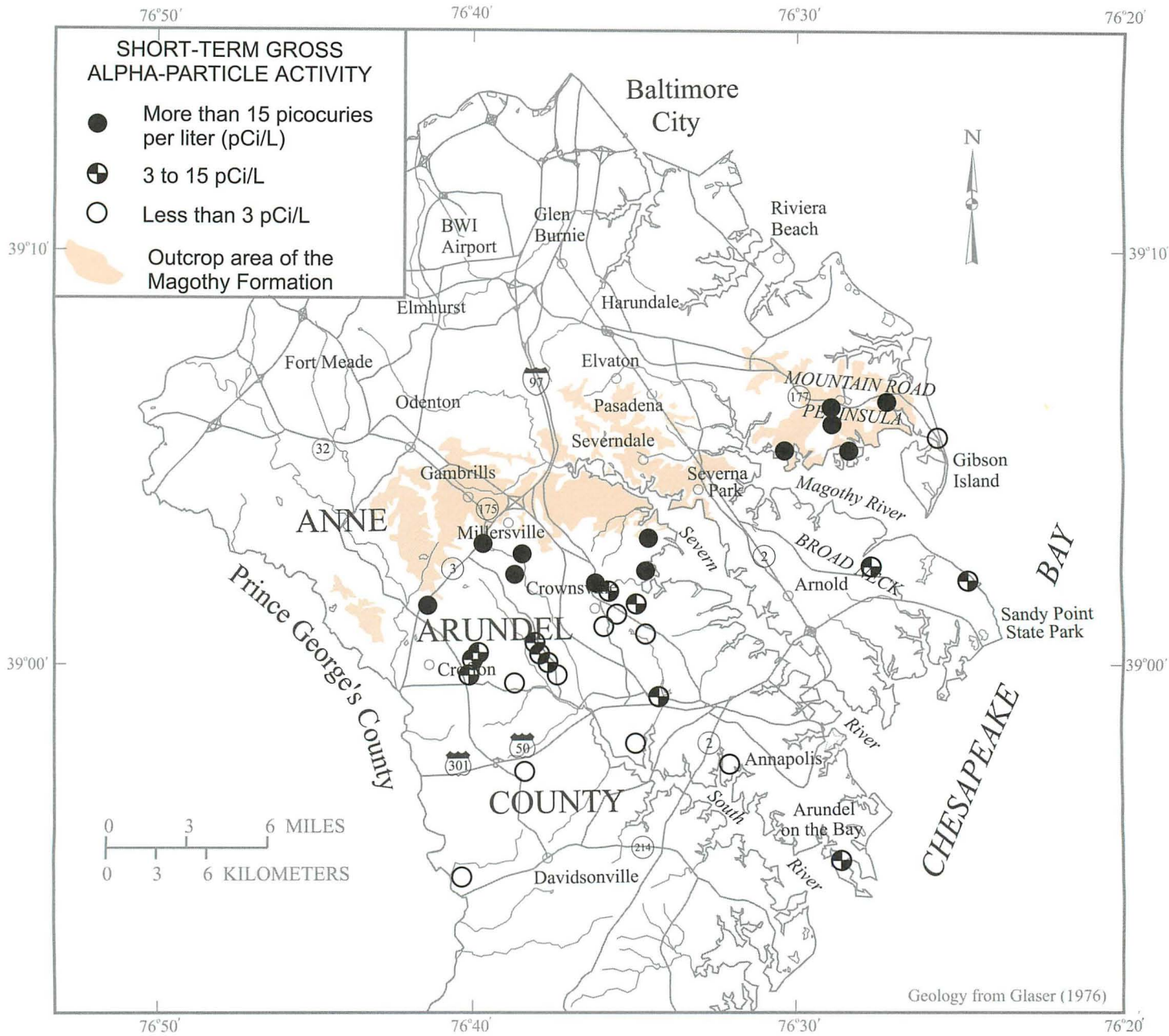


Figure 3. Map showing the distribution of short-term gross alpha-particle activity in ground water from the Magothy Formation in Anne Arundel County.

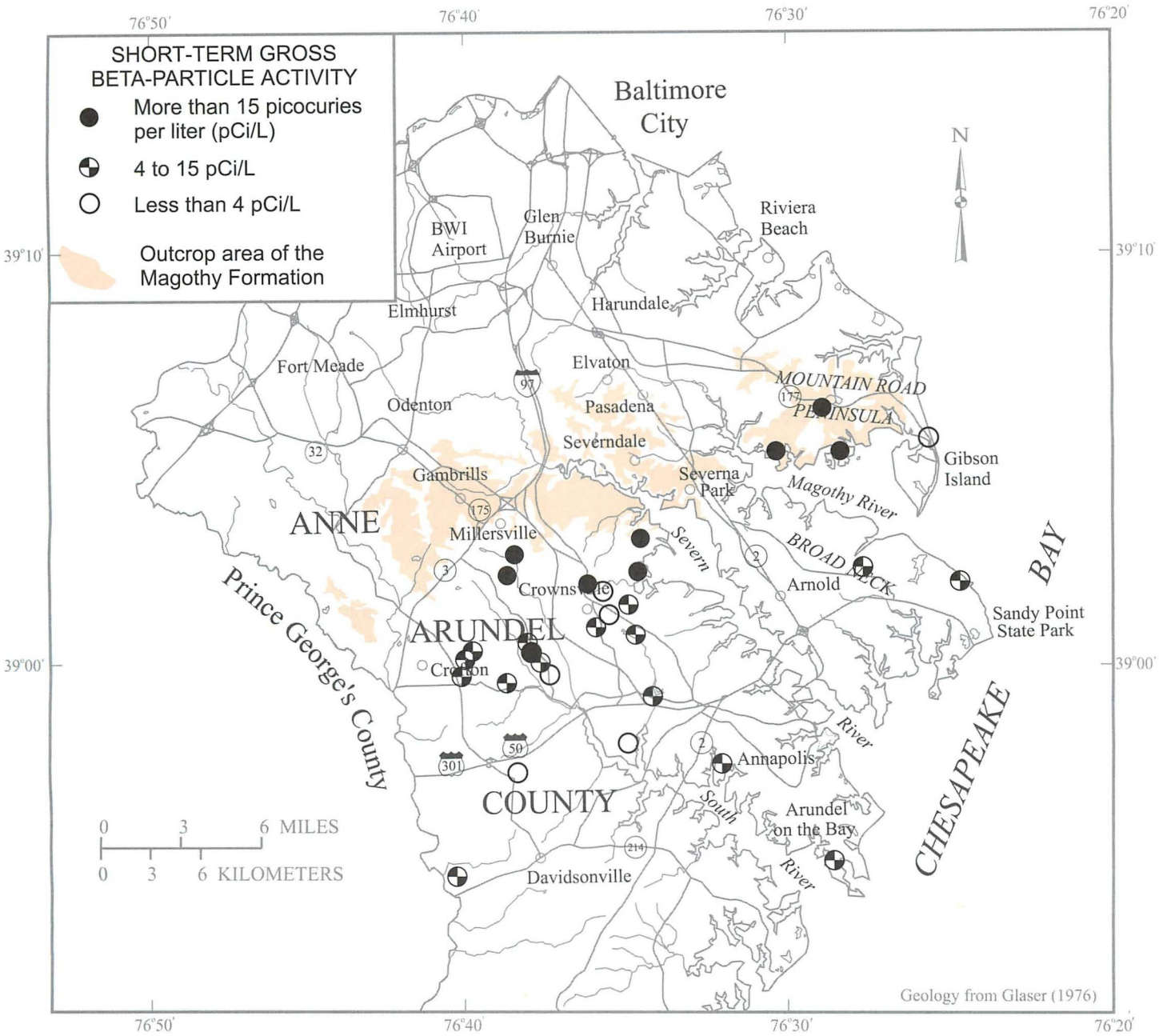


Figure 4. Map showing the distribution of short-term gross beta-particle activity in ground water from the Magothy Formation in Anne Arundel County.

Table 4. Summary of radium-226, radium-228, and radium-226 plus radium-228 concentrations in Anne Arundel County by geologic formation

[pCi/L, picocuries per liter; n, sample size]

Formation	Radium-226		Radium-228		Radium-226 plus radium-228	
	Median (pCi/L)	Range (pCi/L)	Median (pCi/L)	Range (pCi/L)	Median (pCi/L)	Range (pCi/L)
Magothy (n=35)	0.4	<0.1–33	1.4	<1–44	1.9	<1.1–66
Patapsco (n=79)	1.8	<0.1–28	4.1	<1– 40	6.3	<1.1–64
Patuxent (n=8)	1.3	0.31–11	2.1	<1– 12	3.3	<1.1–23
All wells (n=122)	1.6	<0.1–33	3.2	<1– 44	4.8	<1.1–66

Formation wells. This well was screened between 51 and 61 ft below the land surface, and encountered crystalline rock at a depth of 61 ft below land surface. Radium and GAPA concentrations were less than their respective MCLs in wells AA Bc 163, AA Ca 1, and AA Cb 5, which are located two to four miles downdip of the outcrop area.

Gross Alpha-Particle Activity and Gross Beta-Particle Activity in Prince George's, Baltimore, Harford, Cecil, Kent, and Queen Anne's Counties

Magothy Formation

Short-term GAPA was less than 15 pCi/L in samples from all 31 Magothy Formation wells located outside of Anne Arundel County (fig. 11), although short-term GAPA was above the MRL of 3 pCi/L in 20 of the 31 wells. Long-term GAPA was less than 3 pCi/L in 29 of 31 regional wells. Short-term GBPA concentrations were all less than 15 pCi/L, although concentrations were greater than 4 pCi/L in 26 of 31 wells (fig. 12). Long-term GBPA were all less than 15 pCi/L; 7 of 31 samples were less than 4 pCi/L.

Potomac Group

Short-term GAPA exceeded 15 pCi/L in samples from 6 of the 65 regional Potomac Group wells, including two wells in Prince George's County and one well each in Baltimore, Harford, Cecil, and Kent Counties (fig. 13). Short-term GAPA was less than 3 pCi/L in 23 of the 65 wells. Long-term GAPA values greater than 3 were reported in nine of the regional wells in the Potomac Group, and all concentrations were less than 10 pCi/L. Short-term and long-term GBPA concentrations were less than 4 pCi/L in samples from 26 and 37 of the 65 wells, respectively (fig. 14).

RELATION BETWEEN SHORT-TERM AND LONG-TERM MEASUREMENTS OF GROSS ALPHA-PARTICLE ACTIVITY AND GROSS BETA-PARTICLE ACTIVITY

There was a consistent decrease between the short-term and long-term values of GAPA in samples collected throughout the study area. Samples from 82 wells had short-term and long-term GAPA that were both greater than the MRL of 3 pCi/L; of these, 62 samples had long-term GAPA that was less than 40 percent of the short-term value (fig. 15). Long-term GAPA exceeded short-term GAPA in only 1 of 209 samples (AA Ce 147), and the difference between the values for this sample was within the total analytical error. In samples from 75 of 209 wells, short-term GAPA was above 3 pCi/L and long-term GAPA was below 3 pCi/L. Of the 115 samples for which both

(Text continued on p. 28)

Table 5. Summary of short-term and long-term gross alpha-particle and gross beta-particle activity by county and geologic formation

[pCi/L, picocuries per liter]

County	Formation or group	Short-term gross alpha-particle activity			Long-term gross alpha-particle activity			Short-term gross beta-particle activity			Long-term gross beta-particle activity		
		Median (pCi/L)	Range (pCi/L)	Sample size	Median (pCi/L)	Range (pCi/L)	Sample size	Median (pCi/L)	Range (pCi/L)	Sample size	Median (pCi/L)	Range (pCi/L)	Sample size
Anne Arundel	Magothy	9.2	<3-919	34	3.7	<3-530	35	7.4	<4-188	30	5.1	<4-98	35
	Patapsco	22	<3-351	71	5.7	<3-133	80	14	<4-180	66	10	<4-124	80
	Patuxent	12	<3-70	8	3.2	<3-23	8	10	<4-39	8	4.9	<4-25	8
Baltimore	Patapsco	5.0	<3-17	11	<3.0	<3-4.5	11	5.5	<4-13	11	<4	<4-10	11
Cecil	Magothy	–[2]	<3-4.7	2	<3.0	both <3	2	–[2]	5.6-7.6	2	–[2]	5.9-6.4	2
	Potomac [1]	<3.0	<3-140	22	<3.0	<3-9.6	22	<4.0	<4-70	22	<4.0	<4-24	22
Harford	Potomac [1]	4.7	<3-16	9	<3.0	all <3	9	4.6	<4-19	9	<4.0	<4-6.7	9
Kent	Magothy	4.0	<3-8.5	13	<3.0	<3-6.5	13	5.5	<4-9.2	13	4.4	<4-13	13
	Potomac [1]	4.3	<3-36	8	<3.0	<3-8	8	6.1	<4-28	8	5.2	<4-23	8
Prince George's	Magothy	5.0	<3-7.6	9	<3.0	<3-4.4	9	7.1	5-12	9	4.4	<4-5.9	9
	Patapsco	4.4	<3-20	7	<3.0	<3-8.6	7	4.3	<4-14	7	<4.0	<4-9.7	7
	Patuxent	–[2]	4.3-48	2	–[2]	<3-4.5	2	–[2]	6.8-15	2	–[2]	<4-14	2
Queen Anne's	Magothy	4.5	<3-9.9	7	<3.0	all <3	7	8.0	<4-11	7	5.8	5.4-7.6	7
	Patapsco	4.5	<3-10	6	<3.0	all <3	6	6.7	<4-15	6	4.9	<4-7.6	6

[1] Potomac Group is undivided in Cecil, Harford, and Kent Counties.
[2] Median value is not meaningful.

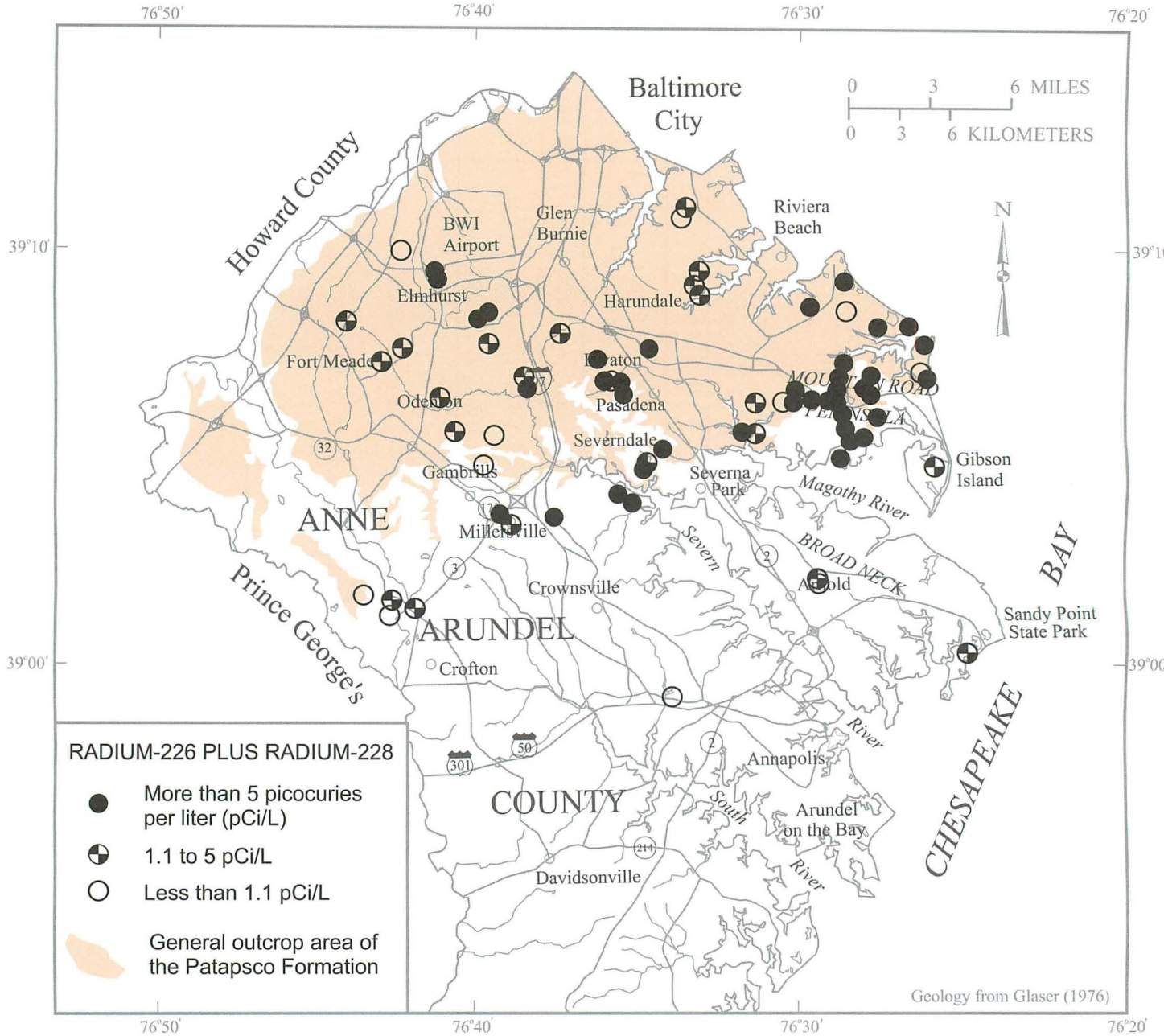


Figure 5. Map showing the distribution of radium-226 plus radium-228 in ground water from the Patapsco Formation in Anne Arundel County.

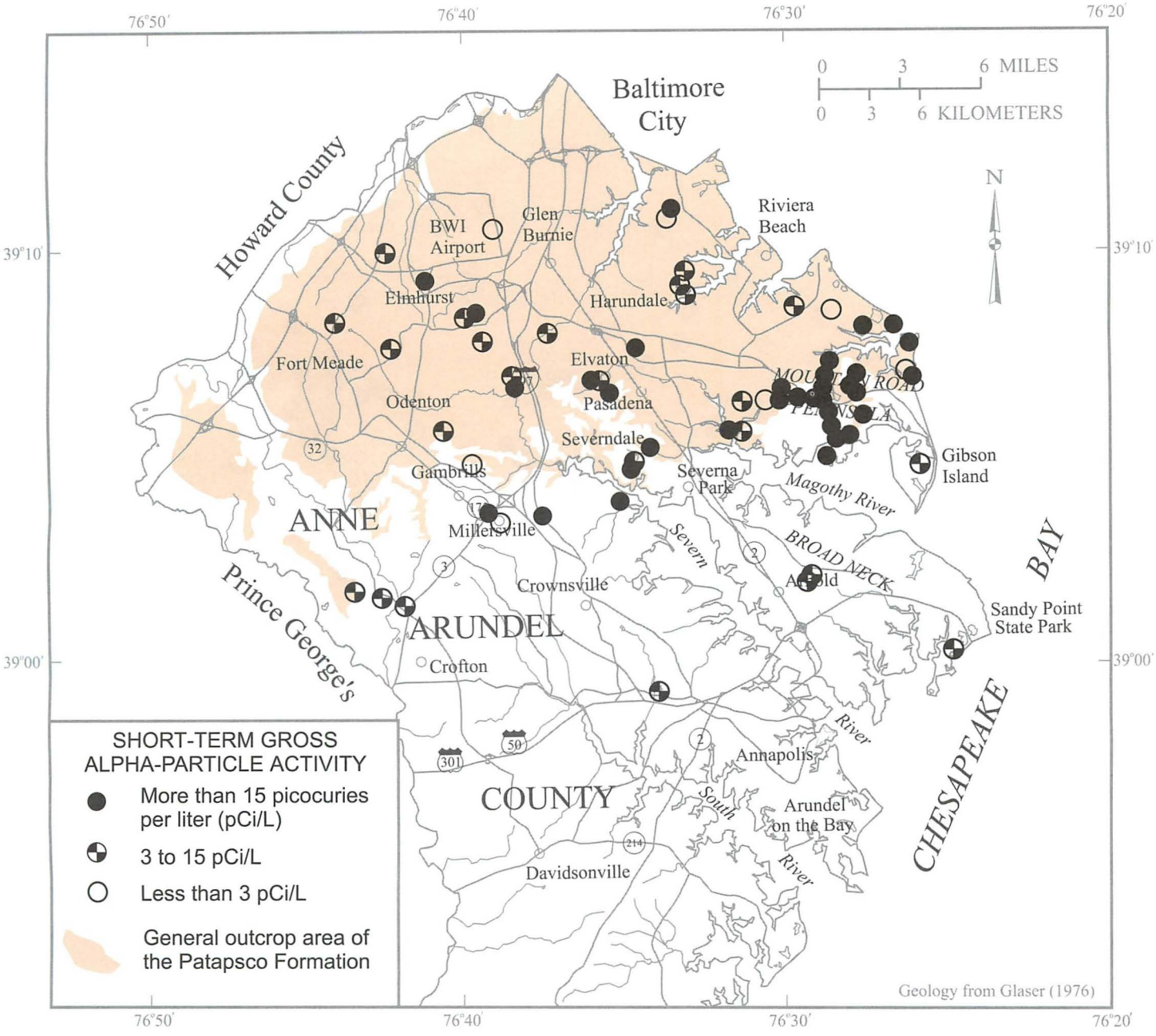


Figure 6. Map showing the distribution of short-term gross alpha-particle activity in ground water from the Patapsco Formation in Anne Arundel County.

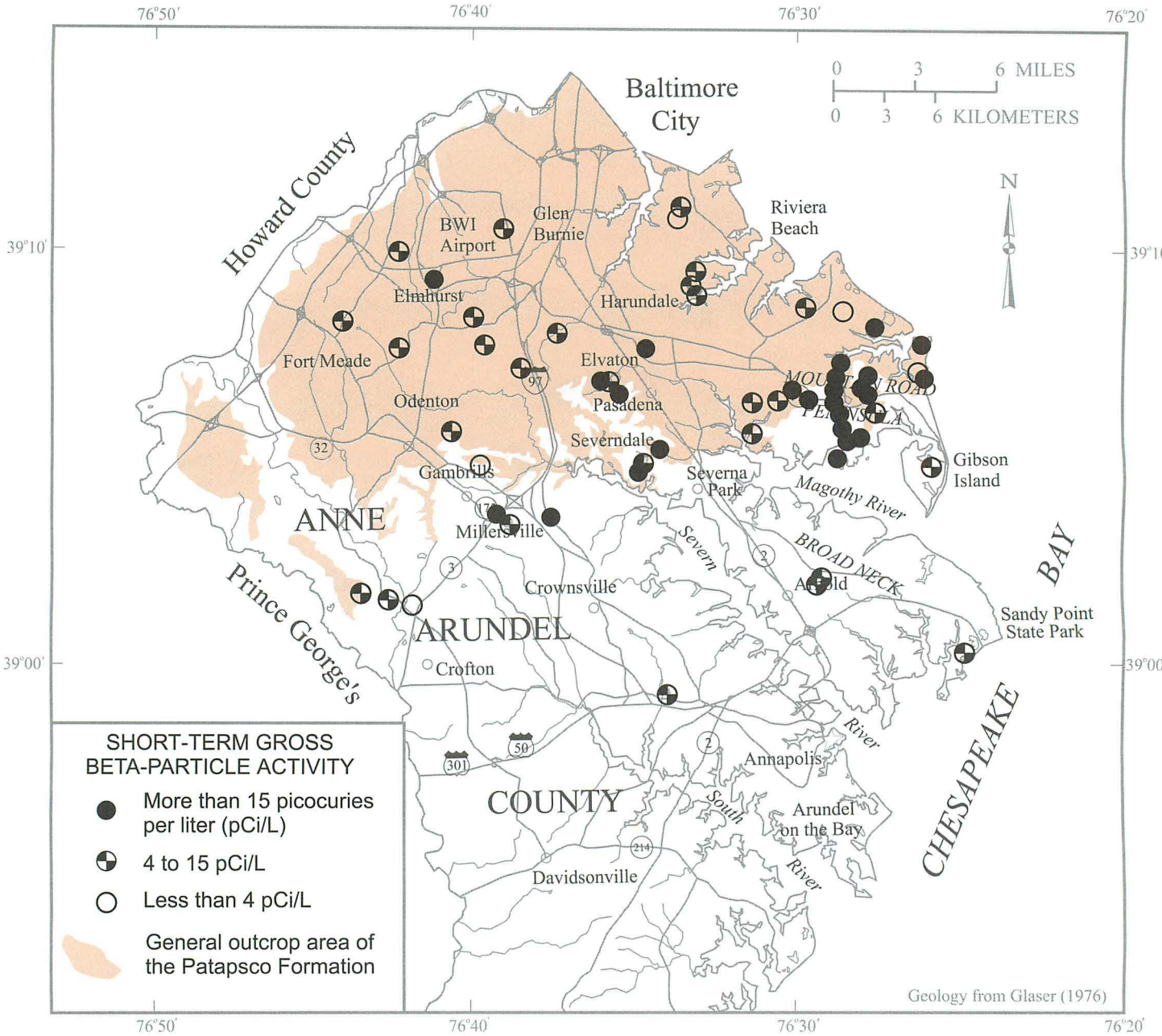


Figure 7. Map showing the distribution of short-term gross beta-particle activity in ground water from the Patapsco Formation in Anne Arundel County.

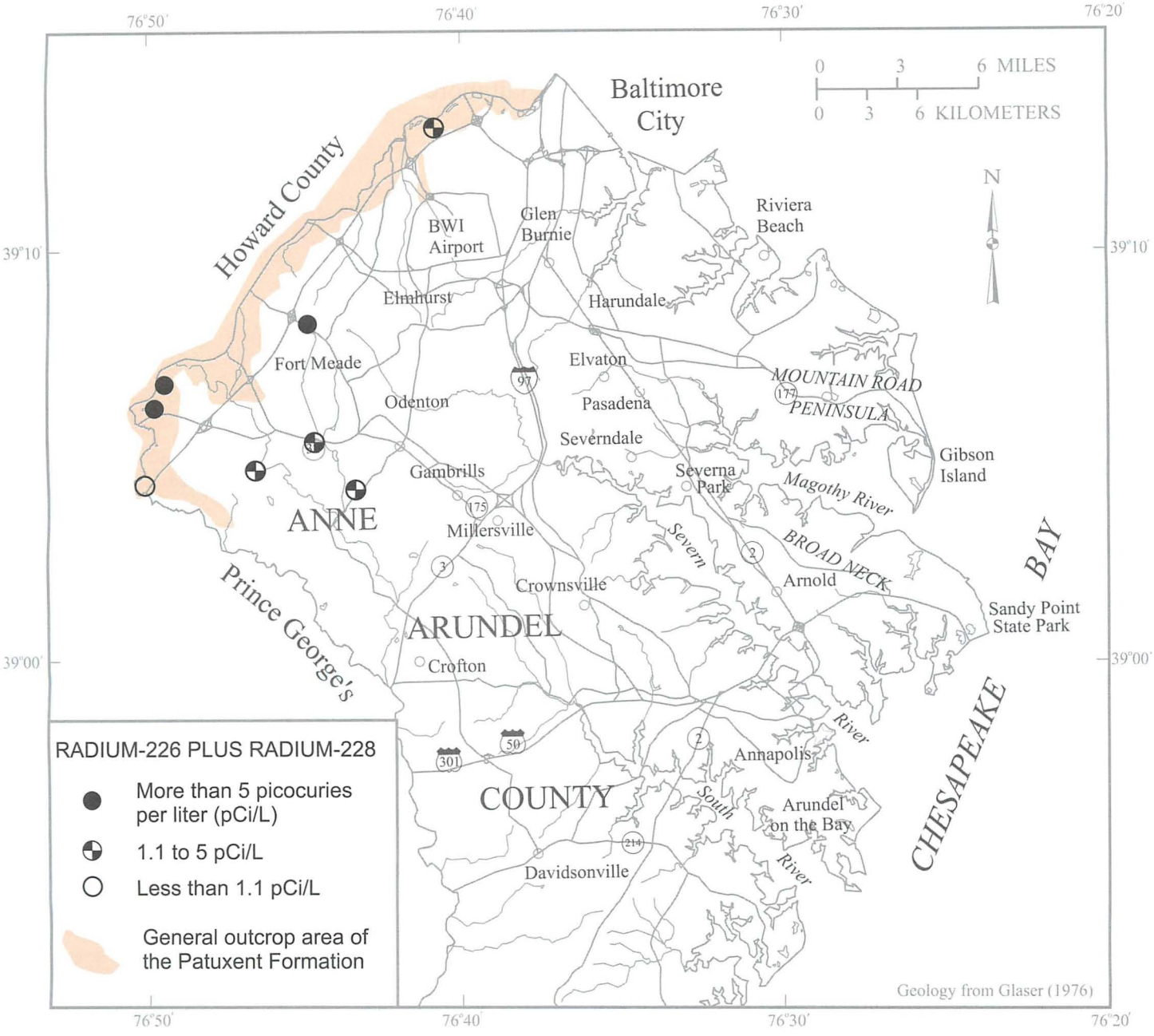


Figure 8. Map showing the distribution of radium-226 plus radium-228 in ground water from the Patuxent Formation in Anne Arundel County.

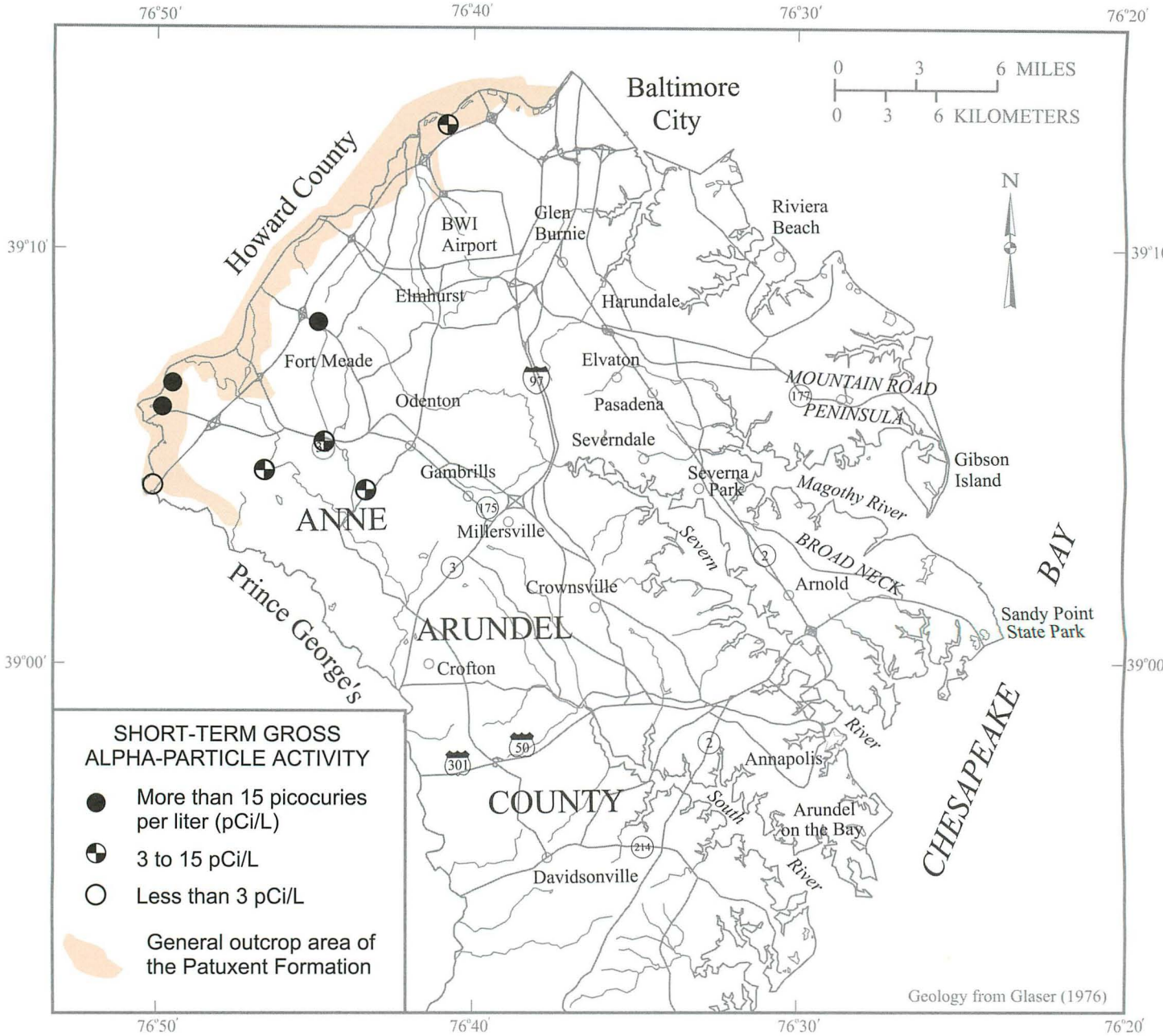


Figure 9. Map showing the distribution of short-term gross alpha-particle activity in ground water from the Patuxent Formation in Anne Arundel County.

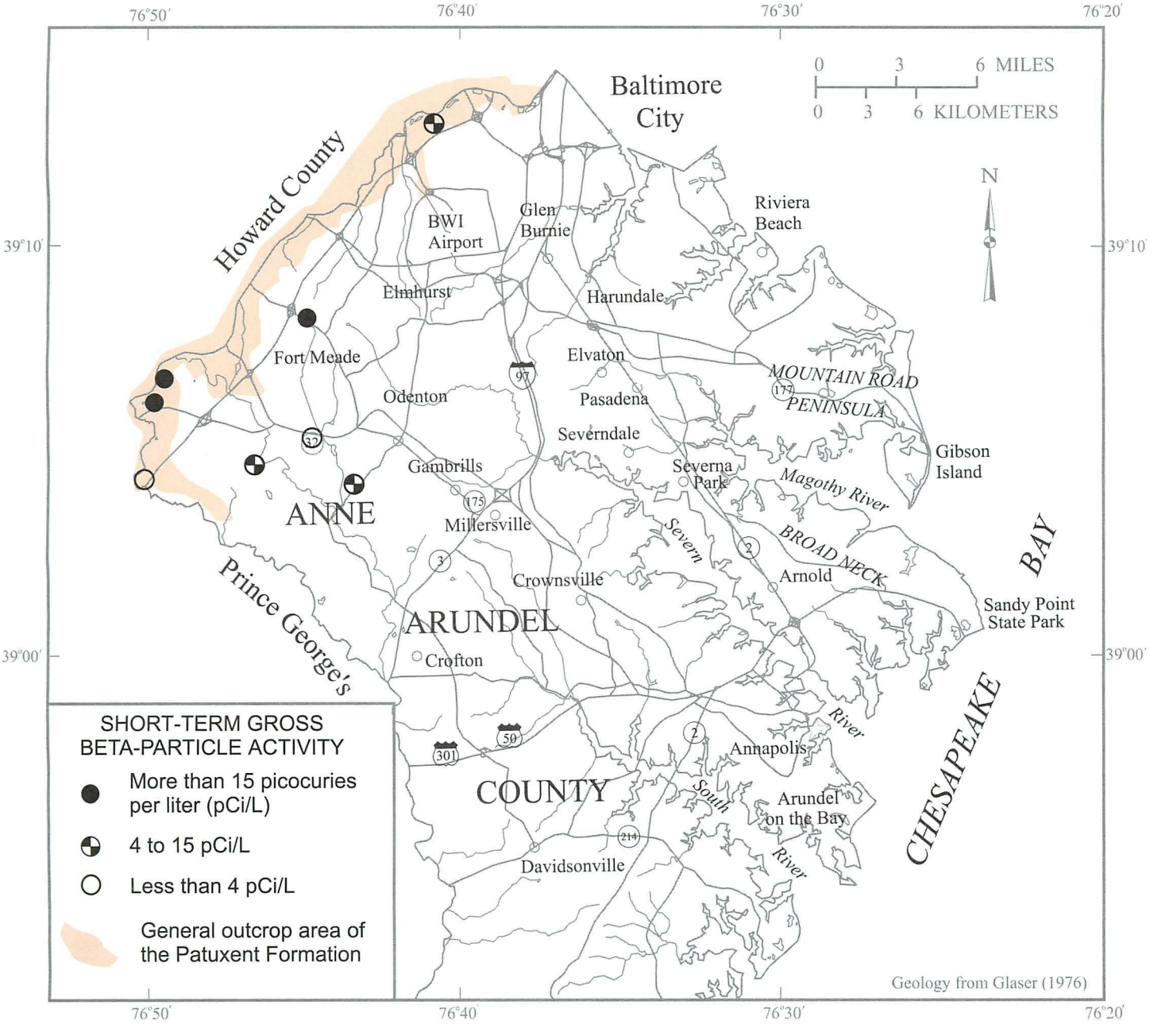


Figure 10. Map showing the distribution of short-term gross beta-particle activity in ground water from the Patuxent Formation in Anne Arundel County.

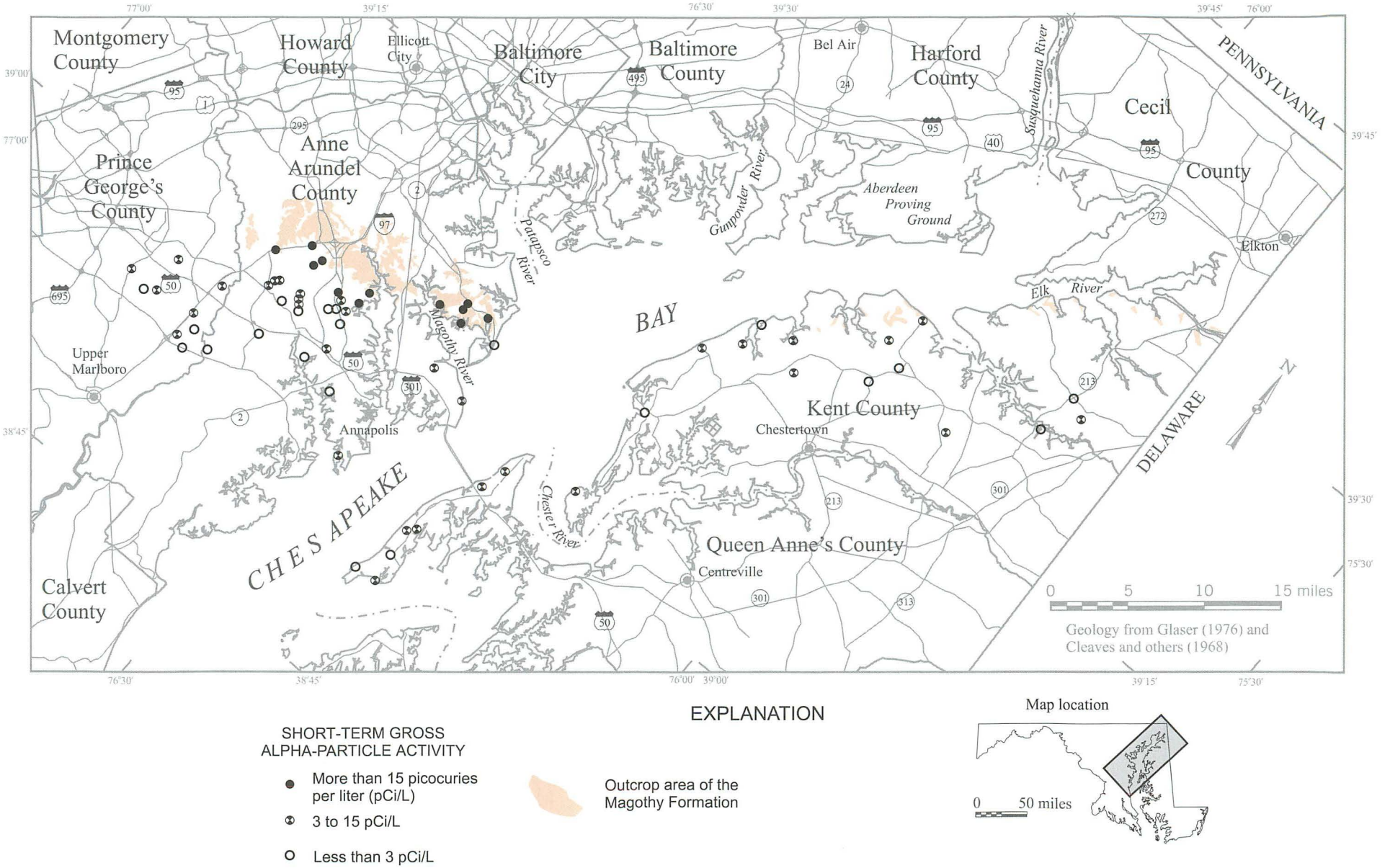


Figure 11. Map showing the distribution of short-term gross alpha-particle activity in ground water from the Magothy Formation in the upper Chesapeake Bay area.

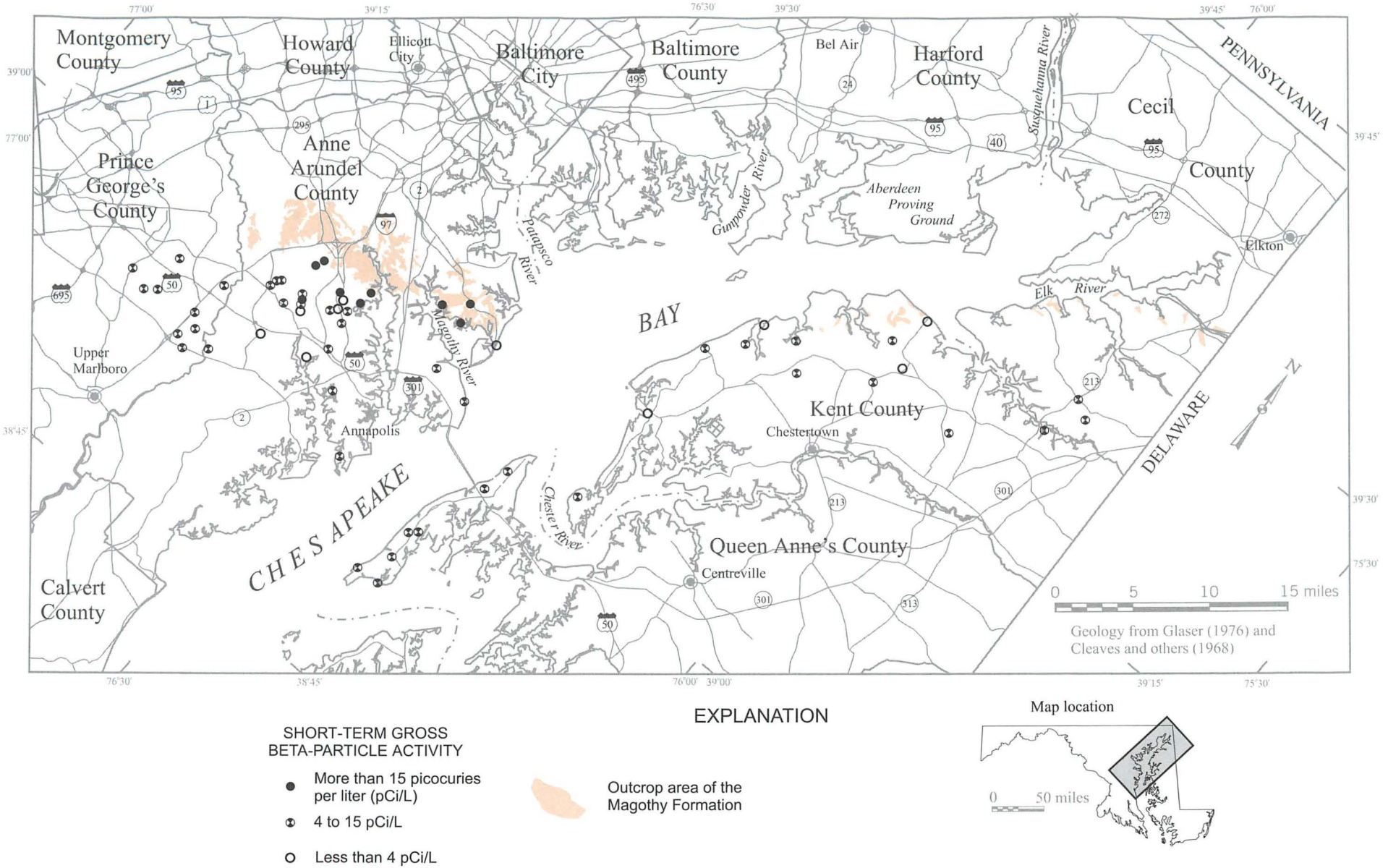


Figure 12. Map showing the distribution of short-term gross beta-particle activity in ground water from the Magothy Formation in the upper Chesapeake Bay area.

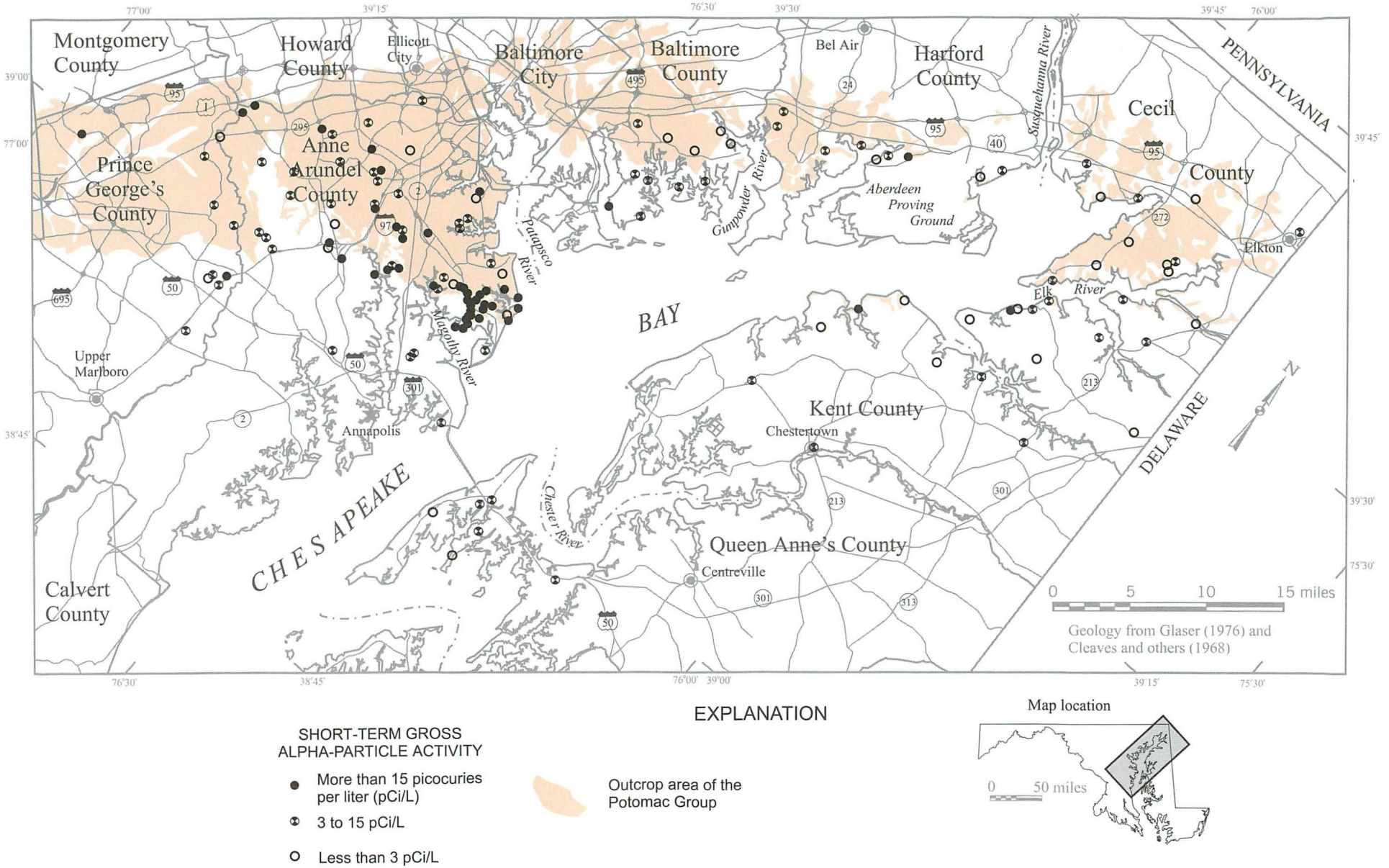


Figure 13. Map showing the distribution of short-term gross alpha-particle activity in ground water from the Potomac Group in the upper Chesapeake Bay area.

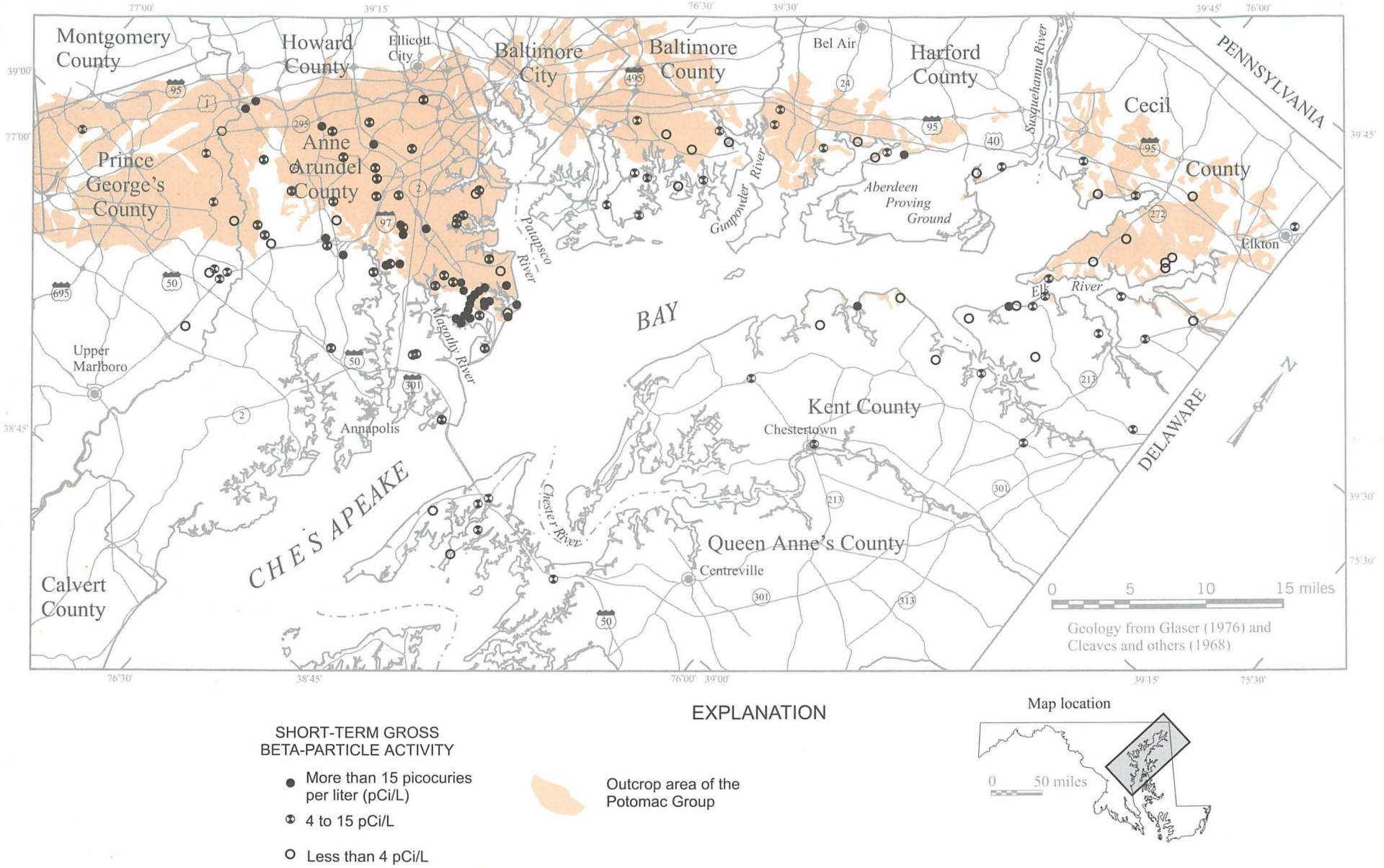


Figure 14. Map showing the distribution of short-term gross beta-particle activity in ground water from the Potomac Group in the upper Chesapeake Bay area.

short-term and long-term GBPA were greater than the MRL of 4 pCi/L, 70 samples had long-term GBPAs between 50 and 80 percent of short-term GBPA (fig. 15). Forty of 199 samples had short-term GBPA above 4 pCi/L and long-term GBPA below 4 pCi/L. Long-term GBPA exceeded short-term GBPA in 20 of 199 samples. Thus there was a large decrease in GBPA between 3 days and 30 days, but not as large a decrease as was observed in GAPA.

The short-term and long-term GAPA data in conjunction with the radium-224 analyses from Anne Arundel County (fig. 16) indicate that radium-224 comprises a significant portion of the total radium content of ground water in the Magothy and Potomac Group aquifers in the upper Chesapeake Bay region. The data also underscore the importance of analyzing GAPA as soon as possible after sample collection. Sixty-two percent (38 of 61) of the samples in this study had short-term GAPA greater than the MCL of 15 pCi/L *and* long-term GAPA less than 15 pCi/L; that is, 62 percent of the samples probably would not have been identified as MCL exceedances had they not been analyzed within 72 hours of sample collection.

The differences between the short-term and long-term GAPA measurements cannot be used to precisely quantify the radium-224 content. For the three wells in the pilot study that had radium-224 and short-term and long-term GAPA, the difference between the short-term and long-term GAPA was 2.4 to 3.0 times the radium-224 concentration (Bolton and Hayes, 1999, p. 29). It is likely that much of the additional GAPA detected within 72 hours but absent after 30 days is due to ingrowth, the process in which the decomposition of radium-224 and its daughter isotopes produce additional alpha-emitting radionuclides. The first two daughter products of radium-224 decay are the alpha-emitting isotopes radon-220 (half-life: 55 seconds) and polonium-216 (half-life: 0.158 seconds). Because of the short half-

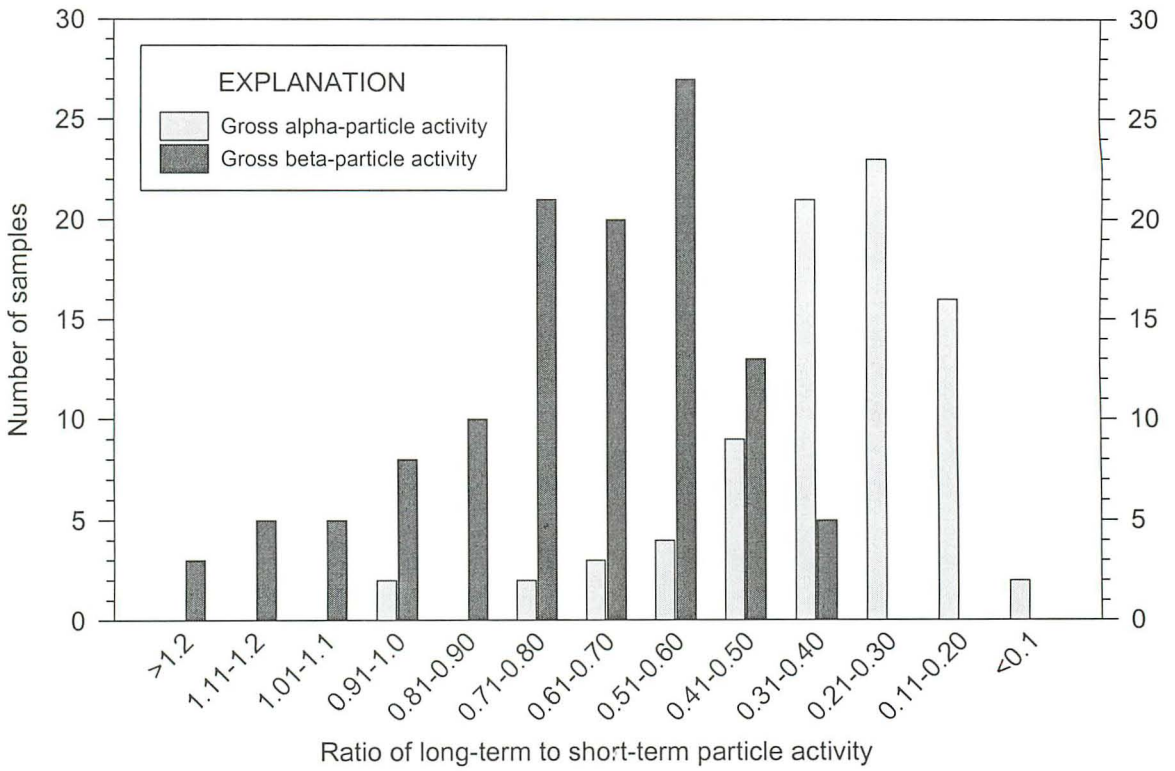


Figure 15. Histogram showing the distribution of the ratio of long-term to short-term gross alpha-particle and beta-particle activity. Histogram includes only samples for which both short-term and long-term values were above minimum reporting levels (3 picocuries per liter for gross alpha-particle activity; 4 picocuries per liter for gross beta-particle activity).

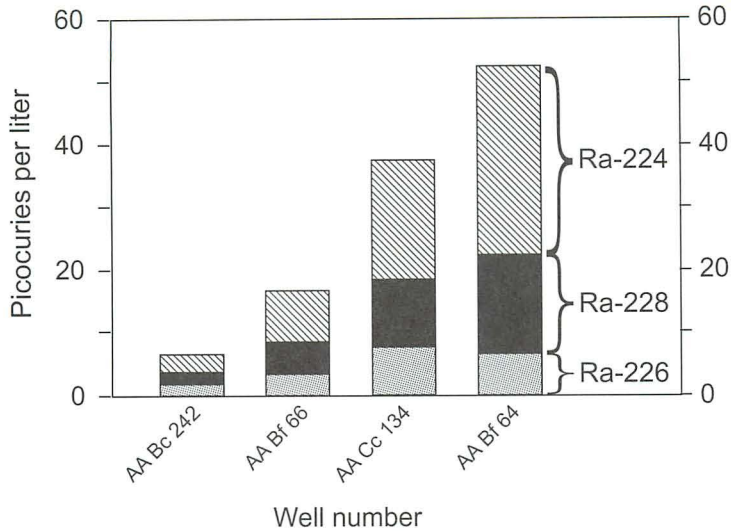


Figure 16. Bar graph showing the concentrations of radium-224, radium-226, and radium-228 in wells in Anne Arundel County. [Source: Bolton and Hayes (1999)]

lives of these progeny, the alpha-particle activity would be expected to increase sharply after the water is removed from the aquifer as these radionuclides grow into the sample, then decline rapidly as the radium-224 decays. Other alpha-emitting radionuclides may also be present in the water, most likely radium-226 and its progeny (Parsa, 1998). Beta-particle-emitting isotopes other than radium-228 were not analyzed in this study or the Anne Arundel County pilot study (Bolton and Hayes, 1999). The short-lived beta-emitting isotopes whose decay is responsible for the decrease in beta-particle activity over the 30-day period thus have not been identified.

FACTORS ASSOCIATED WITH RADIONUCLIDES IN GROUND WATER

Water Quality

pH

A statistically significant negative correlation was found between pH and all measured radionuclides (r_s range, -0.43 to -0.64; Spearman rank correlation test) (figs. 17 and 18; tab. 6). There was also a statistically significant difference in radium-226 plus radium-228 and short-term GAPA when these were grouped according to pH quartiles (Kruskal-Wallis rank sum test; $P<0.01$). The median radium-226 plus radium-228 concentration and short-term GAPA for samples in the lowest pH quartile (12 and 33 pCi/L, respectively) exceeded their respective MCLs, while median values for the other pH quartiles were less than the MCLs (tab. 7). Sixty-five percent (46 of 71) of water samples with pH of 4.5 or less had radium-226 plus radium-228 concentrations greater than 5 pCi/L (fig. 18), while only about 27 percent (14 of 51) of water samples with pH 4.5 or more exceeded this concentration. Sixty-one percent (49 of 80) water samples with pH less than 4.5 had short-term GAPA that exceeded 15 pCi/L; many of these wells are located on the Mountain Road peninsula in Anne Arundel County. Only about 10 percent (13 of 130) of water samples with pH of 4.5 or more had short-term GAPA more than 15 pCi/L.

Water samples from wells in the updip areas of the Potomac Group and Magothy Formation aquifers tended to be more acidic than ground water observed in other aquifers of the Maryland Coastal Plain (Hansen, 1972; Shedlock and others, 1999). The mean annual pH values of precipitation in 1998 in Carroll and Queen Anne's Counties were 4.2 and 4.4, respectively (National Atmospheric Deposition Program/National Trends Network, 2000). However, 38 wells had pH less than 4.0, so additional acidification processes likely occur. Several common chemical processes occurring in the aquifers can

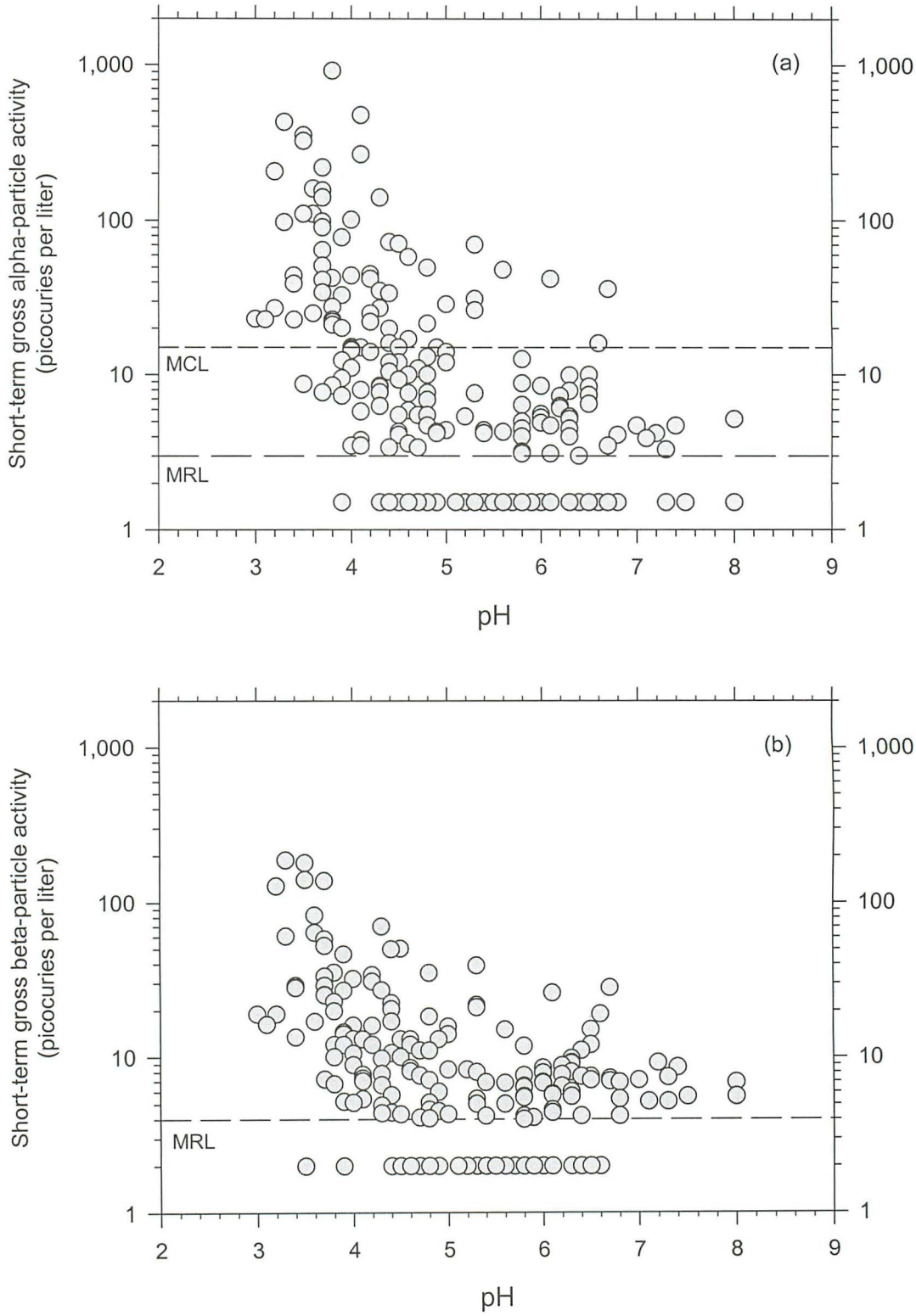


Figure 17. Relations between pH and (a) short-term gross alpha-particle activity, and (b) short-term gross beta-particle activity. MCL, maximum contaminant level; MRL, minimum reporting level. Values less than MRLs are plotted at one-half the MRL.

Table 6. Spearman correlation coefficients for inorganic constituents, depth to screened interval, and radionuclides

[See table 3 for explanation. Shaded cells indicate statistically significant correlations ($P<0.05$)]

Constituent	Short-term gross alpha-particle activity	Long-term gross alpha-particle activity	Short-term gross beta-particle activity	Long-term gross beta-particle activity	Radium-226	Radium-228	Radium-226 plus radium-228
pH	-0.62 <0.01 207	-0.64 <0.01 217	-0.43 <0.01 197	-0.44 <0.01 217	-0.53 <0.01 122	-0.55 <0.01 122	-0.54 <0.01 122
Specific conductance	0.37 <0.01 209	0.37 <0.01 219	0.43 <0.01 199	0.51 <0.01 219	0.69 <0.01 122	0.68 <0.01 122	0.69 <0.01 122
Dissolved oxygen	0.07 0.35 202	0.03 0.63 212	-0.08 0.27 192	-0.04 0.52 212	0.07 0.44 122	0.10 0.30 122	0.09 0.33 122
Calcium (Ca^{2+})	0.29 0.13 29	0.45 <0.01 39	0.03 0.90 19	0.44 <0.01 39	0.42 <0.01 39	0.37 0.02 39	0.38 0.02 39
Magnesium (Mg^{2+})	0.55 <0.01 29	0.65 <0.01 39	0.13 0.61 19	0.63 <0.01 39	0.62 <0.01 39	0.61 <0.01 39	0.62 <0.01 39
Sodium (Na^{+})	0.77 <0.01 29	0.88 <0.01 39	0.48 0.04 19	0.84 <0.01 39	0.80 <0.01 39	0.82 <0.01 39	0.83 <0.01 39
Potassium (K^{+})	0.48 <0.01 29	0.55 <0.01 39	0.05 0.82 19	0.54 <0.01 39	0.52 <0.01 39	0.48 <0.01 39	0.49 <0.01 39
Alkalinity	-0.22 0.26 29	-0.21 0.19 39	-0.31 0.19 19	-0.25 0.12 39	-0.25 0.13 39	-0.37 0.02 39	-0.35 0.03 39
Chloride (Cl^{-})	0.83 <0.01 79	0.82 <0.01 88	0.75 <0.01 69	0.84 <0.01 88	0.81 <0.01 88	0.82 <0.01 88	0.83 <0.01 88
Sulfate (SO_4^{2-})	0.29 0.12 29	0.30 0.07 38	-0.10 0.67 19	0.33 0.04 38	0.31 0.06 38	0.27 0.10 38	0.28 0.09 38
Nitrate (NO_3^{-})	0.43 <0.01 78	0.36 <0.01 88	0.36 <0.01 68	0.43 <0.01 88	0.42 <0.01 88	0.47 <0.01 88	0.47 <0.01 88
Ammonium (NH_4^{+})	0.51 <0.01 29	0.56 <0.01 39	0.11 0.74 19	0.51 <0.01 39	0.43 <0.01 39	0.46 <0.01 39	0.48 <0.01 39
Iron (Fe^{2+})	-0.27 0.16 29	-0.34 0.04 39	-0.19 0.42 19	-0.29 0.08 39	-0.29 0.07 39	-0.32 0.04 39	-0.33 0.04 39
Manganese (Mn^{2+})	-0.01 0.98 29	0.03 0.86 39	-0.10 0.69 19	0.01 0.94 39	0.08 0.62 39	-0.03 0.85 39	-0.01 0.94 39
Silica (SiO_2)	0.19 0.33 29	0.08 0.61 39	-0.45 0.65 19	0.10 0.56 39	0.09 0.62 39	0.01 0.95 39	0.03 0.87 39
Total dissolved solids	0.61 <0.01 28	0.66 <0.01 38	0.22 0.35 19	0.66 <0.01 38	0.61 <0.01 38	0.60 <0.01 38	0.61 <0.01 38
Depth to screened interval	-0.36 <0.01 207	-0.43 <0.01 217	-0.22 <0.01 197	-0.31 <0.01 217	-0.63 <0.01 121	-0.67 <0.01 121	-0.67 <0.01 121

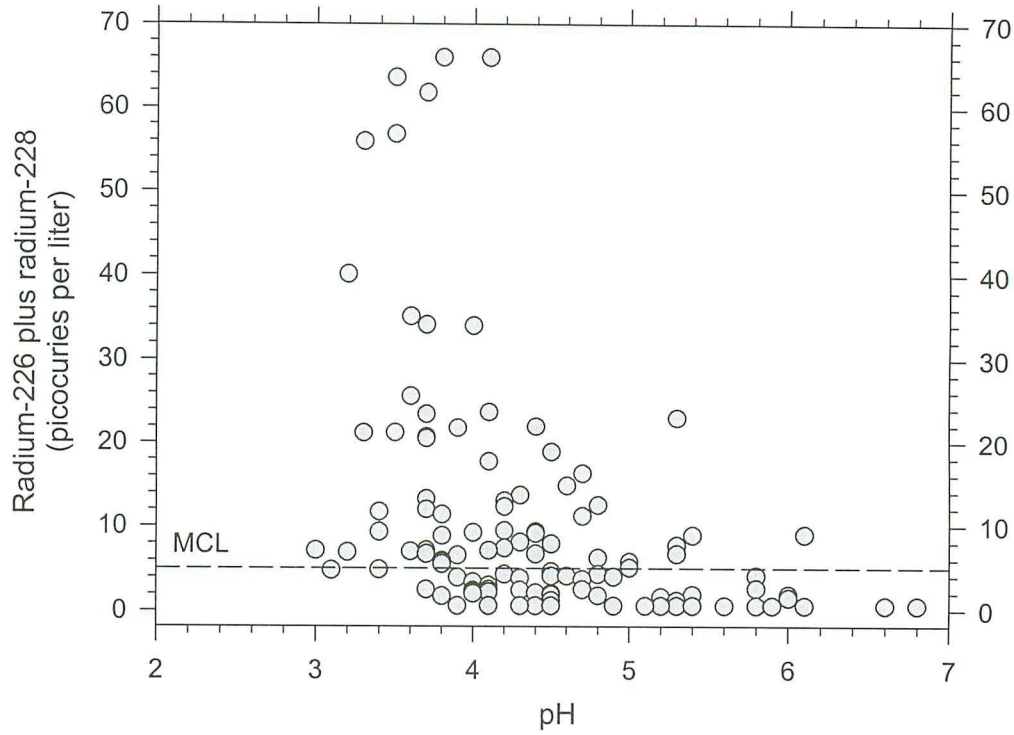


Figure 18. Relation between pH and radium-226 plus radium-228. MCL, maximum contaminant level.

generate hydrogen ions (which can decrease pH). Soil-gas carbon dioxide reacts with water to generate carbonic acid which can lower pH (tab. 8, reaction 1). Decomposition of organic matter in the soil zone (roots and other vegetation) and oxidation of lignite, which is present in the Potomac Group and Magothy Formation aquifers (Glaser, 1969), can produce carbon dioxide (tab. 8, reaction 2).

Pyrite oxidation and precipitation of ferric hydroxide (tab. 8, reactions 3 and 4) can also generate hydrogen ions. Pyrite (FeS_2) is present in the Potomac Group and Magothy Formation, often in association with lignite. Sediments of the Potomac Group are commonly "iron-stained" and contain iron oxide and iron hydroxide minerals (Glaser, 1969). If pyrite oxidation is indeed occurring in the area, interpretation of reaction 3 suggests that dissolved-oxygen concentrations should decrease with increasing iron and sulfate concentrations and decreasing pH, as long as these constituents are not involved in other reactions. The Spearman rank-order correlation coefficients between dissolved oxygen and iron (r_s=-0.71), and sulfate (r_s=-0.38) are consistent with these reactions (tab. 9).

Nitrification, the microbial oxidation of ammonium to nitrate, is another mechanism that generates hydrogen ions and thus can lower pH (tab. 8, reaction 5). Ammonium may be introduced into the environment from application of ammonium-based fertilizers, animal wastes, septic effluent, land-based sewage sludge disposal, and other factors (Hallberg and Keeney, 1993). If nitrification is a significant factor in producing low-pH ground water, reaction 5 (tab. 8) implies that pH should be positively correlated with ammonium concentrations and negatively correlated with nitrate concentrations, and that concentrations of ammonium and nitrate could be negatively correlated. None of these correlations was seen in the data (tab. 9). More data are needed to evaluate the importance of this mechanism because nitrogen is highly mobile and is involved in many complex transformations in the subsurface. For example, nitrogen may be present in large amounts as N_2 gas, a compound whose concentration was not determined in this study. Furthermore, ammonium is easily sorbed onto mineral surfaces. The pH is controlled by many processes, and the absence of an inverse correlation between ammonium and nitrate

Table 7. Statistical summary of short-term gross alpha-particle activity, short-term gross beta-particle activity, and radium-226 plus radium-228 concentrations, grouped by pH quartiles

[pCi/L, picocuries per liter]

pH quartile range	Number of samples	Minimum (pCi/L)	25th percentile (pCi/L)	Median (pCi/L)	75th percentile (pCi/L)	Maximum (pCi/L)
SHORT-TERM GROSS ALPHA-PARTICLE ACTIVITY:						
<4.2	53	3.5	15	33	103	919
4.2–4.8	58	<3.0	3.4	8.4	17	140
4.9–5.9	46	<3.0	<3.0	4.1	6.4	70
>5.9	50	<3.0	<3.0	4.2	6.1	42
SHORT-TERM GROSS BETA-PARTICLE ACTIVITY:						
<4.3	51	<4.0	11	19	34	188
4.3–4.8	50	<4.0	<4.0	5.4	11	70
4.9–6.0	52	<4.0	<4.0	5.0	7.8	39
>6.0	44	<4.0	4.9	6.9	8.7	28
RADIUM-226 PLUS RADIUM-228:						
<3.9	32	1.7	6.8	12	30	66
3.9–4.3	32	<1.1	2.1	3.9	11	66
4.4–4.9	30	<1.1	1.2	4.1	9.1	22
>4.9	28	<1.1	<1.1	<1.1	4.6	23

Table 8. Chemical reactions that may affect the pH of ground water in the study area

[s, solid phase; aq, aqueous phase; g, gas phase; org, organic matter. Sources: Drever (1982); Canter (1996)]

(1) Carbonic acid generation:	$CO_2\,(g) + H_2O \leftrightarrows H_2CO_3\,(aq) \leftrightarrows H^+ + HCO_3^-$
(2) Decomposition of organic matter:	$C_{106}H_{263}O_{110}N_{16}P + 138\,O_2\,(g) \leftrightarrows$ $106\,CO_2\,(g) + 16\,N0_3^- + HPO_4^{2-} + 122\,H_2O + 18\,H^+$
(3) Pyrite oxidation:	$FeS_2\,(s) + H_2O + 3.5\,O_2\,(g) \rightarrow Fe^{2+} + 2\,H^+ + 2\,SO_4^{2-}$
(4) Precipitation of ferric hydroxide:	$Fe^{2+} + 0.25\,O_2\,(g) + 2.5\,H_2O \leftrightarrows Fe(OH)_3\,(s) + 2\,H^+$
(5) Nitrification of ammonium:	$NH_4^+ + 2\,O_2\,(g) \leftrightarrows NO_3^- + H_2O + 2\,H^+$

Table 9. Spearman correlation coefficients for inorganic constituents

[Shaded cells indicate statistically significant correlations ($P<0.05$). See table 3 for explanation of correlation coefficients; see table 6 for explanation of constituent abbreviations.]

	Mg^{2+}	Na^{+}	K^{+}	NH_4^{+}	Alka-linity	Cl^{-}	SO_4^{2-}	NO_3^{-}	Fe^{2+}	Mn^{2+}	SiO_2	pH	DO
Ca^{2+}	0.85 <0.01 39	0.58 <0.01 39	0.92 <0.01 39	0.20 0.21 39	0.49 <0.01 39	0.47 <0.01 37	0.64 <0.01 38	0.31 0.05 39	0.18 0.27 39	0.65 <0.01 39	-0.06 0.71 39	0.14 0.38 39	0.07 0.69 38
Mg^{2+}		0.72 <0.01 39	0.85 <0.01 39	0.35 0.03 39	0.29 0.08 39	0.65 <0.01 37	0.64 <0.01 38	0.35 0.03 39	0.15 0.37 39	0.59 <0.01 39	0.13 0.44 39	-0.16 0.33 39	0.10 0.53 38
Na^{+}			0.62 <0.01 39	0.52 <0.01 39	-0.10 0.55 39	0.91 <0.01 37	0.30 0.07 38	0.72 <0.01 39	-0.35 0.03 39	0.04 0.82 39	0.02 0.91 39	-0.53 <0.01 39	0.41 0.01 38
K^{+}				0.31 0.06 39	0.43 <0.01 39	0.53 <0.01 37	0.72 <0.01 38	0.24 0.14 39	0.25 0.13 39	0.64 <0.01 39	0.06 0.72 39	0.04 0.81 39	-0.05 0.74 38
NH_4^{+}					0.05 0.77 39	0.46 <0.01 38	0.28 0.09 38	0.38 0.01 40	-0.18 0.28 39	-0.08 0.64 39	0.18 0.27 39	-0.30 0.06 39	<0.01 0.97 38
Alka-linity						-0.25 0.13 37	0.39 0.01 38	-0.32 0.04 39	0.41 <0.01 39	0.59 <0.01 39	0.09 0.60 39	0.67 <0.01 39	-0.45 0.01 38
Cl^{-}							0.21 0.21 37	0.59 <0.01 86	-0.44 <0.01 37	-0.05 0.77 37	0.01 0.93 37	-0.47 <0.01 88	0.07 0.50 87
SO_4^{2-}								-0.18 0.29 38	0.63 <0.01 33	0.62 <0.01 38	0.09 0.58 38	0.08 0.61 38	-0.38 0.02 37
NO_3^{-}									-0.74 <0.01 39	-0.31 0.06 39	-0.30 0.06 39	-0.11 0.30 88	0.60 <0.01 87
Fe^{2+}										0.64 <0.01 39	0.30 0.06 39	0.37 0.02 39	-0.71 <0.01 38
Mn^{2+}											0.11 0.50 39	0.40 0.01 39	-0.35 0.03 38
SiO_2												-0.19 0.25 39	-0.50 <0.01 38
pH													-0.22 <0.01 212

does not necessarily discount the possibility that nitrification is an important geochemical process.

Specific Conductance

The concentrations of all radionuclides measured in this study showed a significant positive correlation with specific conductance (r_s range, +0.37 to +0.69; Spearman rank correlation test) (tab. 6; figs. 19 and 20). When samples were grouped by specific conductance quartiles, radium-226 plus radium-228 concentrations and short-term GAPA for the highest specific conductance quartile (median concentrations, 21 and 25 pCi/L, respectively) were significantly higher than the values from the other three specific conductance quartiles (Kruskal-Wallis rank sum test, $P<0.01$) (tab. 10). Seventy-one percent (15 of 21) of water samples with specific conductance greater than 300 µS/cm had short-term GAPA greater than 15 pCi/L; conversely, all 31 water samples with specific conductance values less than 50 µS/cm had short-term GAPA less than 15 pCi/L (fig. 19). All 14 samples having specific conductance greater than 300 pCi/L had radium-226 plus radium-228 concentrations greater than 5 pCi/L; all samples with specific conductances less than 50 µS/cm had radium-226 plus radium-228 concentrations less than 5 pCi/L (fig. 20).

The highest short-term GAPA outside of Anne Arundel County (140 pCi/L) was from well CE Dd 106, located in the West View Shores subdivision near Crystal Beach in southern Cecil County. Water quality in many domestic wells in this subdivision is characterized by low pH, iron, manganese, sodium, chloride, sulfate, dissolved solids, and calcium concentrations that are much higher than ambient ground-water concentrations (Maryland Environmental Service, 1995). The West View Shores subdivision is located between the Chesapeake Bay and the Pearce Creek Upland Dredged Material Facility, which was constructed to receive sediment dredged from the approach channels to the Chesapeake and Delaware Canal. Well CE Dd 106 was sampled because a previous sample from the well exhibited the high TDS and low pH that are associated with radionuclides in Anne Arundel County ground water. A nearby Potomac Group well, CE Dd 105, which previous data indicated was more representative of ambient water-quality conditions, was sampled for comparison. Short-term GAPA from wells CE Dd 105 and CE Dd 106 were <3 and 140 pCi/L, respectively (tab. 11). Similar contrasts between the wells were also seen for long-term GAPA, short-term GBPA, and long-term GBPA. There was also a 93-percent reduction in GAPA and a 66-percent reduction in GBPA between the short-term and long-term measurements in well CE Dd 106.

The correlation between radionuclide concentrations, pH, and specific conductance is illustrated in figure 21. Samples with short-term GAPAs exceeding 15 pCi/L (black circles in fig. 21) tend to have lower pH or higher specific conductance than samples with short-term GAPAs of 15 pCi/L or less (gray circles in fig. 21), although there is overlap in the two groups. 67 of 69 samples having pH greater than 5.5 and specific conductance less than 1,000 µS/cm had short-term GAPA less than 15 pCi/L (fig. 21). Furthermore, 25 of 26 samples having pH less than 4.0 and specific conductance greater than 100 µS/cm had short-term GAPAs greater than 15 pCi/L. Samples with pH between 3.5 and 5.5 and specific conductance between 60 and 500 µS/cm may or may not have short-term GAPAs greater than 15 pCi/L. Figure 21 may be used to determine whether a well should be analyzed for short-term gross alpha: if a well has pH and specific conductance values that plot in an area of the graph where all water samples are below 15 pCi/L, it may be unnecessary to test the sample for short-term GAPA.

Major ions

Sodium, magnesium, potassium, chloride, nitrate, and ammonium were positively correlated with short-term and long-term GAPA, long-term GBPA, radium-226, radium-228, and radium-226 plus radium-228 (tab. 6). Sodium and chloride were the most strongly correlated with the radionuclides, and were also highly correlated with each other (figs. 22 and 23). All samples having sodium concentrations greater than about 10 mg/L and chloride concentrations greater than about 15 mg/L had radium-226 plus radium-228 concentrations greater than 5 pCi/L. For samples with chloride concentrations above about 10 mg/L, the molar ratio of sodium to chloride is almost exactly 1:1, indicating that the source or sources are likely those that contain sodium and chloride in a 1:1 ratio.

High ground-water radium concentrations associated with high specific conductance are likely a result of high concentrations of sodium chloride dissolved in the ground water. Potential sources of sodium chloride include brackish-water intrusion in areas adjacent to the Chesapeake Bay, septic-system leachate, de-icing salts applied to roads, and brine

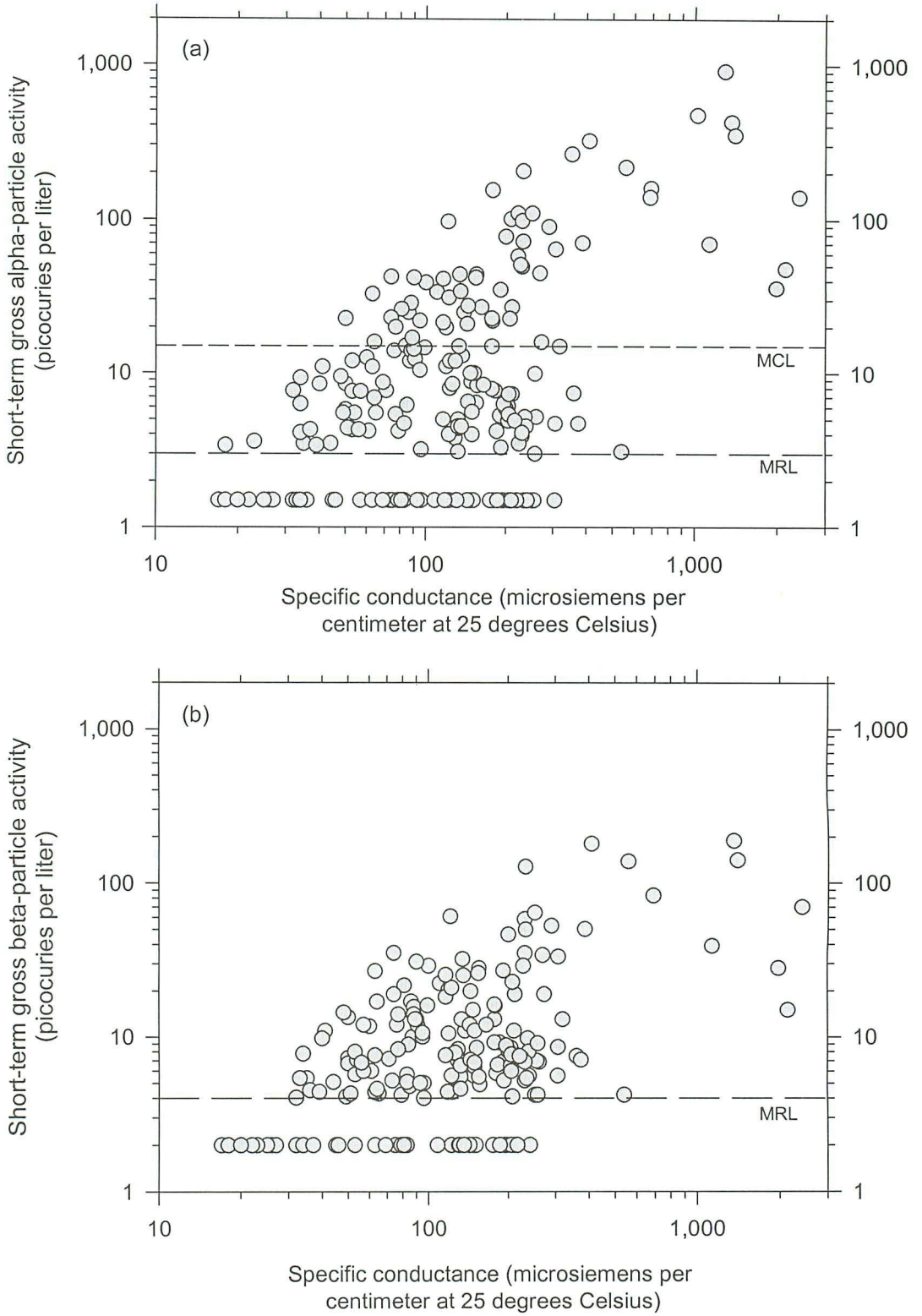


Figure 19. Relations between specific conductance and (a) short-term gross alpha-particle activity; and (b) short-term gross beta-particle activity. MCL, maximum contaminant level; MRL, minimum reporting level. Values less than MRLs are plotted at one-half the MRL.

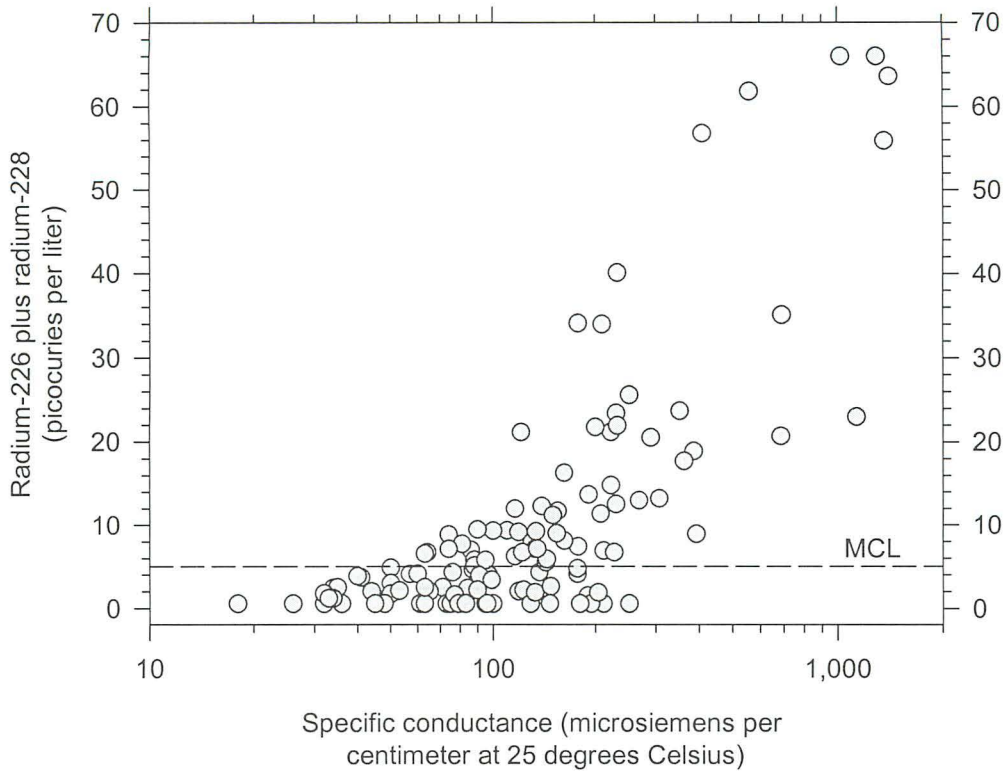


Figure 20. Relation between specific conductance and radium-226 plus radium-228. MCL, maximum contaminant level.

water used to backflush water-softening systems. Brackish-water intrusion does not appear to be related to the high chloride concentrations in the Anne Arundel County wells sampled in this study because most of the affected wells are not adjacent to shorelines, whereas most wells affected by brackish-water intrusion in Anne Arundel County are located within several hundred feet of brackish-water bodies (Drummond, 1988; Fleck and others, 1996). Road de-icing salts include sodium chloride (NaCl), calcium chloride ($CaCl_2$), and magnesium chloride ($MgCl_2$); the amounts of each type were not determined in this study.

Water-softening systems are widely used in Anne Arundel County to remove iron, radium, and other cations. Many systems use an ion-exchange mechanism, in which well water is passed through a column containing resin beads coated with sodium ions. Iron and other undesirable cations (including radium) in the well water replace the sodium ions on the resin beads, increasing the sodium content of the water. Ion-exchange systems have been shown to be effective in removing radium from ground water (Clifford, 1990), and have been demonstrated to work in Anne Arundel County (Bolton and Hayes, 1999). Periodically, the sodium is replenished on the resin beads by passing a sodium-chloride brine solution through the exchange column. This rejuvenation process strips the resin beads of the sorbed iron and other cations and replaces them with sodium. This type of system has the potential to introduce both high-TDS wastewater and sorbed radium into the ground-water system. Brine wastewater from water treatment plant ion-exchange has been shown to increase sodium and chloride concentrations in ground water (Walker, 1969). Radium concentrations in brine wastewater have been shown to be highly concentrated relative to concentrations in untreated ground-water (Hahn, 1990).

Well KE Ac 20, a well completed in the Potomac Group and located at the Coast Guard Station at Still Pond in Kent County, had short-term GAPA and GBPA of 36 and 28 pCi/L, respectively. This sample is noteworthy for two reasons. First, the water had a high specific conductance (1,980 µS/cm) but had a near-neutral pH (6.7), which indicates that ground

Table 10. Statistical summary of short-term gross alpha-particle activity, short-term gross beta-particle activity, and radium-226 plus radium-228 concentrations, grouped by specific conductance quartiles

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; pCi/L, picocuries per liter]

Specific conductance quartile range (µS/cm)	Number of samples	Minimum (pCi/L)	25th percentile (pCi/L)	Median (pCi/L)	75th percentile (pCi/L)	Maximum (pCi/L)
SHORT-TERM GROSS ALPHA-PARTICLE ACTIVITY:						
>205	54	<3.0	3.9	25	101	919
131–205	52	<3.0	4.1	6.5	18	155
69–130	52	<3.0	3.5	11	21	97
<69	51	<3.0	<3.0	4.1	7.6	33
SHORT-TERM GROSS BETA-PARTICLE ACTIVITY:						
>205	47	<4.0	6.9	11	47	188
130-205	51	<4.0	4.7	6.9	12	46
71-129	49	<4.0	5.0	8.9	16	61
<71	52	<4.0	<4.0	4.2	7.0	27
RADIUM-226 PLUS RADIUM-228:						
>194	31	<1.1	13	21	35	66
119–194	30	<1.1	2.2	6.9	9.2	34
71–118	31	<1.1	<1.1	3.9	6.8	12
<71	30	<1.1	<1.1	1.8	3.0	6.7

water with a high dissolved-solids content can have a high level of radioactivity without being very acidic. This is consistent with the findings of Szabo and Zapecza (1991). The dominant ions in the KE Ac 20 sample were sodium and chloride. Second, the well is screened at a depth of 550 to 560 ft below land surface, and is completed in a deep brackish-water zone at the base of the Potomac Group that is found beneath most of Kent and part of Queen Anne's County and Delaware (Otton and Mandle, 1984). This is the deepest screened interval having such a high short-term GAPA. Drummond (1998) has suggested, on the basis of potentiometric-head evidence, that the brackish-water zone more likely originated from salt-water intrusion during a previous highstand of sea level rather than from current-day brackish-water intrusion from the Chesapeake Bay. A sample from the well had a chloride concentration of 560 mg/L and a short-term GAPA of 36 pCi/L. The high GAPA and GBPA suggests that any high-salinity water, such as that associated with brackish-water intrusion, can mobilize radium in these aquifers. The decrease in GAPA between the short-term and long-term measurements (36 to 8.0 pCi/L) also indicates that the source of the radium is the sediment near the screened interval. If the source of the radium was in the intruding brackish water, any radium-224 (the likely source of much of the alpha-particle activity) in the original water would have decayed to less than detectable amounts by the time the brackish water had migrated to the well.

Most of the highest radionuclide and chloride concentrations in Anne Arundel County were from wellwater samples in the Lake Shore area of the Mountain Road peninsula. To investigate the distribution of radium in the area, 18 wells were sampled along a north-south transect running from Main Creek to the Magothy River (fig. 24). Most

Table 11. Comparison of water-quality data and depth of the screened interval from two wells located in the West View Shores subdivision in Cecil County

[ft, feet; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; pCi/L, picocuries per liter; <, less than]

Characteristic	Wells	
	CE Dd 105	CE Dd 106
Depth of screened interval (ft below land surface)	106-110	82-87
Specific conductance (µS/cm)	196	2,410
pH	6.5	4.3
Dissolved oxygen (mg/L)	0.2	2.5
Short-term gross alpha-particle activity (pCi/L)	<3	140
Long-term gross alpha-particle activity (pCi/L)	<3	9.6
Short-term gross beta-particle activity (pCi/L)	<4	70
Long-term gross beta-particle activity (pCi/L)	<4	24

wells in the transect are in the Patapsco Formation, although the contact between the Magothy and the Patapsco Formations is difficult to identify in this area without detailed mineralogical and microfossil data. In any event, the two formations are hydraulically connected. The Magothy and Patapsco aquifers are unconfined in this area. Well depths ranged from 57 to 190 ft deep (median depth: 85 ft). Land use along the transect is mostly residential, with the highest density residential development south of Mountain Road. The area is not serviced by a public water-supply system; water is obtained from private water wells. Sewage is disposed of via on-site waste disposal systems (septic systems).

Radium-226 plus radium-228 concentrations along the transect range from 4.7 to 66 pCi/L; chloride concentrations range from 3 to 380 mg/L. Concentrations of radium-226 plus radium-228 exceeding 20 pCi/L were found in ground water encountered approximately 50 to 175 ft below land surface beneath the central part of the peninsula, with the highest radium concentrations found in water samples from the central and southern parts of the transect at depths of less than 100 ft (fig. 24). The distribution of radium is very similar to the chloride distribution in the same area, but does not correspond as closely to pH distribution. The deepest part of this radium-enriched zone is located beneath the central part of the peninsula just south of Mountain Road. A zone of higher radium and chloride concentrations penetrates deeper into the aquifer near the center of the peninsula. This may correspond to an area where the recharge water has entered a deep flow system near the groundwater divide, where flow lines are nearly vertical, rather than entering the groundwater system away from the divide, where ground-water flow direction may be more lateral. There is, however, insufficient data currently available to fully explain this relation.

The distribution of radium illustrated in figure 24 has important implications for the development of regulations designed to minimize radium

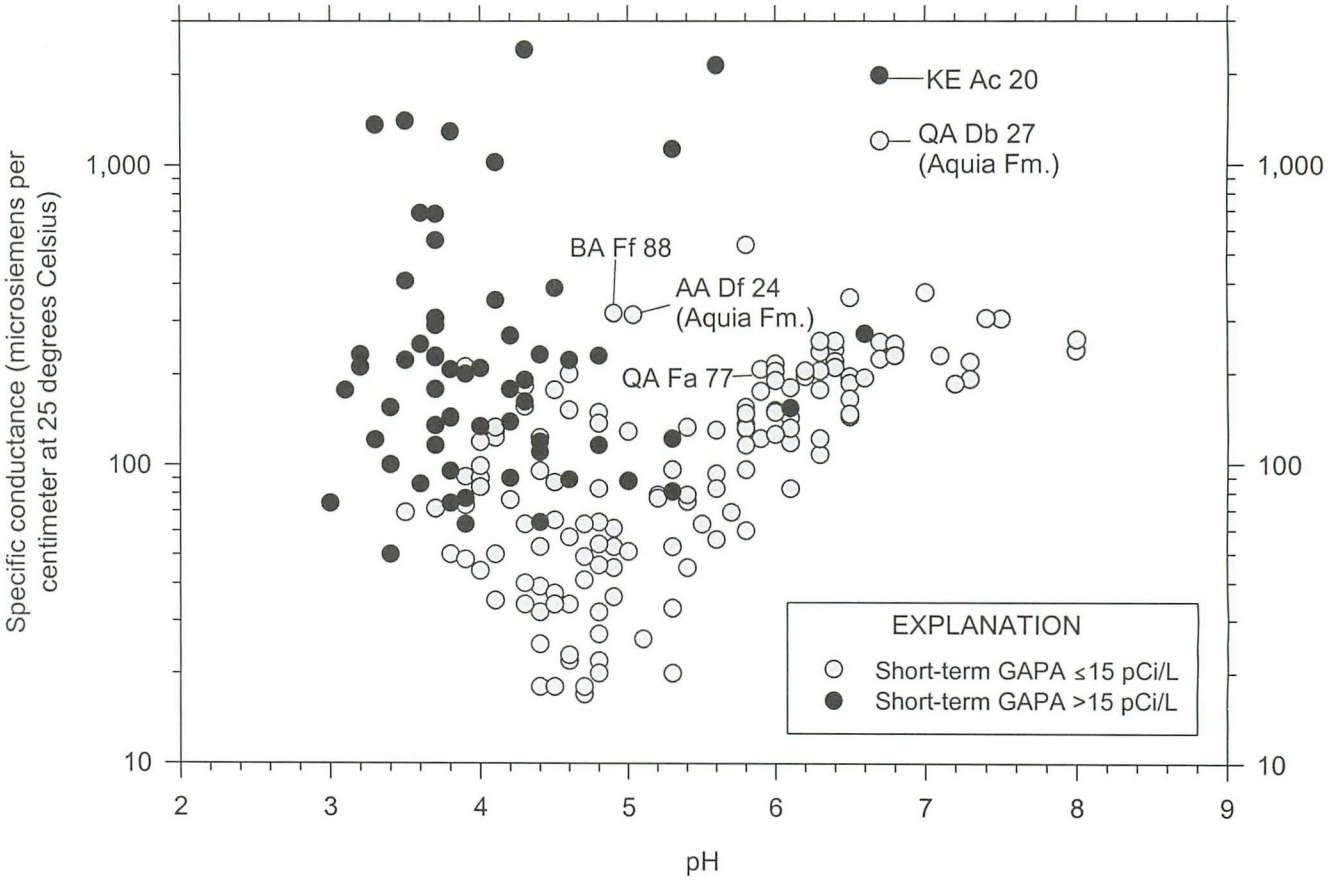


Figure 21. Relation between pH and specific conductance with respect to short-term gross alpha-particle activity. GAPA, gross alpha-particle activity; pCi/L, picocuries per liter.

concentrations in newly drilled wells. Radium concentrations may differ greatly among wells located close to one another and drilled to similar depths, depending upon the position in the flow system, land-use history, and other factors. Furthermore, although the deeper wells tend to have lower radium concentrations than shallower wells, this is not always the case. Knowledge of the local and regional flow systems may be important to predicting the distribution of radium in ground water, particularly in the Patapsco Formation, where the sands are more discontinuous than in the Magothy Formation.

Geochemical transects

Wells were sampled along three other transects in Anne Arundel County to observe changes in radionuclide concentrations and their relation to major-ion chemistry as the wells penetrated progressively deeper parts of the aquifers along regional flow paths (pls. 3, 4, and 5). Some trends were common to all three geochemical transects. Shallow wells in the updip parts of the Potomac Group and Magothy Formation tended to have variable water quality; sodium and chloride were the major ions in many of these wells. Specific conductance was often higher (usually due to higher sodium and chloride concentrations) and pH was lower in the updip and outcrop areas than in the deeper confined parts of the aquifers, where iron, bicarbonate, and sulfate were the dominant ions.

Transect A-A′ extends from the southwest corner of Baltimore-Washington International Airport eastward parallel to Mountain Road, ending at Gibson Island (pl. 3). Most of the wells in the transect are in the unconfined or semiconfined aquifers of the Patapsco Formation. Regional ground-water flow in the Patapsco Formation along the transect is east-southeastward (Curtin and others, 1999a), although most of the wells less than 100 ft deep are probably sampling shallow flow systems which have different

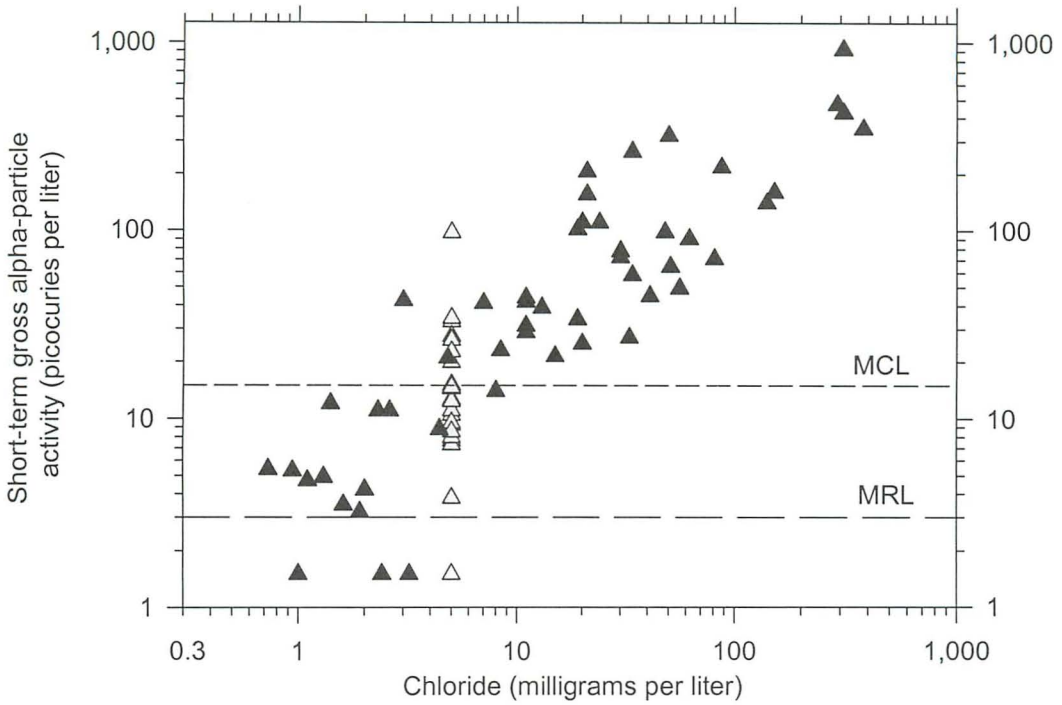


Figure 22. Relation between short-term gross alpha-particle activity and chloride concentrations. Gray triangles are chloride concentrations that were reported as less than 10 mg/L by the laboratory. MCL, Maximum Contaminant Level; MRL, minimum reporting level. Values less than MRLs are plotted at one-half the MRL.

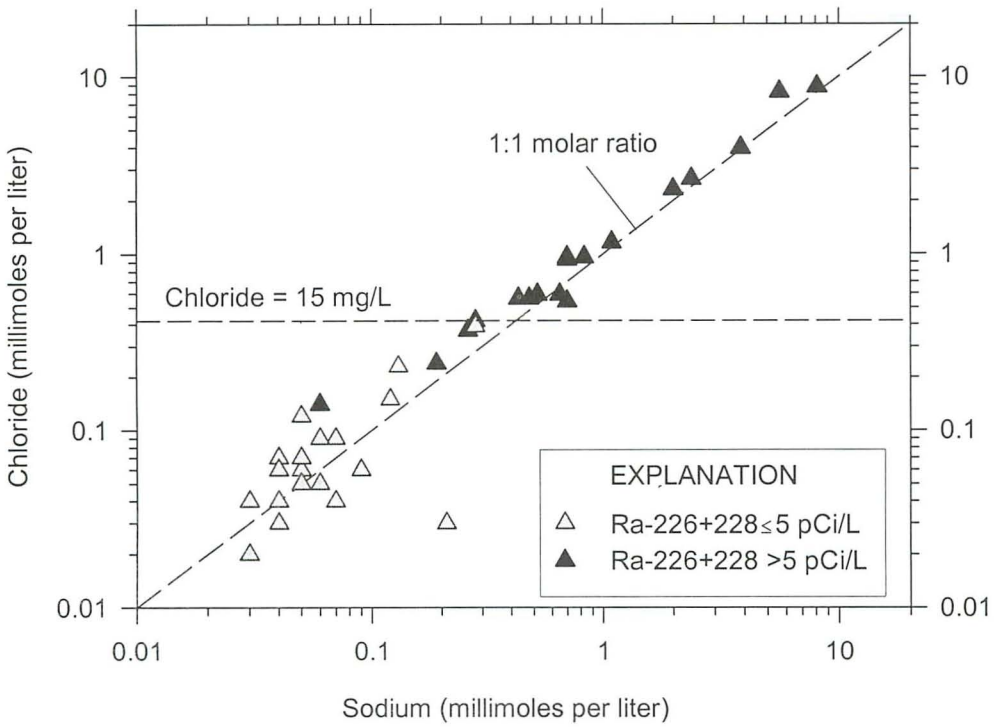


Figure 23. Relation between sodium and chloride concentrations with respect to radium-226 plus radium-228 concentrations. pCi/L, picocuries per liter; mg/L, milligrams per liter.

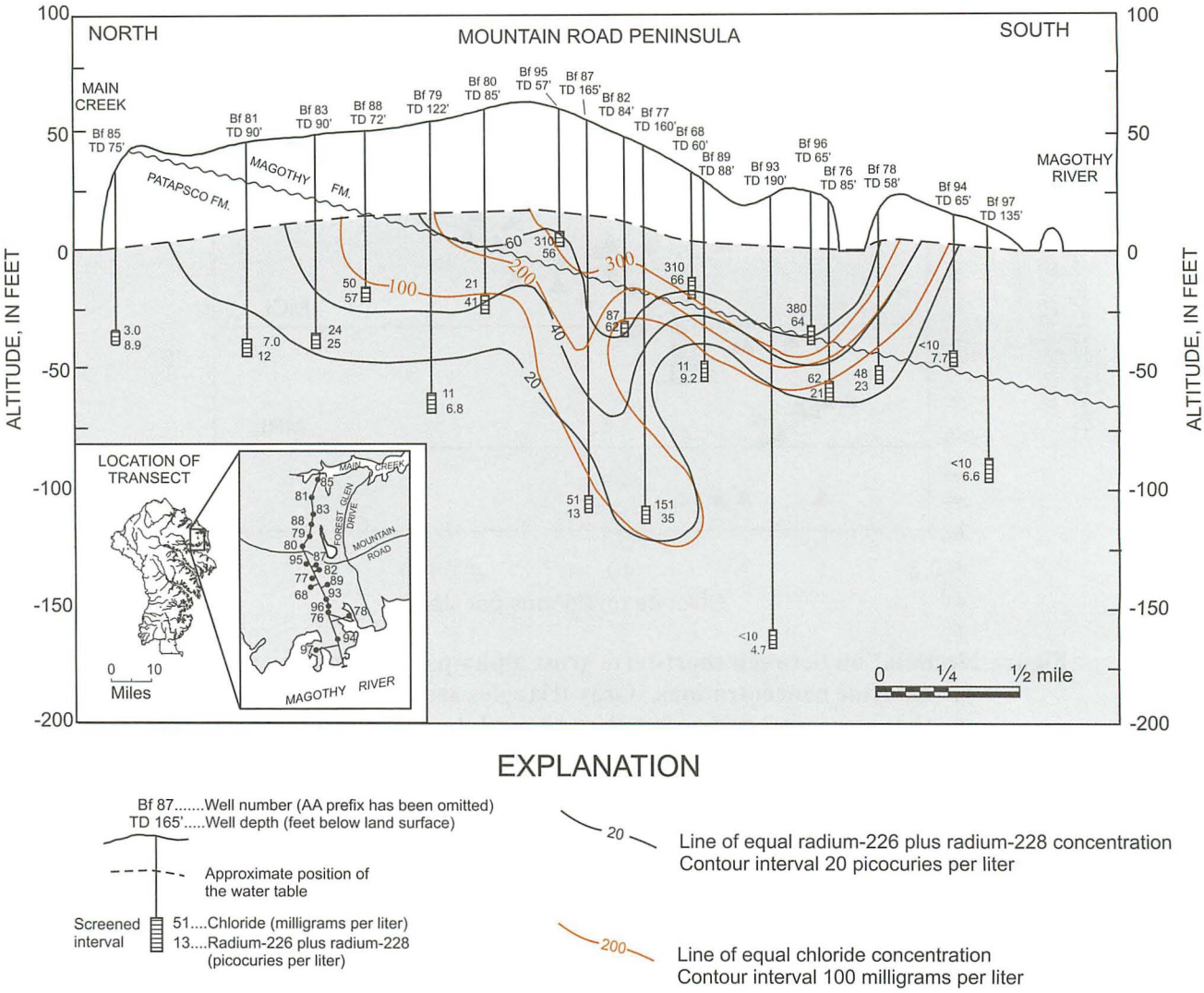


Figure 24. Transect showing the relation between radium-226 plus radium-228 and chloride concentrations on the Mountain Road peninsula in Anne Arundel County.

flow directions. Sodium was the dominant cation and chloride and sulfate were the dominant anions in the relatively shallow (less than about 100 ft deep) wells, although there were large variations in both TDS and the absolute concentrations of the ions. Samples from many shallow wells on the Mountain Road peninsula (e.g., AA Bf 64) area were very acidic (pH less than 4). Water from wells in this area have the highest radionuclide concentrations in the study area. The wells that were greater than 200 ft deep (AA Bd 122; AA Bd 107; and AA Cf 22) were characterized by lower radium and specific conductance than the shallower wells. Iron and sulfate were the dominant ions in the downdip Patapsco well at the eastern end of the transect.

Transect B-B′ extends from I-97 southeast along Broadneck Peninsula to Sandy Point State Park (pl. 4). Most of the wells in this transect are completed in the confined Magothy and Patapsco Formations. Sodium and calcium were the dominant cations, and chloride, sulfate, and nitrate were major anions in samples from three relatively shallow (less than 200 ft deep) wells in the updip portion of the transect. The low pH in samples from these wells in the updip part of the transect corresponds to short-term GAPA and radium concentrations that exceed MCLs. Samples from the wells greater than about 200 ft deep in the updip section (AA Bd 170 and AA Ce 122) were characterized by low TDS and radionuclide concentrations. Southeast of Severna Park, specific

conductance and pH tended to increase downdip in both the Patapsco and Magothy Formations, and short-term GAPA and radium concentrations were consistently less than MCLs. Samples became enriched in iron and sulfate with depth and distance from the outcrop area.

Transect C-C′ extends from the Odenton area southeast down South River Neck to Arundel on the Bay (pl. 5). The potentiometric surfaces of the Magothy and the Upper and Lower Patapsco Formations slope to the southeast along the direction of transect C-C′ (Curtin and others, 1999a; 1999b), indicating that ground-water flow is generally in this direction. Samples from the updip portion of the transect had either low TDS (AA Bc 242, AA Bc 246, and AA Cd 113) or high TDS with a sodium-chloride water type (AA Cd 100). Farther downdip, calcium and iron were the dominant cations and bicarbonate and sulfate became the dominant anions (AA De 2, AA De 139, AA De 213, and AA Df 158). pH decreased from 4.1 in the outcrop area of the Magothy Formation (AA Cd 100) to 3.2 near Crownsville (AA Cd 110), then increased to 6.1 to the southeast (AA De 213). Specific conductance was variable (33 to 1,020 μS/cm) in the updip wells in this transect, and radionuclide concentrations decreased from the outcrop area of the Magothy Formation southeast to Crownsville. From Crownsville to the southeastern end of the transect, specific conductance gradually increased downdip in the Magothy Formation from 73 to 204 μS/cm (wells AA Cd 109 and AA Df 58, respectively), and radionuclide concentrations increased slightly but remained below MCLs.

Mechanisms of Radium Mobilization to Ground Water

Geochemical factors that determine whether radium will be mobilized to ground water include: (1) potential sources of uranium and thorium (radium's parent radionuclides) in the aquifer materials; (2) movement of radium from the aquifer materials into ground water; and (3) processes that may limit radium concentrations in aquifers, such as sorption and desorption.

Potential sources of uranium and thorium in the aquifer materials. Radium isotopes in ground water are derived from uranium and thorium; therefore, processes controlling the distribution of uranium and thorium in the subsurface will affect the distribution of radium. Aquifer materials were not analyzed for uranium and thorium concentrations during this study, and the distribution of these elements in the Magothy Formation and the Potomac Group aquifers is unknown. The heavy-mineral portion of the Patapsco-Raritan and Patuxent Formations, a likely source of uranium and thorium, is composed predominantly of zircon ($ZrSiO_4$) and tourmaline (a borosilicate of Na, Li, Mg, Fe, and Al), with smaller amounts of staurolite (an iron-magnesium aluminosilicate) and rutile (TiO_2) (Glaser, 1969, p. 58). Staurolite is the dominant heavy mineral in the Magothy Formation, with subordinate amounts of zircon and kyanite (Glaser, 1969, p. 56). Zircon is enriched in uranium and thorium relative to other common rocks and minerals (tab. 1). It is reasonable to assume that uranium and thorium are present in the aquifers because of the occurrence of zircon in the aquifer materials, the known presence of uranium and thorium in stream sediments (Hoffman and Buttleman, 1994), and the high radium concentrations in ground water. There is insufficient data currently available to determine the relation between the distribution of uranium and thorium in the aquifer materials and the radium concentrations found in ground water. It is not known, for example, whether uranium and thorium occur in highly concentrated, low-solubility zones or whether they are widely dispersed in soluble forms.

Although the ground-water samples collected during this project were not tested for uranium isotopes (uranium-238, uranium-234, and uranium-235), ground-water uranium concentrations in the study area probably do not exceed the MCL of 20 μg/L. Uranium was detected in only three of the 20 Anne Arundel County pilot-study samples from the Magothy Formation and Potomac Group aquifers (range: less than 1 to 14 μg/L) (Bolton and Hayes, 1999). If dissolved uranium were a major component of ground-water radionuclides, it would be reasonable to expect higher levels of long-term GAPA in the oxic samples (dissolved oxygen greater than 1.2 mg/L) than in the anoxic samples (dissolved oxygen less than 1.2 mg/L) because uranium is more soluble under oxidizing than reducing conditions. However, there was no statistically significant difference in long-term GAPA between the oxic and anoxic samples collected during this project (Mann-Whitney rank-sum test, P=0.28), indicating there is likely little uranium in the ground water. (Long-term GAPA was used because of the long half lives of the uranium isotopes, which are all alpha-emitting isotopes). Furthermore, the large difference observed between most short-term and long-term GAPA indicates that uranium is at best a

small contributor to GAPA, as the alpha emissions from any given amount of uranium do not decrease even on the order of years. Concentrations of uranium in ground water in the New Jersey coastal plain were below 1 pCi/L (Kozinski and others, 1995; Szabo and others, 1997).

Movement of radium from the aquifer materials into ground water. There are several mechanisms by which radium can be mobilized from the aquifer solids to ground water. Radium may be ejected from the aquifer materials into the pore spaces when the thorium precursor in the decay series (thorium-230 for radium-226; thorium-232 for radium-228; thorium-228 for radium-224) undergoes alpha decay. The recoil force from an ejecting alpha particle causes a fraction of the radium atoms to be ejected into the ground-water-filled pore spaces from the mineral surface or (less frequently) the crystal lattice, a process known as alpha recoil (Wanty and Nordstrom, 1993). Radium is also released when minerals containing trace amounts of radium dissolve in ground water. This occurs mainly with sulfate minerals such as barite ($BaSO_4$), celestite ($SrSO_4$), gypsum ($CaSO_4 \cdot 2H_2O$), and anhydrite ($CaSO_4$). Since these minerals are not found in the Magothy or Patapsco Formations except in rare occurrences of secondary gypsum (H. Hansen, Maryland Geological Survey, 2000, written commun.), sulfate mineral dissolution probably does not contribute significant amounts of radium to ground water. Pure radium solids such as $RaCO_3$ and $RaSO_4$ are also not considered likely sources for radium in ground water because the ground-water concentrations of radium are too limited by adsorption and solid solution formation to reach saturation with respect to these minerals (Langmuir and Riese, 1985).

Processes that may limit radium concentrations in ground water. Radium mobility in ground water is controlled largely by adsorption or cation exchange (Herczeg and others, 1988; Szabo and Zapecza, 1991). Radium is strongly sorbed by quartz, kaolinite and other clay minerals, and especially by ferric oxides and hydroxides (Langmuir and Riese, 1982; Ames, McGarrah, and Walker, 1983; Ames, McGarrah, Walker, and Salter, 1983; Beneš and others, 1984). Radium desorption from sediments has been shown to be a function of salinity (Li and others, 1977; Kraemer and Reid, 1984; Miller and Sutcliffe, 1985; Webster and others, 1995). Radium will sorb onto the medium, and radium concentrations in ground water will be low, if the ground water has low TDS, since there are few other cations available to compete for sites on the exchanging medium. In ground water with high TDS, high concentrations of calcium, sodium, and other cations will compete effectively for exchange sites on the sorbing medium, smaller amounts of radium will be sorbed, and the concentration of radium will be higher than in low-TDS ground water. The process can be represented (using sodium as an example) as follows:

$$2Na^+ + Ra_{(ex)} \rightleftharpoons Ra^{2+} + 2Na_{(ex)}$$

where

Na^+ and Ra^{2+} are dissolved species
$Ra_{(ex)}$ and $Na_{(ex)}$ are exchanged species

The high concentrations of radionuclides observed in low-pH and high-TDS ground water, in conjunction with the occurrence of ferric hydroxides, oxyhydroxides, and other sorbing minerals in the Potomac Group and Magothy Formation, suggest that sorption and desorption play a major role in radium mobilization and demobilization in the study area. Adsorption of radium onto kaolinite, ferric hydroxide and quartz particles is highly dependent on pH, with adsorption increasing at higher pH levels (Langmuir and Riese, 1982; Beneš and others, 1984). Sorption of radium is a reversible process that can be explained by ion exchange of radium for hydrogen (Beneš and others, 1984). Desorption is favored at low pH (high concentrations of hydrogen ions in solution). Radium concentrations were positively correlated with TDS in ground water in the Chickies Quartzite in southeastern Pennsylvania (Senior and Vogel, 1995) and in the Kirkwood-Cohansey aquifer system in New Jersey (Kozinski and others, 1995). In a study of ground water in Utah, radium was shown to be most mobile in chloride-rich reducing ground water with high TDS content (Tanner, 1964). Some subsurface brines (defined as ground water having a dissolved-solids content greater than about 100,000 milligrams per liter) have been found to contain high concentrations of radium (e.g., Langmuir and Melchior, 1985; Herczeg and others, 1988). Fisher (1998) reported that TDS and chloride content were the most useful predictors of radium content of oilfield brines. In brines, radium mobility may be greatly increased by the formation of complexes of radium with sulfate and chloride (Herczeg and others, 1988). As in this study, radium concentrations were negatively correlated with pH in ground water in the Chickies Quartzite in southeastern Pennsylvania (Senior and Vogel, 1995) and in the Kirkwood-Cohansey aquifer system in New Jersey (Kozinski and others, 1995).

The discontinuous nature of the individual sand

units in the Patapsco Formation makes it difficult to identify geochemical trends related to flowpaths. The Magothy Formation, which tends to be a more continuous sand deposit, is a better candidate for investigating systematic changes in water quality as the aquifer becomes progressively deeper to the southeast. Short-term GAPA activity in Magothy wells in Anne Arundel County were highest in the updip and outcrop areas, where pH was low and specific conductance was high. In the central part of the county, radium-226 plus radium-228 in the Magothy Formation decreased to less than 5 pCi/L along a fairly distinct boundary located approximately two to four miles southeast of the outcrop area. Southeast of this boundary, specific conductance decreased downdip to less than 100 µS/cm, then increased to over 200 µS/cm at the southeastern end of Annapolis Neck (fig. 25). pH increased from the outcrop area southward, reaching a pH of 6.8 west of Davidsonville. Southeast of the boundary, all radium-226 plus radium-228 from samples in the Magothy Formation were less than 5 pCi/L.

The precise geochemical evolution of ground water in the Magothy Formation cannot be fully defined in the absence of major-ion analyses for representative wells along all potential flowpaths. The following hypothesis is proposed as a general framework based on observed water-quality data collected to date. The high specific conductance from the Magothy wells in the outcrop areas is related to human inputs of soluble constituents, particularly sodium and chloride. Recharge water transports these solutes to the water table in the outcrop area, where they enter the groundwater flow system and migrate downgradient to the southeast. The point where specific conductance decreases to less than about 100 µS/cm may correspond to the downdip limit of ground water that was recharged since the beginning of anthropogenic inputs in the recharge area. As the ground water continues to flow to the southeast, it gradually acquires more dissolved solids as the aquifer minerals are dissolved. The absence of potassium feldspar in outcrop and its presence in core samples from the Magothy Formation from the Eastern Shore indicate that weathering has removed the feldspars in the outcrop area but has not removed them in the downdip part of the Magothy Formation (Knobel and Phillips, 1988). The pH of water from the Magothy Formation gradually increases downgradient as the acidic water reacts with the silicate minerals in the aquifer, consuming hydrogen ions and acquiring base cations (Knobel and Phillips, 1988). This process removes a major competitor (hydrogen ions) for sorption sites and enables a greater portion of radium to be adsorbed than in the acidic water updip.

If radium in the Magothy Formation is mobilized to ground water by human-derived solutes that have entered the ground-water flow system in the recharge area, this implies that the low-radium/high-radium boundary is moving downgradient and may eventually affect wells that currently have low radium concentrations. The groundwater flow rate may be estimated from the following formula:

$$V = (K \times I) / p$$

where

V = velocity of water movement, in feet per day (ft/d)
K = hydraulic conductivity, in ft/d
I = hydraulic gradient
p = effective porosity of the Magothy Formation

Using values of K, I, and p derived from Mack (1974), Curtin (1999b), and Mack and Mandle (1977), respectively:

$$\begin{aligned} V &= (68.6 \text{ ft/d} \times 0.00189) / 0.30 \\ &= 0.432 \text{ ft/d} \\ &= 158 \text{ ft per year} \end{aligned}$$

The groundwater flow rate may or may not correspond to the rate at which the radium front moves in the aquifer. Although simple advective transport may describe the transport of non-reactive ions such as chloride, movement of sodium (which is probably more important than chloride in radium mobilization) and other reactive solutes is far more complicated. Factors that may affect the rate of radium migration include changes in hydraulic and ion-exchange properties of the aquifer, dispersion, complexation, and changes in the distribution of uranium, thorium, and radium in the aquifer materials. It is likely that other factors are involved as well.

Depth to the Screened Interval

The relation between well depth and radionuclide concentrations was evaluated to determine whether deeper wells contain lower concentrations of radionuclides than shallower wells. If such a relation were found to exist, this would enable environmental

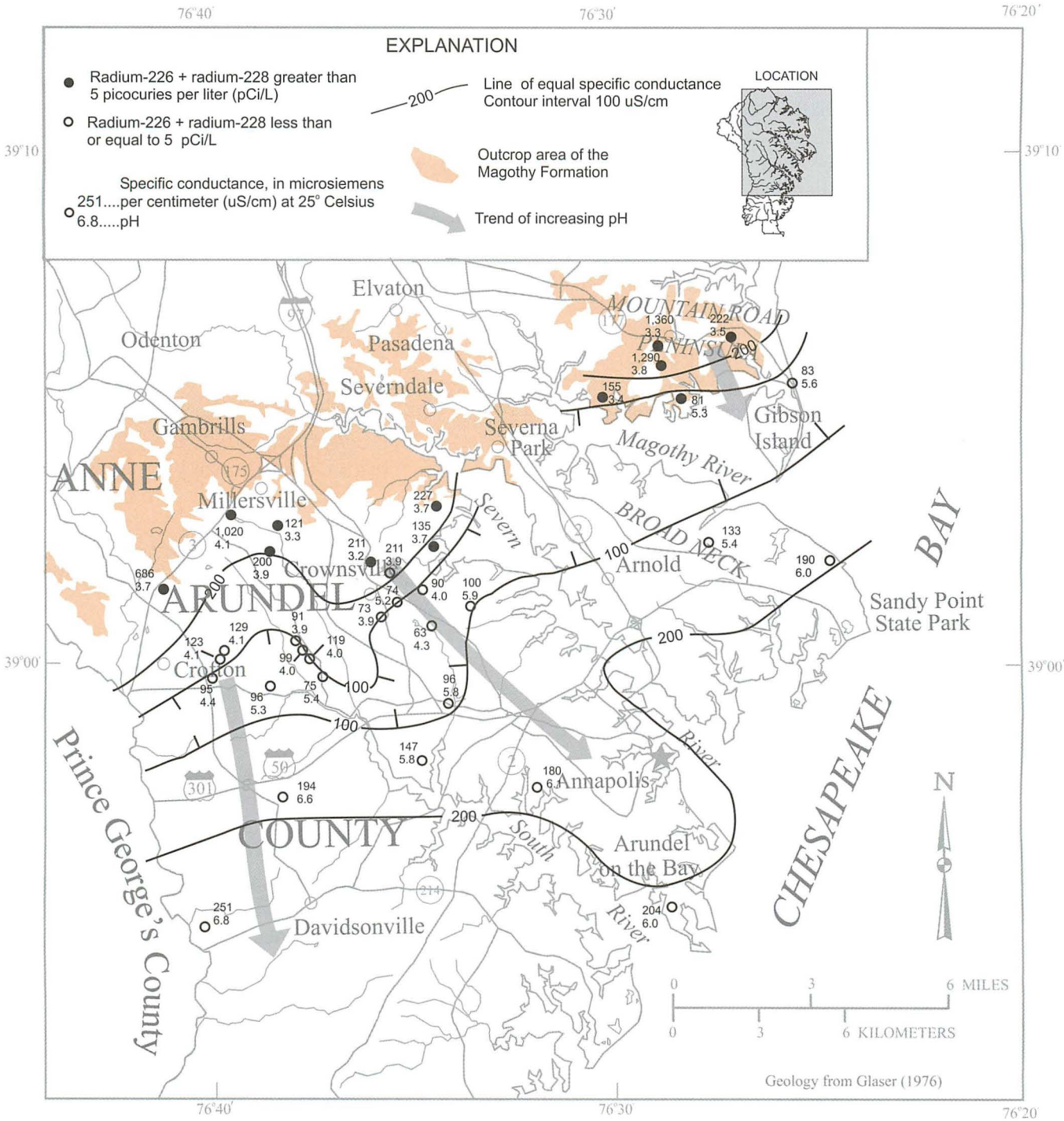


Figure 25. Map showing the distribution of radium-226 plus radium-228 in relation to specific conductance and pH in ground water from the Magothy Formation in Anne Arundel County.

health professionals to develop regulations for minimum well depths in areas known to have high concentrations of radium. Radionuclide concentrations were evaluated with respect to depth to the middle of the screened interval, rather than well depth, because in some of the public-supply wells, there are multiple screened intervals extending over large vertical sections (and the water sample is a composite of the large section). In most wells, however, the top of the screen is within 15 ft of the well bottom. (In this discussion, the depth to the middle of the screened interval is referred to as "depth to the screened interval.")

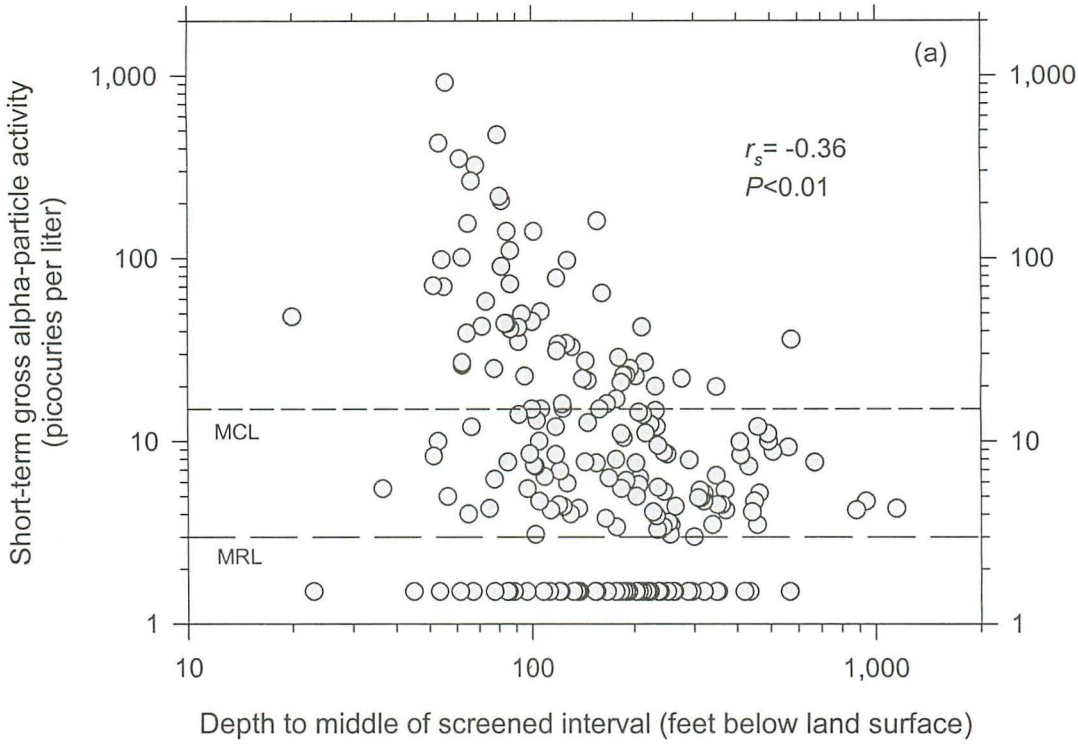
The relation between radium concentrations and depth to the screened interval was investigated in two ways. Radionuclides were plotted against depth to the screened interval for all wells to observe the *overall* relation between these variables throughout the study area. To observe the relation between shallow and deep wells *in the same area,* 15 groups of wells (14 in Anne Arundel County and one in Prince George's County) were sampled, where each group consisted of two or three adjacent or nearby wells having different screen depths. These included many public-supply wells, which were usually deeper than private water wells.

Radionuclide concentrations were negatively correlated with depth to screened interval (Spearman rank correlation test; $P<0.01$) (figs. 26 and 27; tab. 6). When radionuclides were grouped by quartiles corresponding to the depth to the screened interval, the median short-term GAPA, short-term GBPA, and radium-226 plus radium-228 concentrations decreased with increasing depth range of the quartiles (tab. 12). For wells with screened intervals less than 100 ft deep, short-term GAPA exceeded 15 pCi/L in samples from 32 of 55 wells; radium-226 plus radium-228 concentrations exceeded 5 pCi/L in samples from 36 of 40 wells. For wells with screened intervals greater than 300 ft deep, short-term GAPA exceeded 15 pCi/L in samples from only 2 of 36 wells; radium-226 plus radium-228 concentrations exceeded 5 pCi/L in samples from only 1 of 12 wells. The negative correlation is stronger for radium-226, radium-228, and radium-226 plus radium-228 (r_s range: -0.63 to -0.67) than for short-term or long-term GAPA and GBPA (r_s range: -0.22 to -0.43). This probably reflects the large number of samples with GAPA and GBPA below MRLs (GAPA and GBPA were set equal to one-half the MRL to calculate the test statistic). Furthermore, the precision of the analytical methods used to determine concentrations of radium-226 and radium-228 are much greater than those used to determine GAPA and GBPA; thus, variance in results based on analytical technique is much less for radium-226 and radium-228 than for GAPA and GBPA, and the correlations would be expected to be stronger.

For 13 of the 15 well groups, radionuclide concentrations were lower in the deeper wells than the shallower wells (fig. 28), although there was overlap in the error bars for 3 of the 13 groups. In seven of the groups the shallower well exceeded the MCL while the deeper well was less than the MCL (fig. 28a, b, c, h, l, m, and n). For three of these seven groups, the decrease was accompanied by decreasing specific conductance (fig. 28a, h, and m); the other four groups had both decreasing specific conductance and increasing pH (fig. 28b, c, l, and n). Both the shallow and deep wells in each of four groups exceeded MCLs (fig. 28g, i, k, and o); however, except for figure 28o, the deep well in each of these groups was less than 200 ft deep. Radionuclide concentrations were less than MCLs in both the shallow and deep wells in four well groups (fig. 28d, e, f, and j).

Elevated Radium Concentrations in Anne Arundel County Relative to the Rest of the Study Area

The higher radionuclide concentrations in the Magothy Formation and the Potomac Group aquifers in Anne Arundel County wells relative to the other counties in the upper Chesapeake Bay area may be related to several factors. The outcrop areas of the Magothy Formation and Potomac Group are wider in Anne Arundel County than in other counties. The aquifers are usually unconfined in these areas and are more susceptible to contamination from anthropogenic sources which can increase TDS and, therefore, possibly increase radionuclide concentrations. Anne Arundel County wells tended to be shallower (median well depth: 142 ft) and the samples tended to have lower pH (median pH: 4.1) than wells in the other counties (median depth 201 ft; median pH 5.8). Specific conductance tended to be higher in samples from the regional wells than in samples from Anne Arundel County (median: 146 µS/cm and 119 µS/cm, respectively). The higher median specific conductance in the regional wells may reflect the natural geochemical evolution of the ground water along the flowpath (such as increased sodium, calcium, bicarbonate, and sulfate), rather than the high



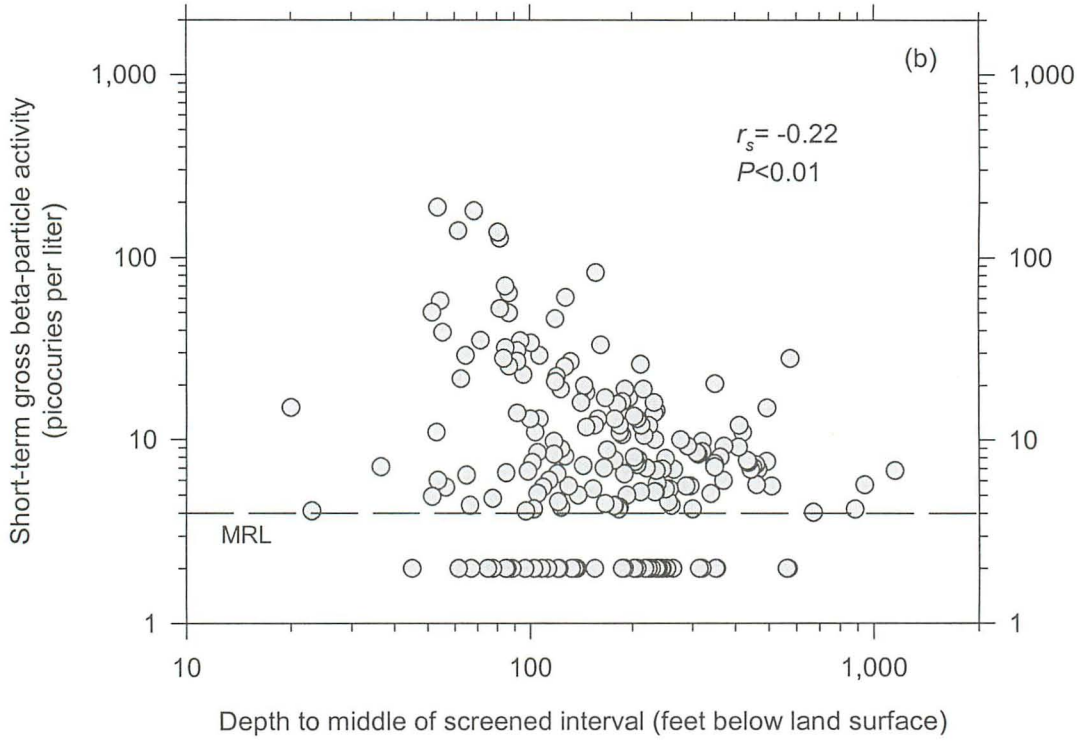


Figure 26. Relations between depth to the middle of the screened interval and (a) short-term gross alpha-particle activity, and (b) short-term gross beta-particle activity. MRL, minimum reporting level; MCL, maximum contaminant level; r_s, Spearman rank correlation coefficient. Values below minimum reporting levels were plotted at one-half the reporting levels.

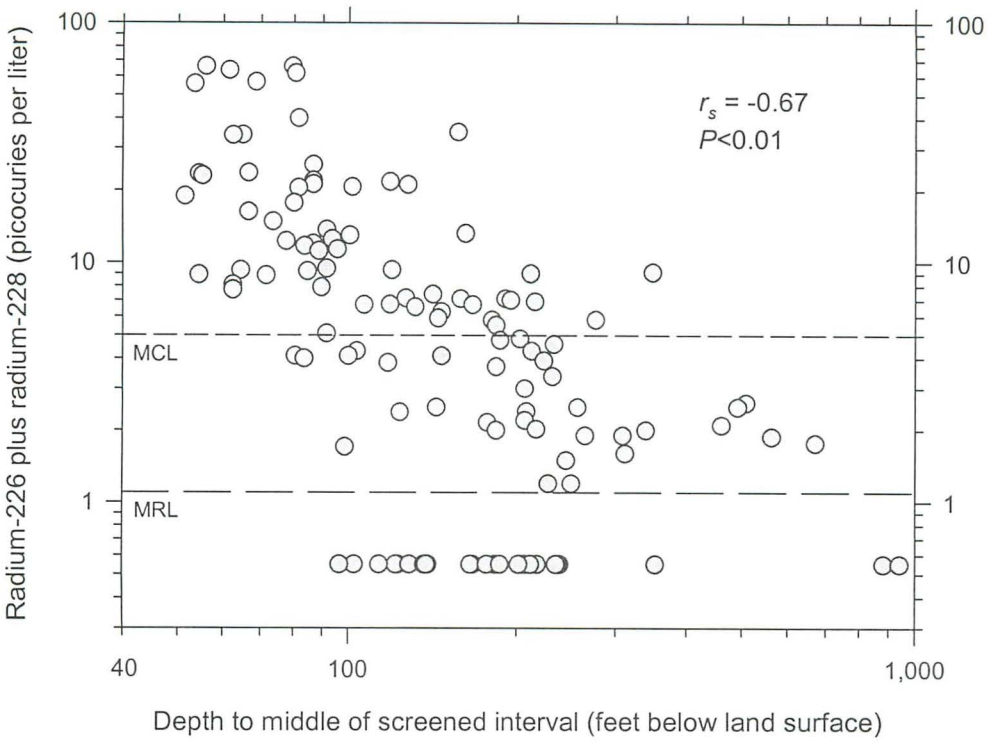


Figure 27. Relation between depth to middle of the screened interval and radium-226 plus radium-228. r_s, Spearman rank correlation coefficient. Values below the minimum reporting level (MRL) are plotted at one-half the reporting level. MCL, maximum contaminant level.

levels of anthropogenic sodium and chloride seen in Anne Arundel County. However, the differences in major-ion chemistry between the two groups of wells are not known since the regional wells were not sampled for major ions. The fact that several widely-spaced wells outside of Anne Arundel County had short-term GAPA exceeding 15 pCi/L indicates that the potential exists to have elevated radium concentrations in these aquifers throughout the upper Chesapeake Bay area under suitable geochemical conditions such as low pH and high TDS.

Radionuclide Concentrations in High-Chloride Wells in the Aquia Formation

Twenty-seven wells sampled during the pilot study were completed in the Aquia Formation; radionuclides were detected in only eight of these wells, and where detected, concentrations were all below the MCLs (maximum radium-226 plus radium-228 concentration: 1.3 pCi/L) (Bolton and Hayes, 1999). However, samples from the Aquia Formation tended to have higher radon-222 concentrations (median: 328 pCi/L) than water samples from the Magothy Formation and Potomac Group (median: 180 pCi/L), indicating the presence of radium-226 (radon's precursor in the uranium-238 decay series) in the aquifer materials. The Aquia Formation samples typically had higher pH values (median: 5.9) than samples from the Magothy and Patapsco Formation wells (median: 4.3), and this may inhibit radium mobility to ground water. Because radionuclide concentrations in water samples from the Potomac Group and Magothy Formations were highly correlated with chloride concentrations, there was concern that parts of the Aquia Formation that contain high-chloride water might have high concentrations of radium as well. Few of the Aquia Formation samples from the pilot study had excessively high chloride concentrations; however, ground-water chloride concentrations in the Aquia Formation are above

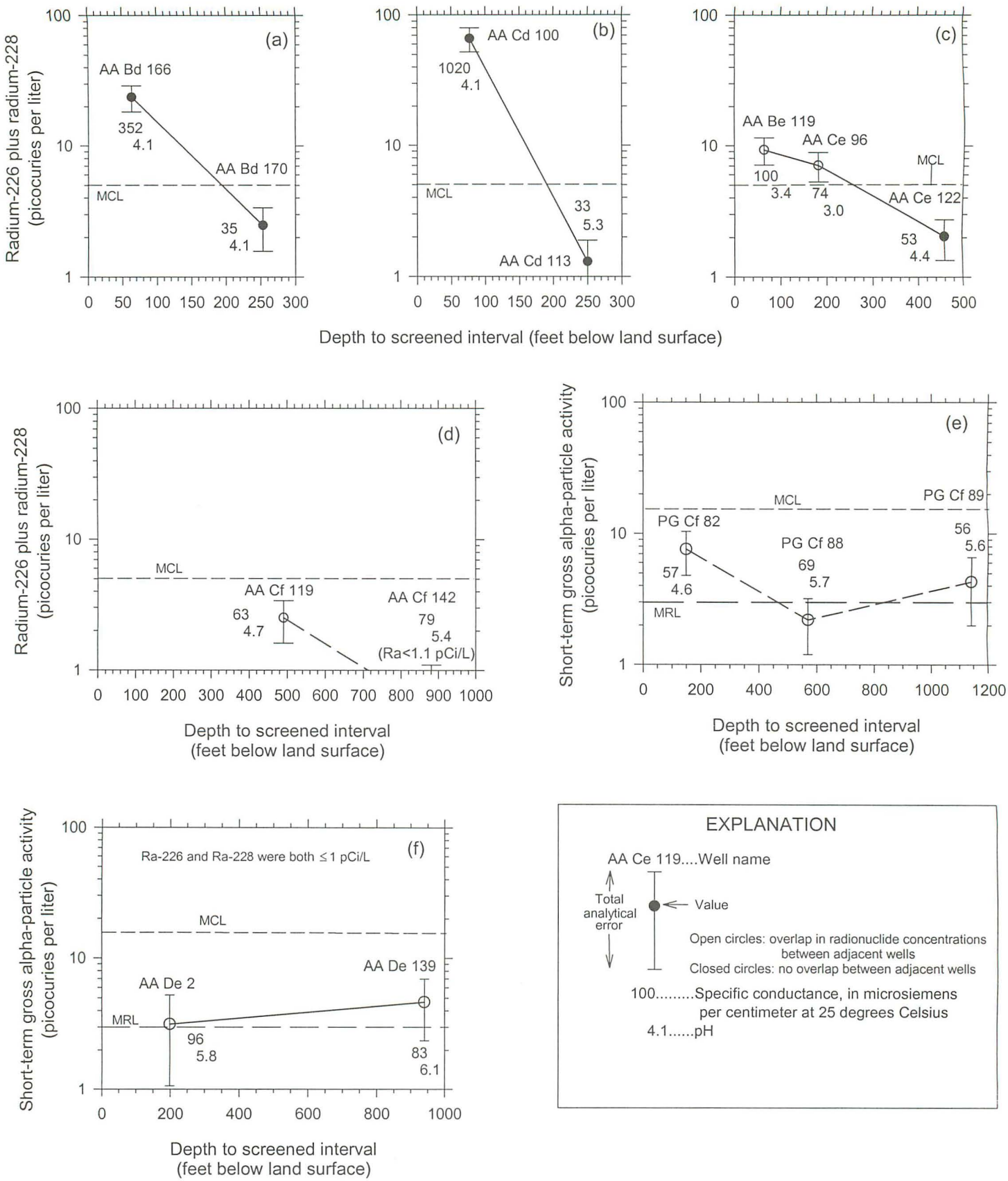


Figure 28. Relation between radionuclide concentrations and depth to the middle of the screened interval for adjacent and nearby wells. MRL, minimum reporting level; Ra, radium-226 plus radium-228. MCL, Maximum Contaminant Level.

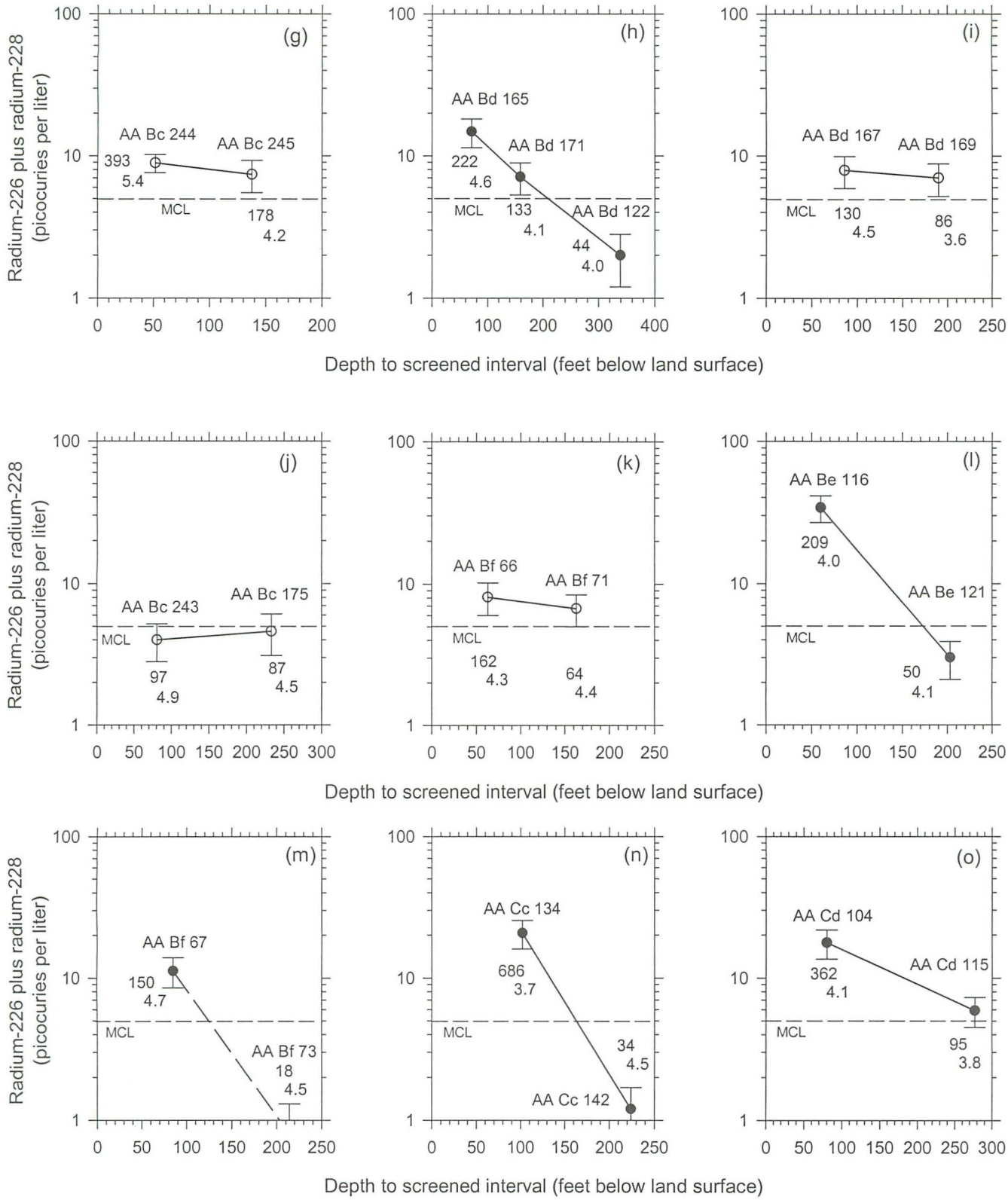


Figure 28 -- Continued

Table 12. Statistical summary of short-term gross alpha-particle activity, short-term gross beta-particle activity, and radium-226 plus radium-228 concentrations, grouped by quartiles corresponding to depth to the middle of the screened interval

[pCi/L, picocuries per liter]

Screened depth quartile range (feet below land surface)	Number of samples	Minimum (pCi/L)	25th percentile (pCi/L)	Median (pCi/L)	75th percentile (pCi/L)	Maximum (pCi/L)
SHORT-TERM GROSS ALPHA-PARTICLE ACTIVITY:						
<97	53	<3.0	4.8	39	99	919
97–165	52	<3.0	3.9	7.7	22	160
166–244	51	<3.0	<3.0	5.8	14	42
>244	51	<3.0	3.0	4.7	7.8	36
SHORT-TERM GROSS BETA-PARTICLE ACTIVITY:						
<104	51	<4.0	4.1	13	35	188
104–176	48	<4.0	4.4	8.2	18	83
177–245	49	<4.0	<4.0	7.0	12	26
>245	49	<4.0	4.4	6.9	8.4	28
RADIUM-226 PLUS RADIUM-228:						
<88	31	4.0	9.9	21	34	66
88-139	30	<1.1	<1.1	5.8	11	22
140–210	30	<1.1	<1.1	3.4	6.3	35
>210	30	<1.1	<1.1	1.9	3.4	9.1

background levels on the western shore of Kent Island (Queen Anne's County) and in some areas in Anne Arundel County due to brackish-water intrusion into the aquifer from the Chesapeake Bay (Drummond, 1988; Fleck and others, 1996). To investigate the relation between radium and chloride concentrations in the Aquia Formation, two Aquia Formation wells having elevated chloride concentrations were sampled for short-term GAPA and GBPA: well AA Df 124, located in the Bay Ridge community southeast of Annapolis (86 mg/L chloride), and QA Db 27, located on the western shore of Kent Island (280 mg/L chloride). Both wells are adjacent to the Chesapeake Bay.

Radionuclide concentrations were lower in samples from the two Aquia wells than in samples with similar pH and specific conductance from the Magothy Formation and Potomac Group (tab. 13). Well QA Fa 77, completed in the Magothy Formation, had a lower specific conductance and higher pH than well AA Df 124, yet had higher short-term GAPA and similar GBPA (fig. 21). If mobilization of radium were occurring due to similar processes in the Aquia Formation and the Magothy Formation, then higher GAPA and GBPA values could be expected in well AA Df 124; these were not seen. QA Db 27 had 280 mg/L chloride, yet the short-term GAPA and GBPA were only 3.0 and 9.5 pCi/L, respectively (tab. 13). Short-term GAPA and GBPA in well QA Db 27 (Aquia Formation) were much lower than those from KE Ac 20 (Potomac Group).

These GAPA and GBPA data, in conjunction with the radon-222 data from the pilot study, suggest that high TDS does not mobilize radium as it does in the

Table 13. Comparison of radionuclide concentrations between wells in the Aquia Formation and wells with similar specific conductance and pH values in the Patapsco and Magothy Formations

[Fm., Formation; Gp., Group; ft, feet below land surface; µS/cm, microsiemens per centimeter at 25 degrees Celsius; pCi/L, picocuries per liter; GAPA, gross alpha-particle activity; GBPA, gross beta-particle activity]

Well	Geologic unit	Top of open interval (ft)	Specific conductance (µS/cm)	pH	Short-term GAPA (pCi/L)	Long-term GAPA (pCi/L)	Short-term GBPA (pCi/L)	Long-term GBPA (pCi/L)
QA Db 27	Aquia Fm.	110	1,310	6.9	3.0	<3.0	9.5	5.6
AA Df 124	Aquia Fm.	22	338	5.1	3.6	<3.0	9.5	5.2
KE Ac 20	Potomac Gp.	550	1,980	6.7	36	8.0	28	23
BA Ff 88	Patapsco Fm.	103	318	4.9	15	4.5	13	10
AA Bc 244	Patapsco Fm.	52	393	5.4	--	7.3	--	22
QA Fa 77	Magothy Fm.	580	257	6.3	9.9	<3.0	9.1	5.4

Magothy Formation and Potomac Group aquifers. The higher radon concentrations in water samples from the Aquia Formation relative to the Magothy and Patapsco Formations indicates that although the Aquia Formation may contain abundant radium-226 near the mineral surfaces (where radon could be ejected into the ground water via alpha recoil), the radium may be too tightly bound within mineral lattices, more strongly sorbed on the mineral surfaces than other exchangeable cations, or otherwise unable to be mobilized in the presence of high-TDS ground water. Differences in aquifer porosity and other factors may also affect ground-water radon concentrations (Wanty and Gundersen, 1987).

The amount of exchangeable calcium and other cations on the mineral surfaces of the Aquia Formation may be a factor in the lack of high radium concentrations. Calcium and magnesium are produced from the dissolution of shell material in the outcrop area of the Aquia Formation. If more calcium and magnesium than radium are available for ion exchange, sodium in ground water may preferentially exchange for calcium rather than radium. Chapelle and Drummond (1983) suggest that the calcium and magnesium from the shell material is quickly exchanged for sodium in the glauconites. Because of the lack of shell material in the Potomac Group and Magothy Formation, there is probably very little calcium on mineral surfaces; thus radium may be the dominant cation available for exchange.

SUMMARY

This study was conducted to provide information on the occurrence and distribution of radium-226, radium-228, and short-term and long-term gross alpha-particle and gross beta-particle activity in the Magothy Formation and Potomac Group aquifers in Anne Arundel County, and to identify other areas in the Coastal Plain of the upper Chesapeake Bay area of Maryland where high radium concentrations may exist in these aquifers. Water samples collected from 203 wells in the study area were analyzed for short-term (measured within 72 hours of sample collection) and long-term (measured 30 days after sample collection) gross alpha-particle and gross beta-particle activity, pH, specific conductance, and dissolved oxygen. Samples from Anne Arundel County were also analyzed for radium-226 and radium-228; additionally,

20 wells were analyzed for major ions.

In Anne Arundel County, radionuclide concentrations in ground water in the Magothy Formation were highest in a three- to four-mile-wide zone extending from the Mountain Road peninsula southwest to Crofton, in or near the outcrop area of the Magothy Formation. All wellwater samples from the Magothy Formation in this zone exceeded the USEPA's MCL of 5 pCi/L for radium-226 plus radium-228. A fairly distinct boundary exists between wells with radium-226 plus radium-228 concentrations greater than 5 pCi/L and those with less than this amount. In the Patapsco Formation, radionuclide concentrations exceeding 5 pCi/L for radium-226 plus radium-228 and 15 pCi/L for short-term GAPA (the MCL) were from wells located in or near the outcrop area, although not all samples from this area exceeded these concentrations. A similar pattern was seen in samples from the Patuxent Formation.

Outside of Anne Arundel County, short-term GAPA and GBPA in the Magothy and Potomac Group aquifers were generally very low. None of the regional wells in the Magothy Formation had short-term GAPA values exceeding 15 pCi/L, although detectable levels (greater than 3 pCi/L) were reported throughout the study area. Short-term GAPA exceeded 15 pCi/L in samples from six regional wells completed in the Patapsco Formation (two wells in Prince George's County and one well each in Baltimore, Harford, Cecil, and Kent Counties). The highest short-term GAPA outside of Anne Arundel County (140 pCi/L) was from a Cecil County well in an area where dissolved solids was considerably higher and pH was lower than ambient ground-water-quality conditions (short-term GAPA from a nearby ambient well was below MCLs). Well KE Ac 20 in Kent County, completed in a deep brackish-water zone of the Patapsco Formation, also had high short-term GAPA, but this well had a near-neutral pH. One of the two wells in the Patuxent Formation exceeded 15 pCi/L for short-term GAPA. The high values of GAPA and GBPA seen in these wells indicates that the potential for high radium concentrations exists throughout the Potomac Group and Magothy Formation aquifers in Maryland.

There was a large percentage decrease in GAPA between the short-term and long-term measurements: the long-term GAPA was between 10 and 40 percent of the short-term GAPA for most samples. This is similar to differences between short-term and long-term GAPA from several samples in the Anne Arundel County pilot study in which radium-224 was detected (Bolton and Hayes, 1999). This suggests that radium-224 comprises a significant percentage of total radium in the Magothy, Patapsco, and Patuxent Formations in the upper Chesapeake Bay area. There was also a significant percentage decrease between the short-term and long-term measurements of GBPA. Individual short-lived beta-emitting isotopes responsible for the decrease were not identified in this study.

Radium, GAPA, and GBPA were negatively correlated with pH. Short-term GAPA exceeded 15 pCi/L in 61 percent of samples with pH values less than 4.5; only about 10 percent of samples with pH values above 4.5 had short-term GAPA above 15 pCi/L. Water samples from many Anne Arundel County wells had pH values less than 4.0, especially those on the Mountain Road peninsula. Potential sources of the acidity are pyrite oxidation and decomposition of organic material. Most samples with specific conductance values greater than 300 μS/cm had short-term GAPA above 15 pCi/L; most samples with specific conductance values less than about 50 μS/cm had short-term GAPA less than 15 pCi/L.

Radium and short-term and long-term GAPA were positively correlated with specific conductance, TDS, sodium, chloride, magnesium, ammonium, nitrate, and potassium; the strongest correlations were with sodium and chloride concentrations. Radium-226 plus radium-228 concentrations exceeded 5 pCi/L in all samples where sodium concentrations and chloride concentrations were greater than about 10 and 15 mg/L, respectively. For samples with sodium and chloride concentrations greater than these amounts, the sodium:chloride molar ratios were almost exactly 1:1, suggesting that the source has a sodium:chloride ratio of 1:1 as well. An 18-well transect across the Mountain Road peninsula showed that the distribution of radium concentrations corresponded very closely to that of chloride concentrations. Potential sodium chloride sources in the study area include de-icing salts applied to roads and driveways, brine water used to backflush water-softening systems, brackish-water intrusion, and septic-system effluent. None of the Magothy or Patapsco wells in this study appear to have been affected by brackish-water intrusion; however, the high dissolved-solids content of brackish water may be expected to mobilize radium in these aquifers. High chloride concentrations (greater than 80 mg/L) in two wells completed in the Aquia Formation were not associated with high levels of short-term GAPA. The relations between radium

concentrations and pH, specific conductance, and major-ion concentrations in the Magothy Formation and Potomac Group aquifers strongly suggest that sorption/desorption processes play a major role in the occurrence of radium in ground water in the area.

Radionuclide concentrations were negatively correlated with depth to the screened interval. Wells with screened intervals less than 100 ft deep had a wide range of radionuclide values, while radionuclides in wells with screened intervals greater than 300 ft deep were almost always below MCLs. For groups of wells adjacent or near one another that had different screen depths, radionuclide concentrations tended to decrease with depth.

Radionuclide concentrations were highest in wells in the updip areas of the aquifers where the wells are shallower, the pH tends to be lower, and specific conductance is often higher than in downdip wells. In the Magothy Formation, the downdip limit of groundwater that exceeds radionuclide MCLs corresponds to an area of decreasing specific conductance, which may correspond to the limit of downgradient migration of human-sourced water-quality constituents. Specific conductance decreased to less than 100 μS/cm at this point and then increased downgradient, possibly due to naturally-occurring weathering reactions in the aquifer. pH levels tended to increase from the outcrop area to the deeper, confined parts of the Magothy Formation.

RECOMMENDATIONS FOR FUTURE STUDY

The data from this study has provided information on the distribution and occurrence of radium and gross alpha-particle and gross beta-particle activity in the Magothy Formation and Potomac Group aquifers in the upper Chesapeake Bay area of Maryland. Additional data are needed in order to understand the details of radium occurrence and mobilization in these aquifers. The following areas of investigation are recommended:

1. Determine the distribution of uranium, thorium, and other radionuclides within the aquifer materials. Both the regional distribution of these elements and their distribution in the aquifer minerals need to be determined.
2. Investigate the cation-exchange capacity and amount of exchangeable cations in the aquifer materials to determine the relation between these factors and radium concentrations in ground water.
3. Evaluate the relative importance of the various sources contributing to TDS of ground water. Site-specific studies of the effects of septic-system effluent, water-softener backflushing, and de-icing salts on radium mobilization would be useful. A comparative study of radionuclides in targeted land-use settings would be helpful.
4. Analyze the processes responsible for generating low-pH ground water in Anne Arundel County. The highest radionuclide concentrations were found in areas where well-water pH is typically less than 4.0.
5. Assess the radionuclide concentrations in wells located near other upland dredged material facilities in Maryland.

GLOSSARY

Activity The number of radioactive decays in a given amount of time. In this report, activities are reported as picocuries per liter (pCi/L).

Anion An ion that has a negative charge. Significant anions in ground water in the study area include chloride, nitrate, sulfate, and bicarbonate (alkalinity).

Aquifer Any subsurface material that yields water in useable quantities.

Cation An ion having a positive charge. Significant cations in ground water in the study area include radium, calcium, potassium, sodium, magnesium, and iron.

Confined aquifer An aquifer that is bounded by confining beds of low permeability. Water levels in wells completed in confined aquifers rise above the top of the aquifer.

Gross alpha-particle activity (GAPA) A measurement of the amount of alpha particles that are generated by the spontaneous decay of alpha-particle-emitting isotopes in a water sample. Radium-224 and radium-226 are alpha-emitting radium isotopes.

Gross beta-particle activity (GBPA) A measurement of the amount of beta particles that are generated by the spontaneous decay of beta-particle-emitting isotopes in a water sample. Radium-228 is a beta-emitting isotope.

Ground water Water that occupies the pore spaces between the grains of aquifer materials (in unconsolidated deposits such as those found in the Maryland Coastal Plain) or in joints, fractures, and bedding planes (in consolidated rocks such as those found in areas outside the Coastal Plain).

Half-life The time required for any given amount of an isotope to be reduced by radioactive disintegration to one-half of the original amount.

Ion exchange The process in which an ion in solution exchanges with another ion on a mineral surface.

Isotopes Different forms of the same element that have the same number of protons but different numbers of neutrons in the nucleus. The three radium isotopes found in the study area are radium-224, radium-226, and radium-228. The number following the element name is equal to the number of protons plus neutrons.

Maximum Contaminant Level (MCL) The maximum permissible level of a contaminant in water which is delivered to any user of a public water system.

Microsiemens per centimeter (µS/cm) A unit of specific conductance; equivalent to micromhos per centimeter.

Milligrams per liter (mg/L) A standard unit used to describe the concentrations of major ions in water. For most ground water, milligrams per liter is approximately equal to parts per million.

Outcrop area The area on the land surface where a geologic formation is exposed at the surface or is covered by a thin layer of overburden or soil.

Oxidation The process in which an element loses an electron.

pH A measure of the acidity or alkalinity of water. pH is defined as the negative logarithm of hydrogen-ion activity (Hem, 1985). Ground water with a pH less than 7 is acidic; ground water with a pH more than 7 is alkaline.

Picocuries per liter (pCi/L) A standard unit of the amount of radioactive decay in a water sample. One picocurie per liter equals approximately 2.2 disintegrations per minute per liter of water, or approximately 1×10^{-9} milligrams per liter (0.000000001 mg/L) of radium-226 plus radium-228.

Radioactive decay series A series of elements that forms sequentially from the spontaneous radioactive decay of a single parent isotope, ending with the formation of a stable isotope.

Radionuclide An isotope of an element that will undergo radioactive decay.

Radium-224 An alpha-emitting radium isotope with a half-life of 3.64 days.

Radium-226 An alpha-emitting radium isotope with a half-life of 1,622 years.

Radium-228 A beta-emitting radium isotope with half-life of 5.75 years.

Recharge The process by which water is replenished to an aquifer.

Specific conductance A measurement of the ability of a water sample to conduct an electric current. It is measured in microsiemens per centimeter (µS/cm) and is standardized to 25 degrees Celsius because it varies with water temperature. Specific conductance is an indicator of the total-dissolved-solids content of a water sample.

Total dissolved solids (TDS) The total amount of

dissolved constituents in a water sample, expressed in milligrams per liter. TDS was determined for this study by evaporating a water sample at 180 degrees Celsius and weighing the dried residue.

Unconfined (water-table) aquifer An aquifer where the water table forms the upper boundary.

Updip; downdip Terms used to describe the relative position in a geologic formation. Updip refers to the area where a formation is relatively close to the land surface (such as in the outcrop area); downdip refers to the area where the formation is relatively deep.

Upgradient; downgradient Terms used to describe the relative position in the groundwater flow system. Upgradient refers to areas of relatively high potentiometric head; downgradient refers to areas with relatively low potentiometric head.

Water table The upper surface of the saturated zone of an unconfined aquifer.

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APPENDIXES

APPENDIX A
WELL CONSTRUCTION AND WELL LOCATION DATA

EXPLANATION:

ft, feet
dd-mm-ss, degrees-minutes-seconds

Use of site:

O	observation
U	unused
W	withdrawal

Use of water:

C	commercial	P	public supply
H	domestic	R	recreational
I	irrigation	S	stock
N	industrial	T	institutional
F	firefighting	U	unused

Drilling method:

H	hydraulic rotary
B	bored or augered
R	reverse rotary
C	cable tool
W	drive, wash
V	driven
P	air percussion
J	jetted

Appendix A. Well construction and well location data

Well number	Latitude (dd-mm-ss)	Longitude (dd-mm-ss)	USGS 7.5-minute quadrangle	Approximate elevation (ft above sea level)	Use of site	Use of water
AA Ac 75	39-12-59	76-40-41	Relay	110	W	H
AA Ac 76	39-10-06	76-42-30	Relay	160	W	H
AA Ad 110	39-10-32	76-38-59	Relay	77	O	U
AA Ae 42	39-11-07	76-33-26	Curtis Bay	65	W	H
AA Ae 43	39-10-57	76-33-27	Curtis Bay	70	W	H
AA Bb 22	39-06-06	76-49-40	Laurel	150	W	C
AA Bb 89	39-06-45	76-49-24	Laurel	230	W	H
AA Bc 163	39-05-24	76-44-25	Odenton	135.11	W	P
AA Bc 175	39-07-36	76-42-14	Relay	195.5	W	P
AA Bc 245	39-09-22	76-41-13	Relay	160	W	H
AA Bc 246	39-05-29	76-40-46	Odenton	225	W	H
AA Bc 248	39-08-12	76-44-43	Relay	280	W	H
AA Bc 249	39-08-24	76-44-00	Relay	220	W	H
AA Bd 107	39-08-01	76-37-23	Curtis Bay	20	W	P
AA Bd 122	39-08-02	76-39-28	Relay	110	W	P
AA Bd 169	39-06-53	76-36-05	Round Bay	140	W	H
AA Bd 170	39-06-53	76-38-21	Odenton	85	W	H
AA Bd 171	39-08-20	76-39-57	Relay	120	W	H
AA Bd 172	39-06-35	76-35-25	Round Bay	140	W	H
AA Bd 173	39-06-53	76-35-39	Round Bay	110	W	H
AA Be 117	39-05-21	76-30-18	Round Bay	40	W	H
AA Be 118	39-09-13	76-33-07	Curtis Bay	35	W	H
AA Be 119	39-05-14	76-34-07	Round Bay	70	W	H
AA Be 120	39-06-35	76-30-30	Round Bay	35	W	H
AA Be 121	39-05-44	76-31-20	Round Bay	20	W	H
AA Be 122	39-06-30	76-31-20	Round Bay	75	W	H
AA Be 123	39-06-45	76-30-05	Round Bay	60	W	C
AA Be 124	39-07-40	76-34-23	Curtis Bay	160	W	T
AA Be 125	39-09-02	76-32-57	Curtis Bay	20	W	H
AA Be 126	39-09-36	76-32-56	Curtis Bay	55	W	H
AA Bf 70	39-06-01	76-27-43	Gibson Island	30	W	H
AA Bf 71	39-08-11	76-27-33	Sparrows Point	25	W	H
AA Bf 72	39-08-39	76-29-34	Sparrows Point	70	W	H
AA Bf 73	39-08-42	76-28-32	Sparrows Point	90	W	H
AA Bf 74	39-05-30	76-25-34	Gibson Island	20	W	H
AA Bf 75	39-06-44	76-27-58	Gibson Island	50	W	H
AA Bf 76	39-05-34	76-28-25	Gibson Island	20	W	H
AA Bf 77	39-06-03	76-28-42	Gibson Island	40	W	H
AA Bf 78	39-05-32	76-28-05	Gibson Island	10	W	H
AA Bf 79	39-06-36	76-28-47	Gibson Island	50	W	H

Well number	Date of construction	Geologic formation	Driller	Drilling method	Well permit number	Depth to top and bottom of well screen (ft below land surface)
AA Ac 75	01-04-1998	Patuxent	Branham Well Drilling	H	AA-94-2250	95-105
AA Ac 76	07-05-1991	Lower Patapsco	H.H. Bunker & Sons	H	AA-88-6234	110-117
AA Ad 110	11-18-1992	Patapsco	Wolford's Well & Pump	B	AA-88-8878	18-28
AA Ae 42	03-14-1994	Patapsco	H.J. Greer & Sons Drilling	H	AA-92-1090	200-205
AA Ae 43	11-09-1993	Patapsco	Wolford's Well & Pump	H	AA-92-0642	118-125
AA Bb 22	05-04-1947	Patuxent	Layne Atlantic	H	AA-00-1432	50.5--60.5
AA Bb 89	03-17-1977	Patuxent	H.H. Bunker & Sons	H	AA-73-6975	117-122
AA Bc 163	02-09-1968	Patuxent	Shannahan Artesian Well	H	AA-68-0667	542-552 573-583
AA Bc 175	10-08-1970	Patapsco	Layne Atlantic	H	AA-71-0122	223-243
AA Bc 245	05-15-1997	Patapsco	Wolford's Well & Pump	H	AA-94-1453	138-145
AA Bc 246	07-29-1994	Patapsco	H.J. Greer & Sons Drilling	H	AA-92-1764	181-186
AA Bc 248	07-18-1978	Patuxent	H.J. Greer & Sons Drilling	H	AA-73-9063	346-351
AA Bc 249	05-30-1996	Lower Patapsco	Allied Environmental Svcs.	H	AA-94-0493	100-107
AA Bd 107	07-08-1969	Patapsco	Layne Atlantic	H	AA-69-1195	185-200 220-240
AA Bd 122	05-03-1982	Patapsco	A.C. Schultes & Sons	H	AA-81-0369	329-349
AA Bd 169	07-07-1992	Upper Patapsco	Atwater Drilling	H	AA-88-7887	190-200
AA Bd 170	04-25-1995	Lower Patapsco	Wolford's Well & Pump	H	AA-93-0629	253-260
AA Bd 171	07-14-1992	Lower Patapsco	Clearwater Well Drilling	H	AA-88-8145	155-162
AA Bd 172	01-08-1994	Patapsco	Island Water Well	H	AA-92-0926	143-150
AA Bd 173	12-07-1992	Patapsco	Wolford's Well & Pump	H	AA-88-8450	143-150
AA Be 117	12-04-1993	Magothy	Wolford's Well & Pump	H	AA-92-0598	80-87
AA Be 118	05-11-1983	Lower Patapsco	Branham Well Drilling	H	AA-81-1681	140-147
AA Be 119	11-21-1997	Patapsco	Frank's Well Drilling	H	AA-94-2128	61-68
AA Be 120	11-06-1992	Patapsco	Branham Well Drilling	H	AA-88-8750	163-170
AA Be 121	07-19-1995	Upper Patapsco	Wolford's Well & Pump	H	AA-93-0948	203-210
AA Be 122	09-30-1997	Upper Patapsco	Allied Environmental Svcs.	H	AA-94-1941	115-120
AA Be 123	11-05-1982	Patapsco	Wolford's Well & Pump	H	AA-81-0980	177-184
AA Be 124	09-02-1972	Patapsco	H.H. Bunker & Sons	H	AA-73-0173	98-103
AA Be 125	02-28-1995	Patapsco	Slater's Well Drilling	H	AA-93-0375	95-102
AA Be 126	01-15-1976	Patapsco	Branham Well Drilling	H	AA-73-5427	120-127
AA Bf 70	03-13-1996	Patapsco	Wolford's Well & Pump	H	AA-94-0238	180-187
AA Bf 71	10-26-1991	Upper Patapsco	Branham Well Drilling	H	AA-88-7027	163-170
AA Bf 72	09-08-1981	Upper Patapsco	Branham Well Drilling	H	AA-74-3608	88-95
AA Bf 73	06-20-1991	Lower Patapsco	Wolford's Well & Pump	H	AA-88-6210	214-221
AA Bf 74	04-13-1998	Magothy	Allied Environmental Svcs.	H	AA-94-2500	93-100
AA Bf 75	11-17-1992	Upper Patapsco	Wolford's Well & Pump	H	AA-88-8353	208-215
AA Bf 76	03-26-1993	Upper Patapsco	Branham Well Drilling	H	AA-88-9437	78-85
AA Bf 77	12-16-1992	Upper Patapsco	Wolford's Well & Pump	H	AA-88-9016	153-160
AA Bf 78	06-11-1991	Upper Patapsco	Branham Well Drilling	H	AA-88-6260	51-58
AA Bf 79	06-03-1997	Upper Patapsco	Keith Jacob	H	AA-94-1549	115-122

Appendix A. Well construction and well location data -- Continued

Well number	Latitude (dd-mm-ss)	Longitude (dd-mm-ss)	USGS 7.5-minute quadrangle	Approximate elevation (ft above sea level)	Use of site	Use of water
AA Bf 80	39-06-28	76-28-54	Gibson Island	60	W	H
AA Bf 81	39-07-09	76-28-41	Gibson Island	40	W	H
AA Bf 82	39-06-08	76-28-34	Gibson Island	40	W	H
AA Bf 83	39-06-57	76-28-40	Gibson Island	50	W	R
AA Bf 84	39-06-32	76-29-31	Gibson Island	50	W	H
AA Bf 85	39-07-27	76-28-34	Gibson Island	45	W	H
AA Bf 86	39-06-36	76-27-54	Gibson Island	80	W	H
AA Bf 87	39-06-14	76-28-36	Gibson Island	50	W	H
AA Bf 88	39-06-47	76-28-42	Gibson Island	50	W	H
AA Bf 89	39-05-56	76-28-25	Gibson Island	40	W	H
AA Bf 90	39-07-53	76-26-01	Sparrows Point	5	W	H
AA Bf 91	39-07-03	76-25-58	Gibson Island	10	W	H
AA Bf 92	39-07-07	76-26-06	Gibson Island	30	W	H
AA Bf 93	39-05-42	76-28-27	Gibson Island	50	W	H
AA Bf 94	39-05-13	76-28-16	Gibson Island	10	W	H
AA Bf 95	39-06-16	76-28-47	Gibson Island	60	W	H
AA Bf 96	39-05-37	76-28-23	Gibson Island	30	W	H
AA Bf 97	39-05-04	76-28-37	Gibson Island	40	W	H
AA Bf 98	39-06-58	76-27-49	Gibson Island	50	W	H
AA Ca 1	39-04-18	76-49-57	Laurel	120	W	R
AA Cb 5	39-04-41	76-46-18	Laurel	100	W	T
AA Cc 123	39-04-19	76-43-19	Odenton	130	W	T
AA Cc 141	39-01-36	76-42-45	Odenton	70	W	H
AA Cc 142	39-01-23	76-41-49	Odenton	90	W	R
AA Cc 143	39-01-43	76-43-25	Odenton	120	W	H
AA Cd 109	39-01-03	76-35-54	Round Bay	140	W	H
AA Cd 110	39-02-05	76-36-10	Round Bay	150	W	H
AA Cd 111	39-04-48	76-39-37	Odenton	200	W	H
AA Cd 112	39-03-43	76-39-08	Odenton	100	W	H
AA Cd 113	39-03-33	76-38-51	Odenton	150	W	T
AA Cd 115	39-04-01	76-35-10	Round Bay	65	W	H
AA Cd 116	39-03-36	76-37-40	Odenton	100	W	T
AA Cd 117	39-00-06	76-37-35	Odenton	140	W	H
AA Cd 118	39-00-40	76-38-07	Odenton	140	W	H
AA Cd 120	39-02-45	76-38-28	Odenton	100	W	H
AA Cd 121	39-02-18	76-38-34	Odenton	135	W	H
AA Cd 122	39-00-27	76-37-52	Odenton	150	W	H
AA Cd 123	39-01-19	76-35-29	Round Bay	130	W	H
AA Cd 124	39-01-51	76-35-40	Round Bay	80	W	H
AA Cd 126	39-00-06	76-39-48	Odenton	150	W	H
AA Cd 127	39-00-19	76-39-36	Odenton	160	W	H

Well number	Date of construction	Geologic formation	Driller	Drilling method	Well permit number	Depth to top and bottom of well screen (ft below land surface)
AA Bf 80	02-17-1993	Upper Patapsco	Wolford's Well & Pump	H	AA-88-9274	78-85
AA Bf 81	10-14-1994	Upper Patapsco	Wolford's Well & Pump	H	AA-92-2093	83-90
AA Bf 82	06-10-1995	Upper Patapsco	Wolford's Well & Pump	H	AA-93-0791	77-84
AA Bf 83	08-17-1990	Upper Patapsco	Wolford's Well & Pump	H	AA-88-4889	83-90
AA Bf 84	09-05-1991	Upper Patapsco	Branham Well Drilling	H	AA-88-6729	83-90
AA Bf 85	09-22-1997	Upper Patapsco	Wolford's Well & Pump	H	AA-94-1877	68-75
AA Bf 86	09-18-1985	Upper Patapsco	Wolford's Well & Pump	H	AA-81-5093	90-97
AA Bf 87	02-13-1998	Upper Patapsco	Allied Environmental Svcs.	H	AA-94-2252	158-165
AA Bf 88	02-24-1996	Upper Patapsco	Allied Environmental Svcs.	H	AA-94-1269	65-72
AA Bf 89	07-29-1998	Upper Patapsco	Wolford's Well & Pump	H	AA-94-2874	81-88
AA Bf 90	03-13-1991	Upper Patapsco	Wolford's Well & Pump	H	AA-88-5870	88-95
AA Bf 91	02-27-1993	Upper Patapsco	Wolford's Well & Pump	H	AA-88-9328	48-55
AA Bf 92	11-23-1991	Upper Patapsco	Wolford's Well & Pump	H	AA-88-7155	133-140
AA Bf 93	08-09-1995	Upper Patapsco	Slater's Well Drilling	H	AA-93-1003	183-190
AA Bf 94	04-18-1978	Magothy	Walter J. Frank	H	AA-73-8930	60-65
AA Bf 95	10-19-1977	Magothy	Slater's Well Drilling	H	AA-73-7907	50-57
AA Bf 96	02-09-1993	Upper Patapsco	Branham Well Drilling	H	AA-88-9205	58-65
AA Bf 97	11-10-1993	Upper Patapsco	Wolford's Well & Pump	H	AA-92-0593	128-135
AA Bf 98	09-26-1997	Upper Patapsco	Frank's Well Drilling	H	AA-94-1912	141-148
AA Ca 1	12-03-1987	Patuxent	H.J. Greer & Sons Drilling	H	AA-81-9579	135-140
AA Cb 5	04-01-1992	Patuxent	CZ Enterprises	H	AA-88-7584	198-218
AA Cc 123	12-12-1984	Patuxent	A.C. Schultes & Sons	R	AA-81-3423	607-630 680-738
AA Cc 141	07-16-1997	Upper Patapsco	Slater's Well Drilling	H	AA-94-1663	180-187
AA Cc 142	07-25-1994	Lower Patapsco	Wolford's Well & Pump	H	AA-92-1577	224-231
AA Cc 143	10-27-1983	Lower Patapsco	H.J. Greer & Sons Drilling	H	AA-81-2350	225-245
AA Cd 109	07-14-1989	Magothy	Branham Well Drilling	H	AA-88-2930	208-215
AA Cd 110	02-05-1990	Magothy	H.J. Greer & Sons Drilling	H	AA-88-3809	213-218
AA Cd 111	11-04-1997	Lower Patapsco	Calvert Well Drilling	H	AA-94-1935	345-360
AA Cd 112	10-21-1996	Upper Patapsco	Wolford's Well & Pump	H	AA-94-0942	92-99
AA Cd 113	12-06-1996	Patapsco	Arundel Well & Pump Svc.	H	AA-94-1048	240-260
AA Cd 115	10-08-1992	Upper Patapsco	Wolford's Well & Pump	H	AA-88-8591	273-280
AA Cd 116	12-30-1970	Upper Patapsco	H.J. Greer & Sons Drilling	H	AA-71-0479	89-94
AA Cd 117	02-25-1976	Magothy	Branham Well Drilling	H	AA-73-5536	213-220
AA Cd 118	12-27-1991	Magothy	Wolford's Well & Pump	H	AA-88-7221	220-227
AA Cd 120	11-09-1992	Magothy	H.J. Greer & Sons Drilling	H	AA-88-8571	125-130
AA Cd 121	05-31-1996	Magothy	H.J. Greer & Sons Drilling	H	AA-94-0366	116-121
AA Cd 122	08-17-1993	Magothy	Wolford's Well & Pump	H	AA-92-0101	228-235
AA Cd 123	03-07-1987	Magothy	Slater's Well Drilling	H	AA-81-7890	183-190
AA Cd 124	11-22-1992	Magothy	Arundel Well & Pump Svc.	H	AA-88-8602	100-105
AA Cd 126	11-04-1996	Magothy	Wolford's Well & Pump	H	AA-94-0996	172-182
AA Cd 127	06-25-1986	Magothy	Branham Well Drilling	H	AA-81-6613	160-170

Appendix A. Well construction and well location data -- Continued

Well number	Latitude (dd-mm-ss)	Longitude (dd-mm-ss)	USGS 7.5-minute quadrangle	Approximate elevation (ft above sea level)	Use of site	Use of water
AA Ce 96	39-04-48	76-34-45	Round Bay	89	W	P
AA Ce 122	39-04-54	76-34-45	Round Bay	62	W	P
AA Ce 143	39-03-08	76-34-33	Round Bay	100	W	H
AA Ce 144	39-01-29	76-34-49	Round Bay	120	W	H
AA Ce 145	39-02-23	76-34-32	Round Bay	40	W	H
AA Ce 147	39-00-48	76-34-40	Round Bay	80	W	S
AA Cf 22	39-04-54	76-25-44	Gibson Island	25	W	P
AA Cf 119	39-02-03	76-29-28	Gibson Island	131.03	W	P
AA Cf 142	39-02-05	76-29-27	Gibson Island	120	W	P
AA Cf 151	39-02-21	76-27-43	Gibson Island	110	W	H
AA Cg 19	39-00-25	76-24-40	Gibson Island	8	W	N
AA Cg 27	39-02-04	76-24-31	Gibson Island	20	W	H
AA Dc 19	38-59-44	76-40-10	Bowie	180	W	H
AA Dd 58	38-59-35	76-38-42	Bowie	130	W	H
AA Dd 59	38-57-28	76-38-22	Bowie	110	W	H
AA Dd 60	38-59-44	76-37-21	South River	120	W	H
AA De 2	38-59-13	76-34-08	South River	14	W	P
AA De 139	38-59-12	76-34-09	South River	55	W	P
AA De 213	38-57-42	76-31-58	South River	20	W	H
AA De 214	38-58-15	76-34-45	South River	100	W	H
AA Df 124	38-56-54	76-27-35	Annapolis	8	W	H
AA Df 158	38-55-29	76-28-32	Annapolis	15	W	H
AA Ec 11	38-55-00	76-40-28	Bowie	60	W	H
BA Ef 59	39-20-24	76-26-06	Middle River	45	W	H
BA Eg 246	39-20-44	76-24-01	Middle River	30	W	H
BA Eg 247	39-22-20	76-22-30	Gunpowder Neck	5	W	H
BA Eg 248	39-22-32	76-23-27	White Marsh	5	W	H
BA Ff 86	39-19-53	76-28-18	Middle River	20	W	H
BA Ff 87	39-17-54	76-25-08	Middle River	10	W	H
BA Ff 88	39-17-40	76-25-58	Middle River	25	W	H
BA Ff 89	39-15-20	76-26-00	Middle River	15	W	H
BA Fg 173	39-16-03	76-23-45	Middle River	20	W	H
BA Fg 174	39-19-50	76-21-58	Gunpowder Neck	5	W	H
BA Fg 175	39-18-43	76-23-06	Middle River	10	W	I
CE Be 122	39-36-54	75-54-56	North East	110	W	C

Well number	Date of construction	Geologic formation	Driller	Drilling method	Well permit number	Depth to top and bottom of well screen (ft below land surface)
AA Ce 96	10-19-1961	Patapsco	Layne Atlantic	H	AA-04-3203	183-198
AA Ce 122	08-18-1975	Patapsco	Layne Atlantic	H	AA-73-4130	390-490 500-530
AA Ce 143	11-13-1993	Magothy	Slater's Well Drilling	H	AA-92-0664	103-110
AA Ce 144	09-19-1996	Magothy	Slater's Well Drilling	H	AA-94-0691	203-210
AA Ce 145	08-13-1997	Magothy	Slater's Well Drilling	H	AA-94-1741	123-130
AA Ce 147	08-10-1992	Magothy	Wolford's Well & Pump	H	AA-88-7950	173-180
AA Cf 22	12- -1950	Patapsco	Layne Atlantic	H	AA-00-6923	304-319
AA Cf 119	08-20-1976	Upper Patapsco	Sydnor Hydrodynamics	H	AA-73-5562	429-432 436-468 474-508 516-554
AA Cf 142	01-27-1990	Lower Patapsco	Sydnor Hydrodynamics	H	AA-88-3644	786-802 810-870 880-900 908-965
AA Cf 151	03-13-1998	Magothy	Wolford's Well & Pump	H	AA-94-2429	261-268
AA Cg 19	11-17-1966	Patapsco	Layne Atlantic	H	AA-67-0122	498-518
AA Cg 27	05-09-1989	Magothy	Slater's Well Drilling	H	AA-88-2552	240-250
AA Dc 19	11-19-1992	Magothy	Slater's Well Drilling	H	AA-88-8858	183-190
AA Dd 58	04-27-1985	Magothy	H.H. Bunker & Sons	H	AA-81-4596	135-142
AA Dd 59	09-29-1977	Magothy	Branham Well Drilling	H	AA-73-7974	235-242
AA Dd 60	04-22-1992	Magothy	Arundel Well & Pump Svc.	H	AA-88-7649	200-205
AA De 2	- -1939	Magothy	Layne Atlantic	--	--	148-156 172-181 202-211 232-250
AA De 139	08-13-1985	Patapsco	Layne Atlantic	H	AA-81-3643	790-870 945-1,090
AA De 213	08-01-1995	Magothy	Slaters's Well Drilling	H	AA-93-1032	233-240
AA De 214	10-16-1997	Magothy	Slater's Well Drilling	H	AA-94-2010	203-210
AA Df 124	02-21-1987	Aquia	H.H. Bunker & Sons	H	AA-81-7771	22-27
AA Df 158	08-06-1992	Magothy	Purner Well Drilling	H	AA-88-8131	305-312
AA Ec 11	05-13-1977	Magothy	Walter J. Frank	H	AA-73-7240	180-185
BA Ef 59	10-31-1996	Patapsco	Frank's Well Drilling	H	BA-94-2207	85-92
BA Eg 246	12-31-1996	Patapsco	Frank's Well Drilling	H	BA-94-2227	109-116
BA Eg 247	12-12-1994	Patapsco	Frank's Well Drilling	H	BA-94-0684	81-88
BA Eg 248	09-26-1996	Patapsco	Frank's Well Drilling	H	BA-94-2000	50-57
BA Ff 86	09-15-1997	Patapsco	Frank's Well Drilling	H	BA-94-2834	63-70
BA Ff 87	04-13-1994	Patapsco	Frank's Well Drilling	H	BA-94-0129	53-60
BA Ff 88	04-27-1994	Patapsco	Frank's Well Drilling	H	BA-94-0144	103-110
BA Ff 89	12-20-1979	Patapsco	William Leonard	H	BA-73-7186	175-180
BA Fg 173	11-21-1997	Patapsco	Frank's Well Drilling	H	BA-94-3064	98-105
BA Fg 174	04-08-1986	Patapsco	Frank's Well Drilling	H	BA-81-4760	33-40
BA Fg 175	08-12-1987	Patapsco	Frank's Well Drilling	H	BA-81-6866	237-250
CE Be 122	12-23-1974	Potomac	Donald S. Newnam	C	CE-73-1092	40-50

Appendix A. Well construction and well location data -- Continued

Well number	Latitude (dd-mm-ss)	Longitude (dd-mm-ss)	USGS 7.5-minute quadrangle	Approximate elevation (ft above sea level)	Use of site	Use of water
CE Bf 87	39-39-10	75-47-55	Newark West	140	W	P
CE Cc 69	39-33-32	76-00-12	Havre De Grace	20	W	H
CE Cc 70	39-34-25	76-02-27	Havre De Grace	120	W	H
CE Cd 86	39-32-41	75-56-35	North East	175	W	T
CE Cd 87	39-34-51	75-58-02	North East	20	W	H
CE Cd 88	39-30-33	75-57-12	North East	140	W	H
CE Ce 57	39-33-30	75-53-12	North East	95	W	P
CE Ce 83	39-33-02	75-53-13	North East	80	W	H
CE Ce 84	39-32-53	75-53-06	North East	80	W	H
CE Ce 85	39-30-09	75-54-09	North East	10	W	H
CE Cf 89	39-31-41	75-49-06	Elkton	40	W	P
CE Dd 85	39-27-23	75-58-13	Earleville	10	W	T
CE Dd 103	39-26-25	75-58-27	Earleville	70	W	P
CE Dd 104	39-28-18	75-58-54	Earleville	70	W	P
CE Dd 105	39-25-58	75-59-23	Earleville	5	W	H
CE Dd 106	39-25-41	75-59-38	Earleville	30	W	H
CE De 56	39-27-39	75-53-35	Earleville	70	W	F
CE De 57	39-29-11	75-50-50	Cecilton	80	W	H
CE Df 41	39-24-56	75-47-27	Cecilton	70	W	C
CE Df 42	39-27-08	75-48-19	Cecilton	75	W	H
CE Df 43	39-26-58	75-47-26	Cecilton	65	W	H
CE Ec 23	39-23-42	76-01-23	Spesutie	60	W	H
CE Ed 27	39-24-31	75-55-59	Earleville	80	W	H
CE Ee 45	39-24-11	75-52-01	Cecilton	80	W	P
CE Ee 54	39-23-41	75-50-37	Cecilton	80	W	H
HA Cf 176	39-31-09	76-06-37	Havre De Grace	40	W	R
HA Cf 177	39-30-02	76-07-38	Aberdeen	20	W	H
HA Dc 120	39-25-37	76-21-07	Edgewood	130	W	H
HA Dd 73	39-25-27	76-17-08	Edgewood	49	W	H
HA Dd 107	39-27-01	76-15-29	Edgewood	20	W	H
HA De 75	39-28-14	76-12-22	Perryman	40	W	P
HA De 164	39-27-38	76-13-28	Perryman	57	W	H
HA De 166	39-26-57	76-13-54	Perryman	17	W	H
HA Ec 48	39-24-46	76-20-44	Edgewood	45	W	H
KE Ac 20	39-20-06	76-07-55	Hanesville	7	O	U
KE Ac 23	39-22-08	76-05-57	Betterton	65	W	H
KE Ad 43	39-21-58	76-03-43	Betterton	82	W	P
KE Ad 60	39-20-02	76-04-37	Betterton	80	W	H
KE Ad 70	39-20-42	76-01-14	Betterton	75	W	H
KE Ae 70	39-21-49	75-58-08	Galena	65	W	H

Well number	Date of construction	Geologic formation	Driller	Drilling method	Well permit number	Depth to top and bottom of well screen (ft below land surface)
CE Bf 87	08-05-1976	Potomac	Delmarva Drilling	R	CE-73-1660	38-68
CE Cc 69	07-28-1993	Potomac	R.J. Seward & Son	H	CE-92-0414	80-90
CE Cc 70	12-08-1997	Potomac	Gurvis Jones Well Drilling	P	CE-94-2243	80-90
CE Cd 86	03-16-1994	Potomac	Shore Well Drillers	V	CE-93-0296	231-241
CE Cd 87	12-12-1995	Potomac	Shore Well Drillers	H	CE-94-1022	50-53
CE Cd 88	10-03-1991	Potomac	American Water Well	H	CE-88-2068	255-270
CE Ce 57	06-29-1981	Potomac	A.C. Schultes & Sons	H	CE-73-3908	240-265
CE Ce 83	12-01-1987	Potomac	Delmarva Drilling	H	CE-81-3426	83-88
CE Ce 84	01-12-1989	Potomac	Delmarva Drilling	H	CE-88-0069	70-85
CE Ce 85	06-02-1997	Potomac	Shore Well Drillers	H	CE-94-1855	75-80
CE Cf 89	06-04-1991	Potomac	Delmarva Drilling	H	CE-88-1648	220-250
CE Dd 85	02-21-1974	Potomac	Delmarva Drilling	H	CE-73-0885	90-120
CE Dd 103	10-07-1997	Potomac	Lifetime Well Drilling	H	CE-94-1759	190-215
CE Dd 104	06-25-1996	Potomac	A.C. Schultes of Maryland	H	CE-94-1324	280-290 300-305 310-320
CE Dd 105	05-18-1977	Potomac	Fred Kielkopf	H	CE-73-2006	106-110
CE Dd 106	06-22-1977	Potomac	Donald S. Newnam	C	CE-73-2075	82-87
CE De 56	06-13-1994	Potomac	Shore Well Drillers	V	CE-94-0065	225-240
CE De 57	01-07-1998	Potomac	Shore Well Drillers	H	CE-94-2223	187-192
CE Df 41	08-09-1989	Potomac	Delmarva Drilling	H	CE-88-0662	335-360
CE Df 42	06-29-1998	Monmouth	Seward	H	CE-94-2494	158-168
CE Df 43	11-20-1992	Monmouth	Lifetime Well Drilling	H	CE-92-0027	100-120
CE Ec 23	05-22-1985	Potomac	Shore Well Drillers	V	CE-81-1425	118-123
CE Ed 27	08-11-1988	Potomac	Lifetime Well Drilling	H	CE-81-4007	125-140
CE Ee 45	05-18-1972	Magothy	Donald S. Newnam	C	CE-72-0111	277-287 287-297
CE Ee 54	08-06-1990	Magothy	Shore Well Drillers	V	CE-88-1305	315-325
HA Cf 176	06-29-1995	Potomac	Jones Well Drilling	H	HA-94-0377	60-70
HA Cf 177	04-03-1996	Potomac	Frank's Well Drilling	H	HA-94-0922	58-65
HA Dc 120	03-09-1982	Potomac	Frank's Well Drilling	H	HA-81-0045	87-107
HA Dd 73	05- -1986	Potomac	Frank's Well Drilling	H	HA-81-2452	117-125
HA Dd 107	06-09-1987	Potomac	Frank's Well Drilling	H	HA-81-3804	70-80
HA De 75	08-15-1966	Potomac	Shannahan Artesian Well	H	HA-66-0813	113-133
HA De 164	07-28-1976	Potomac	William Leonard	H	HA-73-3141	115-120
HA De 166	11-12-1985	Potomac	Frank's Well Drilling	H	HA-81-2322	131-140
HA Ec 48	08-05-1982	Potomac	Frank's Well Drilling	H	HA-81-0250	100-110
KE Ac 20	12-06-1977	Potomac	Sydnor Hydrodynamics	H	KE-73-0658	550-560
KE Ac 23	08-17-1979	Potomac	William Wood	H	KE-73-0906	192-212
KE Ad 43	08-25-1969	Magothy	Delmarva Drilling	H	KE-69-0069	115-140
KE Ad 60	05-01-1985	Magothy	Collier's Well Drilling	H	KE-81-0330	120-140
KE Ad 70	04-16-1971	Potomac	George Kelley	H	KE-71-0074	184-195
KE Ae 70	12-13-1994	Potomac	American Water Well	H	KE-92-0018	228-238

Appendix A. Well construction and well location data -- Continued

Well number	Latitude (dd-mm-ss)	Longitude (dd-mm-ss)	USGS 7.5-minute quadrangle	Approximate elevation (ft above sea level)	Use of site	Use of water
KE Af 29	39-20-27	75-52-43	Galena	70	W	P
KE Af 79	39-21-47	75-52-23	Millington	25	W	H
KE Bb 14	39-16-06	76-12-04	Hanesville	25	W	H
KE Bc 188	39-16-34	76-09-52	Hanesville	40	W	H
KE Bc 189	39-18-03	76-08-58	Hanesville	50	W	H
KE Bc 190	39-15-18	76-08-19	Hanesville	75	W	H
KE Bd 64	39-19-10	76-02-48	Betterton	80	W	C
KE Bd 87	39-17-37	76-03-42	Betterton	70	W	C
KE Be 103	39-18-19	75-57-15	Galena	75	W	S
KE Cb 35	39-13-20	76-10-15	Rock Hall	85	W	P
KE Cb 89	39-14-34	76-12-15	Rock Hall	20	W	T
KE Cb 104	39-13-01	76-14-20	Rock Hall	30	O	U
KE Cd 104	39-12-46	76-03-47	Chestertown	20	W	P
KE Db 57	39-08-12	76-14-14	Rock Hall	15	W	P
KE Eb 14	39-02-18	76-14-09	Langford Creek	15	W	H
PG Bc 37	38-59-17	76-57-20	Washington East	170	O	U
PG Be 33	39-01-02	76-44-57	Odenton	80	W	H
PG Be 34	39-01-12	76-47-02	Laurel	180	W	H
PG Be 35	39-02-48	76-49-38	Laurel	200	W	H
PG Ce 39	38-57-38	76-46-16	Lanham	180	W	H
PG Ce 40	38-55-01	76-46-40	Lanham	140	W	H
PG Ce 41	38-55-24	76-45-53	Lanham	130	W	H
PG Ce 42	38-55-28	76-48-18	Lanham	200	W	T
PG Cf 82	38-58-07	76-42-52	Bowie	110	W	H
PG Cf 83	38-58-41	76-43-03	Bowie	145	W	H
PG Cf 84	38-58-11	76-43-02	Bowie	140	W	H
PG Cf 85	38-55-58	76-42-48	Bowie	100	W	H
PG Cf 86	38-55-20	76-42-09	Bowie	120	W	H
PG Cf 87	38-55-02	76-42-36	Bowie	140	W	H
PG Cf 88	38-58-03	76-43-54	Bowie	125	W	P
PG Cf 89	38-58-13	76-43-48	Bowie	115	W	P
PG Df 38	38-54-27	76-42-47	Bowie	150	W	H
PG Df 39	38-54-05	76-41-54	Bowie	145	W	H
QA Db 27	39-01-17	76-19-13	Love Point	15	W	H
QA Db 44	39-00-40	76-18-56	Love Point	10	W	H
QA Ea 86	38-56-16	76-20-58	Kent Island	15	W	R
QA Ea 87	38-55-02	76-20-54	Kent Island	5	W	H
QA Eb 167	38-58-50	76-18-36	Stevensville	15	W	P
QA Eb 168	38-57-10	76-17-35	Kent Island	15	W	P

Well number	Date of construction	Geologic formation	Driller	Drilling method	Well permit number	Depth to top and bottom of well screen (ft below land surface)
KE Af 29	08-03-1970	Potomac	Shannahan Artesian Well	H	KE-70-0063	454-474
KE Af 79	11-17-1990	Magothy	American Water Well	H	KE-88-0096	290-300
KE Bb 14	01-21-1983	Magothy	Kelley Well Drilling	H	KE-81-0077	62-72
KE Bc 188	07-06-1995	Magothy	Lifetime Well Drilling	H	KE-92-0076	100-105
KE Bc 189	10-05-1990	Potomac	American Water Well	H	KE-88-0065	150-160
KE Bc 190	07-24-1990	Magothy	Lifetime Well Drilling	H	KE-88-0008	240-260
KE Bd 64	04-18-1989	Magothy	American Water Well	H	KE-81-1195	210-230
KE Bd 87	03-13-1958	Magothy	Ennis Bros	W	KE-02-9953	255-265
KE Be 103	06-14-1958	Magothy	Ennis Bros	W	KE-03-1071	368-373
KE Cb 35	09-30-1969	Potomac	Lester V. Lien	H	KE-70-0015	280-300
KE Cb 89	06-16-1964	Magothy	Delmarva Drilling	H	KE-05-7687	110-130
KE Cb 104	09-04-1990	Magothy	American Water Well	H	KE-81-1470	104-114
KE Cd 104	05-27-1981	Potomac	Shannahan Artesian Well	H	KE-73-1097	392-416 416-428
KE Db 57	10-04-1988	Magothy	Delmarva Drilling	R	KE-81-1278	280-290 302-322 349-359
KE Eb 14	02-25-1992	Magothy	CZ Enterprises	H	KE-88-0321	590-630
PG Bc 37	09-22-1984	Patuxent	OEP Waste Mgmt. Admin.	B	PG-81-0661	15-25
PG Be 33	10-19-1984	Patapsco	East Coast Well & Pump	H	PG-81-0355	241-248
PG Be 34	08-11-1977	Patapsco	Walter J. Frank	H	PG-73-0753	175-180
PG Be 35	06-11-1996	Lower Patapsco	H.J. Greer & Sons Drilling	H	PG-92-0679	121-126
PG Ce 39	02-07-1982	Magothy	East Coast Well & Pump	H	PG-73-1378	122-132
PG Ce 40	10-10-1989	Magothy	East Coast Well & Pump	H	PG-81-2048	190-195
PG Ce 41	03-21-1990	Magothy	Wolford's Well & Pump	H	PG-88-0536	200-207
PG Ce 42	04-26-1986	Magothy	H.H. Bunker & Sons	H	PG-81-1164	165-172
PG Cf 82	12-29-1982	Magothy	East Coast Well & Pump	H	PG-81-0242	150-160
PG Cf 83	09-14-1989	Patapsco	Branham Well Drilling	H	PG-88-0526	228-235
PG Cf 84	11-07-1996	Patapsco	Frank's Well Drilling	H	PG-94-0111	250-260
PG Cf 85	08-01-1995	Magothy	Frank's Well Drilling	H	PG-92-0675	230-240
PG Cf 86	12-31-1996	Magothy	Arundel Well & Pump Svc.	H	PG-92-0958	215-225
PG Cf 87	03-08-1993	Patapsco	Atwater Drilling	H	PG-88-2568	345-355
PG Cf 88	--	Patapsco	--	--	--	443-573 604-698
PG Cf 89	08-25-1989	Patuxent	W. C. Services	H	PG-88-0226	1,143-1,153
PG Df 38	05-05-1996	Magothy	Atwater Drilling	H	PG-92-0907	262-272
PG Df 39	06-10-1992	Magothy	Atwater Drilling	H	PG-88-1570	282-292
QA Db 27	02-17-1966	Aquia	A. W. Hudson	J	QA-66-0101	111-145
QA Db 44	04-24-1989	Magothy	Branham Well Drilling	H	QA-88-0317	393-400
QA Ea 86	--	Patapsco	--	--	--	--
QA Ea 87	12-18-1986	Magothy	Collier's Well Drilling	H	QA-81-1950	595-615
QA Eb 167	03-16-1996	Upper Patapsco	A.C. Schultes of Delaware	R	QA-94-0318	606-688 722-760
QA Eb 168	04-23-1988	Upper Patapsco	Queenstown Well Drilling	H	QA-81-2673	720-740

Appendix A. Well construction and well location data -- Continued

Well number	Latitude (dd-mm-ss)	Longitude (dd-mm-ss)	USGS 7.5-minute quadrangle	Approximate elevation (ft above sea level)	Use of site	Use of water
QA Eb 173	38-58-17	76-18-50	Kent Island	5	W	P
QA Eb 181	38-59-12	76-19-26	Kent Island	15	W	P
QA Ec 91	38-57-48	76-11-24	Queenstown	18	W	P
QA Fa 77	38-54-40	76-21-18	Kent Island	10	W	R
QA Fa 79	38-51-23	76-20-42	Claiborne	5	W	H
QA Fa 81	38-53-00	76-21-08	Kent Island	10	W	H
QA Fa 82	38-51-17	76-22-23	Claiborne	10	W	H
QA Fb 3	38-55-01	76-18-03	Kent Island	5	W	H

Well number	Date of construction	Geologic formation	Driller	Drilling method	Well permit number	Depth to top and bottom of well screen (ft below land surface)
QA Eb 173	02-20-1985	Upper Patapsco	Shannahan Artesian Well	H	QA-81-0893	658-693
QA Eb 181	04-24-1986	Magothy	Delmarva Drilling	H	QA-81-1494	455-485
QA Ec 91	04-29-1995	Upper Patapsco	A.C. Schultes of Maryland	H	QA-92-0457	826-836 842-872 880-900 922-952
QA Fa 77	04-08-1986	Magothy	Collier's Well Drilling	H	QA-81-1498	580-620
QA Fa 79	08-16-1994	Magothy	Shannahan Artesian Well	H	QA-92-0135	625-645
QA Fa 81	05-13-1993	Magothy	Collier's Well Drilling	H	QA-88-1730	630-640
QA Fa 82	10-04-1994	Magothy	Shannahan Artesian Well	H	QA-92-0238	615-635
QA Fb 3	05-18-1987	Patapsco	Shannahan Artesian Well	H	QA-81-2125	780-790

APPENDIX B

CHEMICAL CONSTITUENTS, MINIMUM REPORTING LEVELS, SAMPLE TREATMENT, AND ANALYTICAL METHODS

Appendix B1. Chemical and radiological constituents analyzed in this study

Appendix B2. Sample container designations, container descriptions, and sample preservation and treatment

Appendix B1. Chemical and radiological constituents analyzed in this study

[pCi/L, picocuries per liter; µg/L, micrograms per liter; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; AA, atomic absorption; ICP, inductively-coupled plasma; IC, ion-exchange chromatography; NWQL, U.S. Geological Survey National Water Quality Laboratory; Q, Quanterra Environmental Services; MDH, Maryland Department of Health and Mental Hygiene Laboratory. Sample container designations are described in appendix B2]

Constituent	Type of analysis	EPA method or reference	Minimum reporting level	Laboratory	Sample container designation
Radium-226	Precipitation; planchet counting	903.0	0.1 pCi/L	Q	FAR
Radium-228	Radiochemical separation and beta counting	904.0	1.0 pCi/L	Q	FAR
Gross alpha-particle activity (short-term and long-term)	Residue procedure	900.0	3.0 pCi/L	NWQL	FAR
Gross beta-particle activity (short-term and long-term)	Residue procedure	900.0	4.0 pCi/L	NWQL	FAR
Calcium	ICP	Fishman (1993)	0.02 mg/L	NWQL	FA
Magnesium	ICP	Fishman (1993)	0.01 mg/L	NWQL	FA
Sodium	ICP	Fishman (1993)	0.2 mg/L	NWQL	FA
Potassium	AA	Fishman and Friedman (1989)	0.1 mg/L	NWQL	FA
Chloride[1]	IC	Fishman and Friedman (1989)	0.1 mg/L	NWQL	FU
Chloride[2]	Colorimetric	325.2	10 mg/L	MDH	CC
Sulfate	IC	Fishman and Friedman (1989)	0.1 mg/L	NWQL	FU
Alkalinity	Electrometric	Fishman and Friedman (1989)	1 mg/L as $CaCO_3$	NWQL[3]	FU
Fluoride	Colorimetric	Fishman and Friedman (1989)	0.1 mg/L	NWQL	FU
Iron (filtered)	ICP	Fishman (1993)	3 µg/L	NWQL	FA
Iron (unfiltered)	AA	Garbarino and Struzeski (1998)	10 µg/L	NWQL	RA
Manganese (filtered)	ICP	Fishman (1993)	1 µg/L	NWQL	FA
Manganese (unfiltered)	AA	Garbarino and Struzeski (1998)	10 µg/L	NWQL	RA
Silica	Colorimetric	Fishman and Friedman (1989)	0.1 mg/L as SiO_2	NWQL	FU
Residue on evaporation at 180 degrees Celsius	Gravimetric	Fishman and Friedman (1989)	1 mg/L	NWQL	FU

Appendix B1. --Continued

Constituent	Type of analysis	EPA method or reference	Minimum reporting level	Laboratory	Sample container designation
pH	Electrometric	Fishman and Friedman (1989)	--	NWQL[3]	RU
Specific conductance	Electrometric	Fishman and Friedman (1989)	1 µS/cm	NWQL[3]	RU
Color	Electrometric	Fishman and Friedman (1989)	1.0 color units	NWQL	RCB
Nitrate plus nitrite (as nitrogen)[1]	Colorimetric	Fishman (1993)	0.05 mg/L	NWQL	FCC
Nitrate plus nitrite (as nitrogen)[2]	Colorimetric	353.2	0.2 mg/L	MDH	CN
Nitrite	Colorimetric	Fishman (1993)	0.010 mg/L	NWQL	FCC
Ammonia (as N)	Colorimetric	Fishman (1993)	0.02 mg/L	NWQL	FCC
Orthophosphate	Colorimetric	Fishman (1993)	0.010 mg/L	NWQL	FCC
Phosphorus	Colorimetric	Patton and Truitt (1992)	0.05 mg/L	NWQL	FCC
Dissolved oxygen	Titration or electrometric	360.2[4] 360.1[5]	1.0 mg/L[4] 0.1 mg/L[5]	field	BOD

[1] For samples collected before 10/98.
[2] For samples collected after 10/98.
[3] Also measured in the field.
[4] Titration method.
[5] Electrometric method.

Appendix B2. Sample container designations, container descriptions, and sample preservation and treatment

[μ, micron; <, less than]

Sample container designation	Container description	Sample preservation and treatment
FAR	Polyethylene bottle, acid-rinsed	Unfiltered, acidified with HNO_3 to pH<2.
FA	Polyethylene bottle, acid-rinsed	0.45μ-filtered, acidified with HNO_3 to pH<2 in bottle rinsed with filtered sample water.
FU	Polyethylene bottle	0.45μ-filtered, in bottle rinsed with filtered sample water.
RA	Polyethylene bottle, acid-rinsed	Unfiltered, acidified with HNO_3 to pH<2 in bottle rinsed with sample water.
RU	Polyethylene bottle	Unfiltered, in bottle rinsed with sample water.
RCB	Polyethylene bottle	Unfiltered, chilled and maintained at 4 degrees Celsius in bottle rinsed with sample water.
FCC	Opaque polyethylene bottle	0.45μ-filtered, chilled and maintained at 4 degrees Celsius in bottle rinsed with filtered sample water.
CN	Polyethylene bottle	Unfiltered, acidified with H_2SO_4 to pH<2 in bottle rinsed with sample water; chilled and maintained at 4 degrees Celsius; delivered to lab the same day.
CC	Polyethylene bottle	Unfiltered, in bottle rinsed with sample water, chilled and maintained at 4 degrees Celsius; delivered to lab the same day.
BOD	Glass-stoppered glass bottle	None (sample titrated immediately after collection).

APPENDIX C
WATER-QUALITY DATA

Appendix C1. Radionuclides and field water-quality data from well-water samples in the upper Chesapeake Bay area, Maryland

Appendix C2. Major ions and field water-quality data from well-water samples in the upper Chesapeake Bay area, Maryland

Water-quality data from the 20 Magothy and Patapsco Formation wells sampled during the Anne Arundel County pilot study are not included in these data tables. They can be found in Bolton and Hayes [1999]).

ABBREVIATIONS:

µS/cm	microsiemens per centimeter at 25 degrees Celsius
mg/L	milligrams per liter
µg/L	micrograms per liter
ROE	residue on evaporation at 180 degrees Celsius
$CaCO_3$	calcium carbonate
SiO_2	silicon dioxide
2 sigma	total analytical error (2 standard deviations)
S-T GAPA	short-term gross alpha particle activity
L-T GAPA	long-term gross alpha particle activity
S-T GBPA	short-term gross beta particle activity
L-T GBPA	long-term gross beta particle activity
pCi/L	picocuries per liter

Appendix C1. Radionuclides and field water-quality data from well-water samples in the upper Chesapeake Bay area, Maryland

Well number	Date sampled	Specific conductance (µS/cm)	pH	Dissolved oxygen (mg/L)	S-T GAPA (pCi/L)	2 sigma S-T GAPA (pCi/L)	L-T GAPA (pCi/L)	2 sigma L-T GAPA (pCi/L)
AA Ac 75	06-09-98	177	4.5	6.8	15	3.7	4.8	2.5
AA Ac 76	06-23-98	61	4.9	8.1	4.2	2.2	<3.0	1.6
AA Ad 110	10-05-98	207	5.9	<1.0	<3.0	2.1	<3.0	1.9
AA Ae 42	10-26-98	50	3.4	<1.0	23	4.4	8.4	2.9
AA Ae 43	11-02-98	32	4.4	0.2	<3.0	1.9	<3.0	1.6
AA Bb 22	06-08-98	1,130	5.3	1.5	70	11	23	6.7
AA Bb 89	11-09-98	110	4.4	1.7	34	5.3	13	3.5
AA Bc 163	11-04-98	34	4.5	0.3	9.3	3.0	<3.0	1.6
AA Bc 175	06-08-98	87	4.5	8.5	12	3.3	<3.0	1.9
AA Bc 245	06-09-98	178	4.2	7.4	22	4.4	4.2	2.3
AA Bc 246	06-24-98	41	4.7	8.4	11	3.2	<3.0	1.8
AA Bc 248	11-18-98	119	4.4	0.3	20	4.2	18	4.1
AA Bc 249	06-23-98	137	4.8	6.0	13	3.5	4.2	2.3
AA Bd 107	06-15-98	76	4.2	7.2	14	3.4	4.2	2.2
AA Bd 122	06-08-98	44	4.0	4.5	3.5	2.0	<3.0	1.6
AA Bd 169	06-10-98	86	3.6	1.0	25	4.5	10	3.0
AA Bd 170	06-10-98	35	4.1	8.3	3.5	2.0	<3.0	1.5
AA Bd 171	06-18-98	133	4.1	4.1	15	3.7	6.2	2.6
AA Bd 172	10-21-98	116	4.8	4.9	21	4.4	4.6	2.3
AA Bd 173	11-18-98	60	5.8	6.5	13	3.4	4.0	2.3
AA Be 117	06-09-98	155	3.4	1.1	44	6.0	12	3.4
AA Be 118	06-09-98	71	3.7	1.1	7.7	2.7	<3.0	1.8
AA Be 119	06-24-98	100	3.4	8.7	39	5.6	5.1	2.4
AA Be 120	06-18-98	36	4.9	5.6	<3.0	2.0	<3.0	1.5
AA Be 121	06-30-98	50	4.1	1.1	5.8	2.4	3.4	2.1
AA Be 122	07-22-98	40	4.3	8.3	8.5	2.9	3.3	2.2
AA Be 123	10-20-98	88	5.0	9.7	29	4.9	3.8	2.2
AA Be 124	06-24-98	268	4.2	9.6	45	6.4	7.9	3.0
AA Be 125	11-02-98	50	3.8	0.2	8.5	2.9	<3.0	1.7
AA Be 126	11-04-98	84	4.0	0.2	15	3.6	5.4	2.4
AA Bf 70	06-25-98	143	3.8	1.0	21	4.3	3.1	2.1
AA Bf 71	06-18-98	64	4.4	4.5	16	3.7	3.3	2.0
AA Bf 72	06-23-98	88	5.0	6.9	14	3.6	<3.0	2.0
AA Bf 73	06-30-98	18	4.5	8.4	<3.0	1.7	<3.0	1.5
AA Bf 74	06-25-98	83	5.6	1.0	<3.0	1.8	<3.0	1.5
AA Bf 75	07-06-98	154	6.1	0.7	42	6.1	7.2	2.9
AA Bf 76	10-11-98	290	3.7	<1.0	90	8.8	18	4.2
AA Bf 77	10-20-98	691	3.6	0.2	160	13	68	8.7
AA Bf 78	10-13-98	230	3.7	<1.0	98	9.1	15	3.7
AA Bf 79	10-14-98	122	5.3	0.2	31	5.2	11	3.3
AA Bf 80	10-26-98	232	3.2	<1.0	206	13	46	6.3
AA Bf 81	10-14-98	116	3.7	0.3	41	5.8	20	4.1
AA Bf 82	10-28-98	559	3.7	<1.0	218	15	133	12

Well number	Date sampled	S-T GBPA (pCi/L)	2-sigma S-T GBPA	L-T GBPA (pCi/L)	2 sigma L-T GBPA (pCi/L)	Radium-226 (pCi/L)	2 sigma Radium-226 (pCi/L)	Radium-228 (pCi/L)	2 sigma Radium-228 (pCi/L)
AA Ac 75	06-09-98	13	4.2	7.8	3.9	1.8	0.47	2.3	0.7
AA Ac 76	06-23-98	6.0	3.8	<4.0	3.5	0.3	0.12	<1.0	0.5
AA Ad 110	10-05-98	4.1	3.9	4.0	3.8	--	--	--	--
AA Ae 42	10-26-98	13	4.1	8.3	3.9	1.5	0.447	3.3	0.9
AA Ae 43	11-02-98	<4.0	3.6	<4.0	3.6	0.2	0.107	<1.0	0.4
AA Bb 22	06-08-98	39	5.6	25	5.0	11	2.24	12	2.9
AA Bb 89	11-09-98	22	4.5	16	4.3	4.7	1.08	4.6	1.2
AA Bc 163	11-04-98	<4.0	3.7	<4.0	3.7	0.7	0.25	1.2	0.5
AA Bc 175	06-08-98	10	4.0	5.7	3.8	1.8	0.493	2.8	0.8
AA Bc 245	06-09-98	16	4.3	11	4.0	2.3	0.579	5.1	1.3
AA Bc 246	06-24-98	11	4.0	5.7	3.7	0.6	0.179	3.1	0.9
AA Bc 248	11-18-98	20	4.4	14	4.1	4	0.865	5.1	1.4
AA Bc 249	06-23-98	11	4.0	4.3	3.7	1.7	0.4	2.6	0.8
AA Bd 107	06-15-98	12	4.1	7.0	3.8	1.6	0.435	2.7	0.8
AA Bd 122	06-08-98	5.1	3.7	<4.0	3.6	0.9	0.304	1.1	0.5
AA Bd 169	06-10-98	17	4.3	9.2	3.9	2.9	0.691	4.1	1.1
AA Bd 170	06-10-98	5.4	3.8	<4.0	3.6	0.7	0.237	1.8	0.6
AA Bd 171	06-18-98	13	4.1	7.6	3.9	3.8	0.885	3.3	0.9
AA Bd 172	10-21-98	18	4.3	11	3.9	1.4	0.401	4.9	1.3
AA Bd 173	11-18-98	12	4.0	8.3	3.9	1.1	0.285	3	0.9
AA Be 117	06-09-98	28	4.7	17	4.3	3.5	0.802	8.2	2
AA Be 118	06-09-98	7.2	3.8	4.8	3.7	0.7	0.229	1.8	0.6
AA Be 119	06-24-98	29	4.7	16	4.2	1.3	0.314	8	1.9
AA Be 120	06-18-98	4.5	3.7	<4.0	3.6	0.4	0.195	<1.0	0.4
AA Be 121	06-30-98	7.3	3.8	4.6	3.6	0.8	0.224	2.2	0.7
AA Be 122	07-22-98	9.8	3.9	6.2	3.8	1.4	0.37	2.5	0.7
AA Be 123	10-20-98	16	4.2	11	4.0	1.4	0.417	4.4	1.1
AA Be 124	06-24-98	34	5.0	16	4.3	3.8	0.795	9.2	2.2
AA Be 125	11-02-98	6.7	3.8	6.3	3.8	0.3	0.157	1.4	0.6
AA Be 126	11-04-98	8.9	3.9	5.4	3.8	0.9	0.324	1.4	0.5
AA Bf 70	06-25-98	12	4.1	5.6	3.7	2.5	0.555	3	0.8
AA Bf 71	06-18-98	17	4.3	11	4.0	1.6	0.437	5.1	1.3
AA Bf 72	06-23-98	14	4.1	6.1	3.8	1.3	0.327	3.9	1
AA Bf 73	06-30-98	<4.0	3.5	<4.0	3.4	0.2	0.092	<1.0	0.5
AA Bf 74	06-25-98	<4.0	3.6	<4.0	3.5	0.2	0.078	<1.0	0.3
AA Bf 75	07-06-98	26	4.7	13	4.1	2	0.488	7	1.7
AA Bf 76	10-11-98	53	5.7	27	4.6	5.7	1.28	15	3.3
AA Bf 77	10-20-98	83	6.7	65	6.1	14	2.82	21	4.7
AA Bf 78	10-13-98	58	5.9	36	5.0	5.3	1.17	18	4
AA Bf 79	10-14-98	21	4.6	15	4.2	2.7	0.669	4.1	1.1
AA Bf 80	10-26-98	127	7.7	72	6.3	9.5	2.01	31	6.7
AA Bf 81	10-14-98	25	4.7	19	4.3	6.4	1.56	5.6	1.4
AA Bf 82	10-28-98	138	8.1	124	7.8	28	5.68	34	7.4

Appendix C1. Radionuclides and field water-quality data from well-water samples in the upper Chesapeake Bay area, Maryland -- Continued

Well number	Date sampled	Specific conductance (µS/cm)	pH	Dissolved oxygen (mg/L)	S-T GAPA (pCi/L)	2 sigma S-T GAPA (pCi/L)	L-T GAPA (pCi/L)	2 sigma L-T GAPA (pCi/L)
AA Bf 83	10-19-98	251	3.6	0.1	110	9.6	55	6.9
AA Bf 84	10-19-98	232	4.4	5.0	72	8.0	28	5.1
AA Bf 85	10-14-98	74	3.8	0.4	42	5.8	8.6	2.8
AA Bf 86	10-20-98	230	4.8	0.2	49	6.8	9.2	3.2
AA Bf 87	10-19-98	307	3.7	0.1	64	7.5	27	4.9
AA Bf 88	10-19-98	409	3.5	0.2	321	17	100	9.6
AA Bf 89	10-20-98	134	4.0	0.1	44	6.1	16	3.8
AA Bf 90	10-21-98	90	4.2	0.9	42	5.9	8.7	2.9
AA Bf 91	10-21-98	386	4.5	6.0	71	8.3	13	3.8
AA Bf 92	10-26-98	45	4.9	<1.0	<3.0	2.0	<3.0	1.7
AA Bf 93	10-28-98	177	3.1	<1.0	23	4.5	7.0	2.8
AA Bf 94	10-26-98	81	5.3	<1.0	26	4.8	11	3.3
AA Bf 95	11-02-98	1,360	3.3	0.3	426	27	69	11
AA Bf 96	11-02-98	1,400	3.5	0.4	351	25	90	13
AA Bf 97	11-02-98	63	3.9	0.2	33	5.2	7.4	2.7
AA Bf 98	11-18-98	144	3.8	0.4	27	4.8	9.8	3.1
AA Ca 1	11-09-98	26	5.1	9.1	<3.0	1.8	<3.0	1.8
AA Cb 5	06-08-98	34	4.3	6.5	6.3	2.5	<3.0	1.4
AA Cc 123	11-04-98	32	4.8	1.1	7.7	2.8	<3.0	1.7
AA Cc 141	06-16-98	65	4.5	1.2	5.5	2.3	<3.0	1.9
AA Cc 142	07-06-98	34	4.5	0.5	4.1	2.2	<3.0	1.7
AA Cc 143	10-28-98	48	3.9	<1.0	9.5	3.1	6.1	2.6
AA Cd 109	06-10-98	73	3.9	0.9	<3.0	1.4	<3.0	1.5
AA Cd 110	06-09-98	211	3.2	1.1	27	4.8	11	3.3
AA Cd 111	06-16-98	45	5.4	9.0	<3.0	1.8	<3.0	1.8
AA Cd 112	09-21-98	207	3.8	7.0	23	4.7	10	3.4
AA Cd 113	06-23-98	33	5.3	--	<3.0	1.9	<3.0	1.3
AA Cd 115	07-08-98	95	3.8	0.3	22	4.3	5.9	2.5
AA Cd 116	06-08-98	191	4.3	9.1	35	5.5	8.4	3.0
AA Cd 117	10-27-98	119	4.0	<1.0	11	3.3	3.7	2.2
AA Cd 118	10-27-98	91	3.9	<1.0	12	3.4	4.2	2.3
AA Cd 120	10-27-98	121	3.3	6.4	97	8.7	22	4.4
AA Cd 121	10-27-98	200	3.9	7.0	78	8.1	22	4.5
AA Cd 122	11-04-98	99	4.0	0.2	15	3.6	4.2	2.3
AA Cd 123	11-09-98	79	5.2	0.2	<3.0	1.6	<3.0	1.4
AA Cd 124	11-09-98	211	3.9	0.3	7.3	2.8	4.2	2.4
AA Cd 126	11-04-98	123	4.1	0.2	8.0	2.9	5.2	2.5
AA Cd 127	11-16-98	129	4.1	0.3	3.8	2.2	<3.0	1.9
AA Ce 96	06-15-98	74	3.0	7.5	23	4.4	3.1	2.1
AA Ce 122	06-15-98	53	4.4	1.3	12	3.2	<3.0	1.8
AA Ce 143	06-18-98	227	3.7	2.4	51	6.5	9.5	3.1
AA Ce 144	10-28-98	90	4.0	<1.0	14	3.6	3.1	2.1
AA Ce 145	10-28-98	135	3.7	<1.0	34	5.3	10	3.1

Well number	Date sampled	S-T GBPA (pCi/L)	2-sigma S-T GBPA	L-T GBPA (pCi/L)	2 sigma L-T GBPA (pCi/L)	Radium-226 (pCi/L)	2 sigma Radium-226 (pCi/L)	Radium-228 (pCi/L)	2 sigma Radium-228 (pCi/L)
AA Bf 83	10-19-98	64	6.0	51	5.5	10	2.1	15	3.5
AA Bf 84	10-19-98	50	5.5	36	5.0	9	1.89	13	3
AA Bf 85	10-14-98	35	5.1	15	4.1	2.1	0.566	6.7	1.7
AA Bf 86	10-20-98	35	5.0	22	4.5	3.1	0.738	9.4	2.2
AA Bf 87	10-19-98	33	5.0	25	4.6	6.1	1.35	7.1	1.7
AA Bf 88	10-19-98	180	8.9	115	7.4	21	4.31	36	7.8
AA Bf 89	10-20-98	32	4.9	18	4.3	3.3	0.786	5.9	1.5
AA Bf 90	10-21-98	31	4.8	15	4.1	2.9	0.695	6.5	1.6
AA Bf 91	10-21-98	50	5.6	28	4.8	4.8	1.09	14	3.2
AA Bf 92	10-26-98	<4.0	3.7	<4.0	3.6	0.4	0.182	<1.0	0.4
AA Bf 93	10-28-98	16	4.3	10	4.1	1.4	0.41	3.3	1
AA Bf 94	10-26-98	22	4.5	9.6	4.0	3.2	0.757	4.5	1.2
AA Bf 95	11-02-98	188	9.6	98	7.5	12	2.48	44	9.6
AA Bf 96	11-02-98	140	8.6	82	7.1	24	4.74	40	8.8
AA Bf 97	11-02-98	27	4.7	10	4.0	1.8	0.475	4.8	1.3
AA Bf 98	11-18-98	20	4.3	16	4.2	1.6	0.382	4.3	1.2
AA Ca 1	11-09-98	<4.0	3.6	<4.0	3.6	0.3	0.168	<1.0	0.5
AA Cb 5	06-08-98	7.8	3.9	<4.0	3.6	0.6	0.24	1.8	0.6
AA Cc 123	11-04-98	4.0	3.7	<4.0	3.7	0.7	0.276	1	0.5
AA Cc 141	06-16-98	4.3	3.7	4.8	3.7	0.5	0.214	1.5	0.6
AA Cc 142	07-06-98	<4.0	3.6	<4.0	3.5	0.2	0.102	1	0.4
AA Cc 143	10-28-98	14	4.2	5.5	3.8	0.6	0.238	<1.0	0.4
AA Cd 109	06-10-98	5.2	3.8	<4.0	3.7	0.3	0.145	<1.0	0.4
AA Cd 110	06-09-98	19	4.4	11	4.0	2.3	0.569	4.6	1.2
AA Cd 111	06-16-98	<4.0	3.5	4.5	3.7	0.2	0.133	<1.0	0.4
AA Cd 112	09-21-98	23	4.6	18	4.4	3.7	0.85	7.7	1.9
AA Cd 113	06-23-98	5.4	3.7	<4.0	3.6	0.1	0.075	1.1	0.5
AA Cd 115	07-08-98	10	4.0	11	3.9	1.9	0.44	3.9	1
AA Cd 116	06-08-98	27	4.7	19	4.4	5.1	1.15	8.6	2
AA Cd 117	10-27-98	11	4.0	5.3	3.8	0.7	0.25	1.4	0.5
AA Cd 118	10-27-98	12	4.1	<4.0	3.6	1.5	0.438	2.4	0.7
AA Cd 120	10-27-98	61	5.8	27	4.7	5.7	1.27	16	3.6
AA Cd 121	10-27-98	46	5.4	27	4.8	9.6	1.97	12	2.8
AA Cd 122	11-04-98	16	4.3	6.9	3.9	1.1	0.36	2.2	0.7
AA Cd 123	11-09-98	<4.0	3.7	<4.0	3.5	<0.1	0.044	<1.0	0.3
AA Cd 124	11-09-98	<4.0	3.7	5.4	3.9	0.3	0.161	<1.0	0.4
AA Cd 126	11-04-98	7.7	3.9	4.0	3.8	0.8	0.291	1.4	0.6
AA Cd 127	11-16-98	7.0	3.8	<4.0	3.5	0.2	0.081	<1.0	0.4
AA Ce 96	06-15-98	19	4.3	11	4.0	1.8	0.471	5.3	1.3
AA Ce 122	06-15-98	5.7	3.8	6.0	3.8	0.7	0.234	1.4	0.5
AA Ce 143	06-18-98	29	4.8	16	4.2	2.3	0.589	4.4	1.1
AA Ce 144	10-28-98	13	4.1	5.1	3.8	0.6	0.22	1.6	0.5
AA Ce 145	10-28-98	25	4.6	12	4.1	1.8	0.485	5.4	1.4

Appendix C1. Radionuclides and field water-quality data from well-water samples in the upper Chesapeake Bay area, Maryland -- Continued

Well number	Date sampled	Specific conductance (µS/cm)	pH	Dissolved oxygen (mg/L)	S-T GAPA (pCi/L)	2 sigma S-T GAPA (pCi/L)	L-T GAPA (pCi/L)	2 sigma L-T GAPA (pCi/L)
AA Ce 147	11-04-98	63	4.3	0.2	<3.0	1.9	3.8	2.2
AA Cf 22	06-15-98	77	5.2	1.0	5.4	2.4	<3.0	1.8
AA Cf 119	06-16-98	63	4.7	1.2	11	3.1	3.1	2.1
AA Cf 142	06-16-98	79	5.4	1.7	4.2	2.2	<3.0	1.8
AA Cf 151	06-30-98	133	5.4	1.2	4.4	2.4	<3.0	2.0
AA Cg 19	06-30-98	148	5.8	1.1	8.8	3.1	<3.0	1.9
AA Cg 27	06-25-98	190	6.0	1.1	5.3	2.6	<3.0	2.0
AA Dc 19	11-16-98	95	4.4	0.2	10	3.3	<3.0	1.7
AA Dd 58	06-10-98	96	5.3	1.1	<3.0	1.5	<3.0	1.6
AA Dd 59	09-15-98	194	6.6	0.7	<3.0	2.3	<3.0	2.1
AA Dd 60	10-27-98	75	5.4	<1.0	<3.0	1.8	<3.0	1.6
AA De 2	06-22-98	96	5.8	1.1	3.2	2.1	<3.0	1.4
AA De 139	06-22-98	83	6.1	0.9	4.7	2.3	<3.0	1.6
AA De 213	06-22-98	180	6.1	1.1	<3.0	1.8	<3.0	1.6
AA De 214	06-30-98	147	5.8	1.2	<3.0	1.8	<3.0	1.8
AA Df 124	11-16-98	338	5.1	0.4	3.6	2.4	<3.0	2.0
AA Df 158	06-29-98	204	6.0	1.0	4.9	2.6	<3.0	1.8
AA Ec 11	06-29-98	251	6.8	0.9	<3.0	2.2	<3.0	1.9
BA Ef 59	07-07-98	34	4.6	4.5	<3.0	1.9	<3.0	1.5
BA Eg 246	07-07-98	17	4.7	4.7	<3.0	1.9	<3.0	1.5
BA Eg 247	07-07-98	18	4.4	4.7	<3.0	1.8	<3.0	1.4
BA Eg 248	09-28-98	57	--	--	<3.0	2.0	<3.0	1.8
BA Ff 86	07-07-98	123	4.4	9.5	12	3.6	<3.0	2.0
BA Ff 87	09-30-98	132	5.8	0.2	5.0	2.6	<3.0	2.0
BA Ff 88	07-08-98	318	4.9	1.0	15	4.0	4.5	2.6
BA Ff 89	07-14-98	89	4.6	0.9	17	3.9	3.5	2.1
BA Fg 173	07-07-98	359	6.5	0.5	7.4	3.3	<3.0	1.7
BA Fg 174	07-08-98	54	4.8	5.8	5.5	2.5	<3.0	1.4
BA Fg 175	07-14-98	18	4.7	5.9	3.4	2.1	<3.0	1.4
CE Be 122	08-25-98	27	4.8	9.2	<3.0	1.9	<3.0	1.4
CE Bf 87	08-20-98	149	4.8	9.3	10	3.3	3.1	2.2
CE Cc 69	08-31-98	22	4.6	9.0	<3.0	1.7	<3.0	1.7
CE Cc 70	08-31-98	182	4.3	8.3	7.7	2.9	<3.0	1.7
CE Cd 86	08-19-98	20	4.8	8.0	<3.0	2.0	<3.0	1.5
CE Cd 87	08-31-98	156	4.3	4.3	8.3	3.0	<3.0	1.7
CE Cd 88	08-31-98	25	4.4	5.9	<3.0	1.9	<3.0	1.6
CE Ce 57	08-18-98	23	4.6	4.8	3.6	2.2	<3.0	1.6
CE Ce 83	08-20-98	22	4.8	6.7	<3.0	1.8	<3.0	1.4
CE Ce 84	08-20-98	46	4.8	6.9	<3.0	1.9	<3.0	1.3
CE Ce 85	09-28-98	85	--	--	6.2	2.6	<3.0	1.8
CE Cf 89	08-18-98	151	6.0	0.5	<3.0	2.2	<3.0	2.1
CE Dd 85	08-25-98	152	4.6	4.1	10	3.3	<3.0	2.0
CE Dd 103	08-19-98	53	5.3	5.3	7.6	2.8	3.2	2.1

Well number	Date sampled	S-T GBPA (pCi/L)	2-sigma S-T GBPA	L-T GBPA (pCi/L)	2 sigma L-T GBPA (pCi/L)	Radium-226 (pCi/L)	2 sigma Radium-226 (pCi/L)	Radium-228 (pCi/L)	2 sigma Radium-228 (pCi/L)
AA Ce 147	11-04-98	4.4	3.7	<4.0	3.7	0.4	0.183	<1.0	0.3
AA Cf 22	06-15-98	8.3	3.9	<4.0	3.6	0.5	0.205	1.1	0.4
AA Cf 119	06-16-98	7.6	3.9	4.8	3.7	1.2	0.366	1.3	0.5
AA Cf 142	06-16-98	4.2	3.7	<4.0	3.6	0.5	0.221	<1.0	0.4
AA Cf 151	06-30-98	6.9	3.8	4.2	3.7	0.4	0.146	1.5	0.5
AA Cg 19	06-30-98	5.6	3.8	<4.0	3.7	0.7	0.216	1.9	0.6
AA Cg 27	06-25-98	6.9	3.9	<4.0	3.6	0.4	0.129	1.1	0.5
AA Dc 19	11-16-98	11	4.0	7.8	3.9	0.4	0.132	<1.0	0.4
AA Dd 58	06-10-98	5.0	3.8	<4.0	3.6	0.3	0.15	<1.0	0.3
AA Dd 59	09-15-98	<4.0	3.7	<4.0	3.8	0.2	0.117	<1.0	0.4
AA Dd 60	10-27-98	<4.0	3.7	<4.0	3.7	<0.1	0.072	<1.0	0.3
AA De 2	06-22-98	4.0	3.7	<4.0	3.6	0.4	0.173	<1.0	0.3
AA De 139	06-22-98	5.7	3.8	<4.0	3.7	1	0.314	<1.0	0.3
AA De 213	06-22-98	5.8	3.8	<4.0	3.6	0.3	0.162	<1.0	0.3
AA De 214	06-30-98	<4.0	3.7	<4.0	3.7	0.4	0.141	<1.0	0.4
AA Df 124	11-16-98	9.5	4.0	5.2	3.8	<.1	0.043	<1.0	0.4
AA Df 158	06-29-98	8.5	4.0	6.1	3.8	0.4	0.15	1.5	0.5
AA Ec 11	06-29-98	4.2	3.8	<4.0	3.7	0.3	0.139	<1.0	0.4
BA Ef 59	07-07-98	<4.0	3.5	<4.0	3.5	--	--	--	--
BA Eg 246	07-07-98	<4.0	3.6	<4.0	3.5	--	--	--	--
BA Eg 247	07-07-98	<4.0	3.6	<4.0	3.6	--	--	--	--
BA Eg 248	09-28-98	6.0	3.8	6.2	3.8	--	--	--	--
BA Ff 86	07-07-98	4.4	3.7	4.2	3.7	--	--	--	--
BA Ff 87	09-30-98	5.5	3.8	<4.0	3.6	--	--	--	--
BA Ff 88	07-08-98	13	4.2	10	4.0	--	--	--	--
BA Ff 89	07-14-98	13	4.1	6.3	3.7	--	--	--	--
BA Fg 173	07-07-98	7.5	4.0	4.5	3.8	--	--	--	--
BA Fg 174	07-08-98	7.1	3.8	<4.0	3.6	--	--	--	--
BA Fg 175	07-14-98	<4.0	3.6	<4.0	3.5	--	--	--	--
CE Be 122	08-25-98	<4.0	3.5	<4.0	3.6	--	--	--	--
CE Bf 87	08-20-98	11	4.0	<4.0	3.6	--	--	--	--
CE Cc 69	08-31-98	<4.0	3.6	<4.0	3.5	--	--	--	--
CE Cc 70	08-31-98	6.6	3.8	<4.0	3.7	--	--	--	--
CE Cd 86	08-19-98	<4.0	3.6	<4.0	3.6	--	--	--	--
CE Cd 87	08-31-98	4.9	3.7	<4.0	3.7	--	--	--	--
CE Cd 88	08-31-98	<4.0	3.6	4.8	3.8	--	--	--	--
CE Ce 57	08-18-98	<4.0	3.6	<4.0	3.6	--	--	--	--
CE Ce 83	08-20-98	<4.0	3.6	<4.0	3.6	--	--	--	--
CE Ce 84	08-20-98	<4.0	3.6	<4.0	3.6	--	--	--	--
CE Ce 85	09-28-98	4.8	3.8	4.6	3.7	--	--	--	--
CE Cf 89	08-18-98	<4.0	3.7	<4.0	3.6	--	--	--	--
CE Dd 85	08-25-98	8.5	3.9	7.9	3.9	--	--	--	--
CE Dd 103	08-19-98	8.0	3.9	<4.0	3.6	--	--	--	--

Appendix C1. Radionuclides and field water-quality data from well-water samples in the upper Chesapeake Bay area, Maryland -- Continued

Well number	Date sampled	Specific conductance (µS/cm)	pH	Dissolved oxygen (mg/L)	S-T GAPA (pCi/L)	2 sigma S-T GAPA (pCi/L)	L-T GAPA (pCi/L)	2 sigma L-T GAPA (pCi/L)
CE Dd 104	08-27-98	257	6.4	0.3	3.0	2.3	<3.0	2.0
CE Dd 105	09-01-98	196	6.5	0.2	<3.0	1.8	<3.0	1.5
CE Dd 106	09-01-98	2,410	4.3	2.5	140	26	9.6	10
CE De 56	08-25-98	230	7.1	0.3	3.9	2.6	<3.0	2.0
CE De 57	10-05-98	204	6.2	0.3	6.1	2.9	<3.0	2.1
CE Df 41	09-08-98	219	7.3	0.6	<3.0	2.2	<3.0	1.8
CE Df 42	09-28-98	269	--	--	<3.0	2.2	<3.0	2.2
CE Df 43	10-01-98	234	7.8	0.1	3.2	2.4	<3.0	1.4
CE Ec 23	09-03-98	63	5.5	0.3	<3.0	1.4	<3.0	1.5
CE Ed 27	09-02-98	122	5.9	0.2	<3.0	1.8	<3.0	1.6
CE Ee 45	08-18-98	305	7.5	0.1	<3.0	2.2	<3.0	1.8
CE Ee 54	09-01-98	306	7.4	0.3	4.7	2.8	<3.0	2.3
HA Cf 176	08-05-98	149	5.8	2.4	4.0	2.3	<3.0	1.4
HA Cf 177	08-12-98	143	6.1	1.2	<3.0	1.8	<3.0	1.3
HA Dc 120	08-18-98	49	4.7	8.6	5.5	2.4	<3.0	2.0
HA Dd 73	08-04-98	64	4.8	0.4	6.9	2.6	<3.0	1.8
HA Dd 107	08-03-98	37	4.5	5.1	4.3	2.2	<3.0	1.7
HA De 75	08-12-98	272	6.6	7.0	16	4.1	<3.0	1.8
HA De 164	08-04-98	129	5.0	9.1	12	3.4	<3.0	1.9
HA De 166	08-05-98	20	5.3	6.7	<3.0	1.5	<3.0	1.3
HA Ec 48	08-03-98	83	4.8	3.2	4.7	2.3	<3.0	1.8
KE Ac 20	09-08-98	1,980	6.7	0.7	36	11	8.0	7.2
KE Ac 23	09-21-98	175	5.9	0.2	<3.0	1.9	<3.0	1.8
KE Ad 43	08-27-98	53	4.9	7.4	4.3	2.3	<3.0	1.4
KE Ad 60	08-06-98	122	6.3	0.1	4.0	2.3	<3.0	1.7
KE Ad 70	09-29-98	130	5.6	--	<3.0	1.9	<3.0	1.5
KE Ae 70	08-06-98	192	7.3	0.1	3.3	2.3	<3.0	1.7
KE Af 29	09-22-98	260	8.0	0.2	5.2	2.7	3.8	2.5
KE Af 79	09-14-98	239	8.0	0.2	<3.0	1.9	<3.0	2.0
KE Bb 14	09-14-98	81	5.3	0.2	<3.0	1.5	<3.0	1.8
KE Bc 188	09-21-98	539	5.8	0.2	3.1	2.8	<3.0	2.6
KE Bc 189	09-29-98	131	5.8	--	<3.0	1.6	<3.0	1.4
KE Bc 190	09-29-98	126	6.0	--	8.5	3.1	<3.0	1.8
KE Bd 64	08-06-98	108	6.3	0.2	<3.0	1.7	<3.0	1.7
KE Bd 87	09-21-98	118	6.1	3.8	<3.0	2.0	<3.0	1.8
KE Be 103	09-14-98	185	7.2	0.2	4.2	2.5	<3.0	1.9
KE Cb 35	09-02-98	177	6.3	0.4	7.9	3.0	<3.0	1.9
KE Cb 89	09-23-98	132	5.8	0.6	4.5	2.5	<3.0	1.5
KE Cb 104	09-23-98	155	5.8	0.8	6.4	2.8	<3.0	2.3
KE Cd 104	08-27-98	165	6.5	0.1	8.4	3.1	<3.0	2.0
KE Db 57	08-26-98	205	6.3	0.2	<3.0	2.1	<3.0	2.3
KE Eb 14	09-24-98	144	6.5	--	6.5	2.8	6.5	2.8
PG Bc 37	07-29-98	2,140	5.6	--	48	13	4.5	7.1

Well number	Date sampled	S-T GBPA (pCi/L)	2-sigma S-T GBPA	L-T GBPA (pCi/L)	2 sigma L-T GBPA (pCi/L)	Radium-226 (pCi/L)	2 sigma Radium-226 (pCi/L)	Radium-228 (pCi/L)	2 sigma Radium-228 (pCi/L)
CE Dd 104	08-27-98	4.2	3.8	<4.0	3.8	--	--	--	--
CE Dd 105	09-01-98	<4.0	3.7	<4.0	3.7	--	--	--	--
CE Dd 106	09-01-98	70	16	24	14	--	--	--	--
CE De 56	08-25-98	5.2	3.8	4.5	3.8	--	--	--	--
CE De 57	10-05-98	6.5	4.0	7.2	3.9	--	--	--	--
CE Df 41	09-08-98	7.4	3.9	5.8	4.0	--	--	--	--
CE Df 42	09-28-98	<4.0	3.7	4.5	3.9	--	--	--	--
CE Df 43	10-01-98	5.1	3.9	<4.0	3.8	--	--	--	--
CE Ec 23	09-03-98	<4.0	3.5	4.8	3.8	--	--	--	--
CE Ed 27	09-02-98	<4.0	3.5	<4.0	3.7	--	--	--	--
CE Ee 45	08-18-98	5.6	3.9	6.4	3.9	--	--	--	--
CE Ee 54	09-01-98	8.6	4.0	5.9	3.9	--	--	--	--
HA Cf 176	08-05-98	6.4	3.8	<4.0	3.6	--	--	--	--
HA Cf 177	08-12-98	<4.0	3.6	<4.0	3.6	--	--	--	--
HA Dc 120	08-18-98	4.1	3.6	4.4	3.7	--	--	--	--
HA Dd 73	08-04-98	4.6	3.6	5.6	3.8	--	--	--	--
HA Dd 107	08-03-98	<4.0	3.5	<4.0	3.6	--	--	--	--
HA De 75	08-12-98	19	4.4	<4.0	3.7	--	--	--	--
HA De 164	08-04-98	8.3	3.8	6.7	3.8	--	--	--	--
HA De 166	08-05-98	<4.0	3.5	<4.0	3.5	--	--	--	--
HA Ec 48	08-03-98	5.1	3.7	<4.0	3.6	--	--	--	--
KE Ac 20	09-08-98	28	5.5	23	5.4	--	--	--	--
KE Ac 23	09-21-98	<4.0	3.7	<4.0	3.6	--	--	--	--
KE Ad 43	08-27-98	<4.0	3.7	<4.0	3.6	--	--	--	--
KE Ad 60	08-06-98	5.6	3.7	4.7	3.8	--	--	--	--
KE Ad 70	09-29-98	<4.0	3.6	<4.0	3.5	--	--	--	--
KE Ae 70	08-06-98	5.2	3.7	5.1	3.8	--	--	--	--
KE Af 29	09-22-98	6.9	4.0	5.3	3.8	--	--	--	--
KE Af 79	09-14-98	5.6	3.9	<4.0	3.9	--	--	--	--
KE Bb 14	09-14-98	<4.0	3.6	<4.0	3.7	--	--	--	--
KE Bc 188	09-21-98	4.2	3.9	5.7	4.0	--	--	--	--
KE Bc 189	09-29-98	<4.0	3.6	<4.0	3.5	--	--	--	--
KE Bc 190	09-29-98	7.9	4.0	5.3	3.8	--	--	--	--
KE Bd 64	08-06-98	<4.0	3.6	5.9	3.8	--	--	--	--
KE Bd 87	09-21-98	4.4	3.8	<4.0	3.7	--	--	--	--
KE Be 103	09-14-98	9.2	4.0	7.3	4.0	--	--	--	--
KE Cb 35	09-02-98	9.2	4.0	7.5	3.9	--	--	--	--
KE Cb 89	09-23-98	6.5	3.9	<4.0	3.7	--	--	--	--
KE Cb 104	09-23-98	5.5	3.9	4.4	3.8	--	--	--	--
KE Cd 104	08-27-98	12	4.1	8.6	4.0	--	--	--	--
KE Db 57	08-26-98	<4.0	3.8	4.3	3.8	--	--	--	--
KE Eb 14	09-24-98	7.1	3.9	13	4.2	--	--	--	--
PG Bc 37	07-29-98	15	5.0	14	5.1	--	--	--	--

Appendix C1. Radionuclides and field water-quality data from well-water samples in the upper Chesapeake Bay area, Maryland -- Continued

Well number	Date sampled	Specific conductance (µS/cm)	pH	Dissolved oxygen (mg/L)	S-T GAPA (pCi/L)	2 sigma S-T GAPA (pCi/L)	L-T GAPA (pCi/L)	2 sigma L-T GAPA (pCi/L)
PG Be 33	07-16-98	69	3.5	0.8	8.7	2.9	<3.0	2.0
PG Be 34	07-22-98	39	4.4	0.9	3.4	2.1	<3.0	1.7
PG Be 35	07-29-98	51	5.0	7.8	4.4	2.3	<3.0	1.7
PG Ce 39	07-16-98	200	4.6	0.9	5.9	2.7	4.4	2.5
PG Ce 40	07-20-98	93	5.6	0.9	<3.0	2.0	<3.0	2.0
PG Ce 41	07-20-98	116	5.8	--	5.0	2.5	<3.0	2.0
PG Ce 42	09-15-98	196	6.2	0.5	6.3	2.8	<3.0	2.4
PG Cf 82	07-15-98	57	4.6	0.9	7.6	2.8	<3.0	1.7
PG Cf 83	07-15-98	77	3.9	0.8	20	4.1	8.6	2.9
PG Cf 84	07-15-98	132	6.1	0.9	3.1	2.2	<3.0	1.8
PG Cf 85	07-16-98	149	6.0	0.8	5.6	2.6	<3.0	1.9
PG Cf 86	07-20-98	255	6.7	0.9	<3.0	2.4	<3.0	2.1
PG Cf 87	07-20-98	136	5.8	0.9	4.5	2.5	<3.0	1.8
PG Cf 88	07-29-98	69	5.7	0.3	<3.0	1.9	<3.0	1.8
PG Cf 89	07-29-98	56	5.6	0.1	4.3	2.3	<3.0	1.6
PG Df 38	07-16-98	373	7.0	0.8	4.7	2.9	<3.0	1.9
PG Df 39	07-22-98	234	6.8	0.9	<3.0	2.5	<3.0	1.7
QA Db 27	09-16-98	1,310	6.9	--	3.0	4.7	<3.0	3.9
QA Db 44	07-27-98	236	6.3	0.2	5.2	2.7	<3.0	1.8
QA Ea 86	05-26-98	241	6.4	<1	<3.0	1.9	<3.0	1.8
QA Ea 87	07-27-98	238	6.3	0.2	4.5	2.6	<3.0	2.1
QA Eb 167	05-20-98	205	6.3	<1	5.4	2.6	<3.0	1.9
QA Eb 168	05-26-98	224	6.7	<1	3.5	2.3	<3.0	1.6
QA Eb 173	05-20-98	205	6.2	<1	7.3	2.9	<3.0	1.8
QA Eb 181	05-20-98	216	6.0	<1	4.9	2.6	<3.0	2.1
QA Ec 91	04-02-98	147	6.5	<1	10	3.2	<3.0	1.6
QA Fa 77	07-27-98	257	6.3	<2.4	9.9	3.5	<3.0	2.2
QA Fa 79	07-27-98	230	6.8	0.4	4.1	2.5	<3.0	1.5
QA Fa 81	07-28-98	220	6.4	0.1	<3.0	2.1	<3.0	2.1
QA Fa 82	07-28-98	210	6.4	0.2	<3.0	2.1	<3.0	2.0
QA Fb 3	07-28-98	186	6.5	0.1	<3.0	2.1	<3.0	1.5

Well number	Date sampled	S-T GBPA (pCi/L)	2-sigma S-T GBPA	L-T GBPA (pCi/L)	2 sigma L-T GBPA (pCi/L)	Radium-226 (pCi/L)	2 sigma Radium-226 (pCi/L)	Radium-228 (pCi/L)	2 sigma Radium-228 (pCi/L)
PG Be 33	07-16-98	<4.0	3.6	6.2	3.8	--	--	--	--
PG Be 34	07-22-98	4.4	3.7	<4.0	3.6	--	--	--	--
PG Be 35	07-29-98	4.3	3.6	<4.0	3.6	--	--	--	--
PG Ce 39	07-16-98	8.1	3.9	4.2	3.8	--	--	--	--
PG Ce 40	07-20-98	5.0	3.8	<4.0	3.6	--	--	--	--
PG Ce 41	07-20-98	7.6	3.9	5.4	3.8	--	--	--	--
PG Ce 42	09-15-98	8.8	4.0	5.8	4.0	--	--	--	--
PG Cf 82	07-15-98	12	4.0	4.9	3.7	--	--	--	--
PG Cf 83	07-15-98	14	4.1	9.7	4.0	--	--	--	--
PG Cf 84	07-15-98	4.6	3.8	<4.0	3.7	--	--	--	--
PG Cf 85	07-16-98	6.8	3.8	5.9	3.8	--	--	--	--
PG Cf 86	07-20-98	7.0	3.9	4.3	3.8	--	--	--	--
PG Cf 87	07-20-98	<4.0	3.7	<4.0	3.7	--	--	--	--
PG Cf 88	07-29-98	<4.0	3.5	<4.0	3.6	--	--	--	--
PG Cf 89	07-29-98	6.8	3.8	<4.0	3.7	--	--	--	--
PG Df 38	07-16-98	7.1	4.0	<4.0	3.8	--	--	--	--
PG Df 39	07-22-98	5.4	3.9	4.4	3.9	--	--	--	--
QA Db 27	09-16-98	9.5	4.5	4.8	4.4	--	--	--	--
QA Db 44	07-27-98	9.8	4.0	5.8	3.9	--	--	--	--
QA Ea 86	05-26-98	<4.0	4.0	4.5	3.8	--	--	--	--
QA Ea 87	07-27-98	8.0	3.9	6.6	3.9	--	--	--	--
QA Eb 167	05-20-98	6.0	4.1	<4.0	3.7	--	--	--	--
QA Eb 168	05-26-98	7.3	4.2	5.4	3.8	--	--	--	--
QA Eb 173	05-20-98	7.7	4.2	7.6	3.9	--	--	--	--
QA Eb 181	05-20-98	<4.0	4.0	5.5	3.8	--	--	--	--
QA Ec 91	04-02-98	15	4.3	7.6	3.9	--	--	--	--
QA Fa 77	07-27-98	9.1	4.0	5.4	3.9	--	--	--	--
QA Fa 79	07-27-98	6.9	3.8	7.6	4.0	--	--	--	--
QA Fa 81	07-28-98	7.5	3.9	5.8	3.9	--	--	--	--
QA Fa 82	07-28-98	11	4.0	5.8	3.9	--	--	--	--
QA Fb 3	07-28-98	<4.0	3.7	<4.0	3.6	--	--	--	--

Appendix C2. Major ions and field water-quality data from well-water samples in the upper Chesapeake Bay area, Maryland

Well number	Date sampled	Specific conductance (µS/cm)	pH	Dissolved oxygen (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)
AA Ae 42	10-26-98	50	3.4	<1.0	--	--	--	--
AA Ae 43	11-02-98	32	4.4	0.2	--	--	--	--
AA Bb 89	11-09-98	110	4.4	1.7	--	--	--	--
AA Bc 163	11-04-98	34	4.5	0.3	--	--	--	--
AA Bc 246	06-24-98	41	4.7	8.4	0.44	0.22	1.2	0.53
AA Bc 248	11-18-98	119	4.4	0.3	--	--	--	--
AA Bd 107	06-15-98	76	4.2	7.2	1.9	0.77	3.0	0.79
AA Bd 170	06-10-98	35	4.1	8.3	0.62	0.24	1.1	0.59
AA Bd 172	10-21-98	116	4.8	4.9	--	--	--	--
AA Bd 173	11-18-98	60	5.8	6.5	--	--	--	--
AA Be 119	06-24-98	100	3.4	8.7	1.2	1.8	5.9	0.98
AA Be 120	06-18-98	36	4.9	5.6	0.49	0.23	2.1	0.55
AA Be 123	10-20-98	88	5.0	9.7	--	--	--	--
AA Be 124	06-24-98	268	4.2	9.6	8.7	4.9	25	2.8
AA Be 125	11-02-98	50	3.8	0.2	--	--	--	--
AA Be 126	11-04-98	84	4.0	0.2	--	--	--	--
AA Bf 70	06-25-98	143	3.8	1.0	0.45	0.69	1.4	1.0
AA Bf 74	06-25-98	83	5.6	1.0	2.1	1.1	1.0	1.2
AA Bf 76	10-11-98	290	3.7	<1.0	--	--	--	--
AA Bf 77	10-20-98	691	3.6	0.2	--	--	--	--
AA Bf 78	10-13-98	230	3.7	<1.0	--	--	--	--
AA Bf 79	10-14-98	122	5.3	0.2	--	--	--	--
AA Bf 80	10-26-98	232	3.2	<1.0	--	--	--	--
AA Bf 81	10-14-98	116	3.7	0.3	--	--	--	--
AA Bf 82	10-28-98	559	3.7	<1.0	--	--	--	--
AA Bf 83	10-19-98	251	3.6	0.1	--	--	--	--
AA Bf 84	10-19-98	232	4.4	5.0	--	--	--	--
AA Bf 85	10-14-98	74	3.8	0.4	--	--	--	--
AA Bf 86	10-20-98	230	4.8	0.2	--	--	--	--
AA Bf 87	10-19-98	307	3.7	0.1	--	--	--	--
AA Bf 88	10-19-98	409	3.5	0.2	--	--	--	--
AA Bf 89	10-20-98	134	4.0	0.1	--	--	--	--
AA Bf 90	10-21-98	90	4.2	0.9	--	--	--	--
AA Bf 91	10-21-98	386	4.5	6.0	--	--	--	--
AA Bf 92	10-26-98	45	4.9	<1.0	--	--	--	--
AA Bf 93	10-28-98	177	3.1	<1.0	--	--	--	--
AA Bf 94	10-26-98	81	5.3	<1.0	--	--	--	--
AA Bf 95	11-02-98	1,360	3.3	0.3	--	--	--	--
AA Bf 96	11-02-98	1,400	3.5	0.4	--	--	--	--
AA Bf 97	11-02-98	63	3.9	0.2	--	--	--	--
AA Bf 98	11-18-98	144	3.8	0.4	--	--	--	--
AA Ca 1	11-09-98	26	5.1	9.1	--	--	--	--
AA Cc 123	11-04-98	32	4.8	1.1	--	--	--	--

Well name	Date sampled	Alkalinity (mg/L as $CaCO_3$)	Chloride (mg/L)	Sulfate (mg/L)	Nitrate plus nitrite (mg/L as N)	Nitrite (mg/L as N)	Ammonium (mg/L as N)	Phosphorus (mg/L)	Ortho phosphorus (mg/L)
AA Ae 42	10-26-98	--	<10	--	<0.2	--	--	--	--
AA Ae 43	11-02-98	--	<10	--	<0.2	--	--	--	--
AA Bb 89	11-09-98	--	19	--	1.3	--	--	--	--
AA Bc 163	11-04-98	--	<10	--	<0.2	--	--	--	--
AA Bc 246	06-24-98	--	2.3	3.6	0.29	<.010	0.088	<.010	<.010
AA Bc 248	11-18-98	--	<10	--	<0.2	--	--	--	--
AA Bd 107	06-15-98	--	8.0	2.5	1.75	<.010	<.020	<.010	<.010
AA Bd 170	06-10-98	--	1.6	1.3	0.89	0.015	0.035	<.010	0.01
AA Bd 172	10-21-98	--	15	--	6.4	--	--	--	--
AA Bd 173	11-18-98	--	<10	--	1.1	--	--	--	--
AA Be 119	06-24-98	--	13	6.0	1.43	<.010	0.084	<.010	<.010
AA Be 120	06-18-98	--	--	7.0	0.61	<.010	0.061	<.010	<.010
AA Be 123	10-20-98	--	11	--	5.8	--	--	--	--
AA Be 124	06-24-98	--	41	13	8.4	<.010	0.084	<.010	<.010
AA Be 125	11-02-98	--	<10	--	<0.2	--	--	--	--
AA Be 126	11-04-98	--	<10	--	<0.2	--	--	--	--
AA Bf 70	06-25-98	--	4.8	41	<.050	<.010	0.057	0.013	0.021
AA Bf 74	06-25-98	16	1.0	11	<.050	<.010	0.959	0.197	0.21
AA Bf 76	10-11-98	--	62	--	--	--	--	--	--
AA Bf 77	10-20-98	--	151	--	<0.2	--	--	--	--
AA Bf 78	10-13-98	--	48	--	<0.2	--	--	--	--
AA Bf 79	10-14-98	--	11	--	<0.2	--	--	--	--
AA Bf 80	10-26-98	--	21	--	<0.2	--	--	--	--
AA Bf 81	10-14-98	--	7.0	--	<0.2	--	--	--	--
AA Bf 82	10-28-98	--	87	--	<0.2	--	--	--	--
AA Bf 83	10-19-98	--	24	--	<0.2	--	--	--	--
AA Bf 84	10-19-98	--	30	--	8.4	--	--	--	--
AA Bf 85	10-14-98	--	3.0	--	<0.2	--	--	--	--
AA Bf 86	10-20-98	--	56	--	<0.2	--	--	--	--
AA Bf 87	10-19-98	--	51	--	<0.2	--	--	--	--
AA Bf 88	10-19-98	--	50	--	2.6	--	--	--	--
AA Bf 89	10-20-98	--	11	--	<0.2	--	--	--	--
AA Bf 90	10-21-98	--	11	--	0.2	--	--	--	--
AA Bf 91	10-21-98	--	81	--	5.4	--	--	--	--
AA Bf 92	10-26-98	--	<10	--	<0.2	--	--	--	--
AA Bf 93	10-28-98	--	<10	--	<0.2	--	--	--	--
AA Bf 94	10-26-98	--	<10	--	<0.2	--	--	--	--
AA Bf 95	11-02-98	--	310	--	<0.2	--	--	--	--
AA Bf 96	11-02-98	--	380	--	<0.2	--	--	--	--
AA Bf 97	11-02-98	--	<10	--	<0.2	--	--	--	--
AA Bf 98	11-18-98	--	<10	--	<0.2	--	--	--	--
AA Ca 1	11-09-98	--	<10	--	0.9	--	--	--	--
AA Cc 123	11-04-98	--	<10	--	<0.2	--	--	--	--

Appendix C2. Major ions and field water-quality data from well-water samples in the upper Chesapeake Bay area, Maryland -- Continued

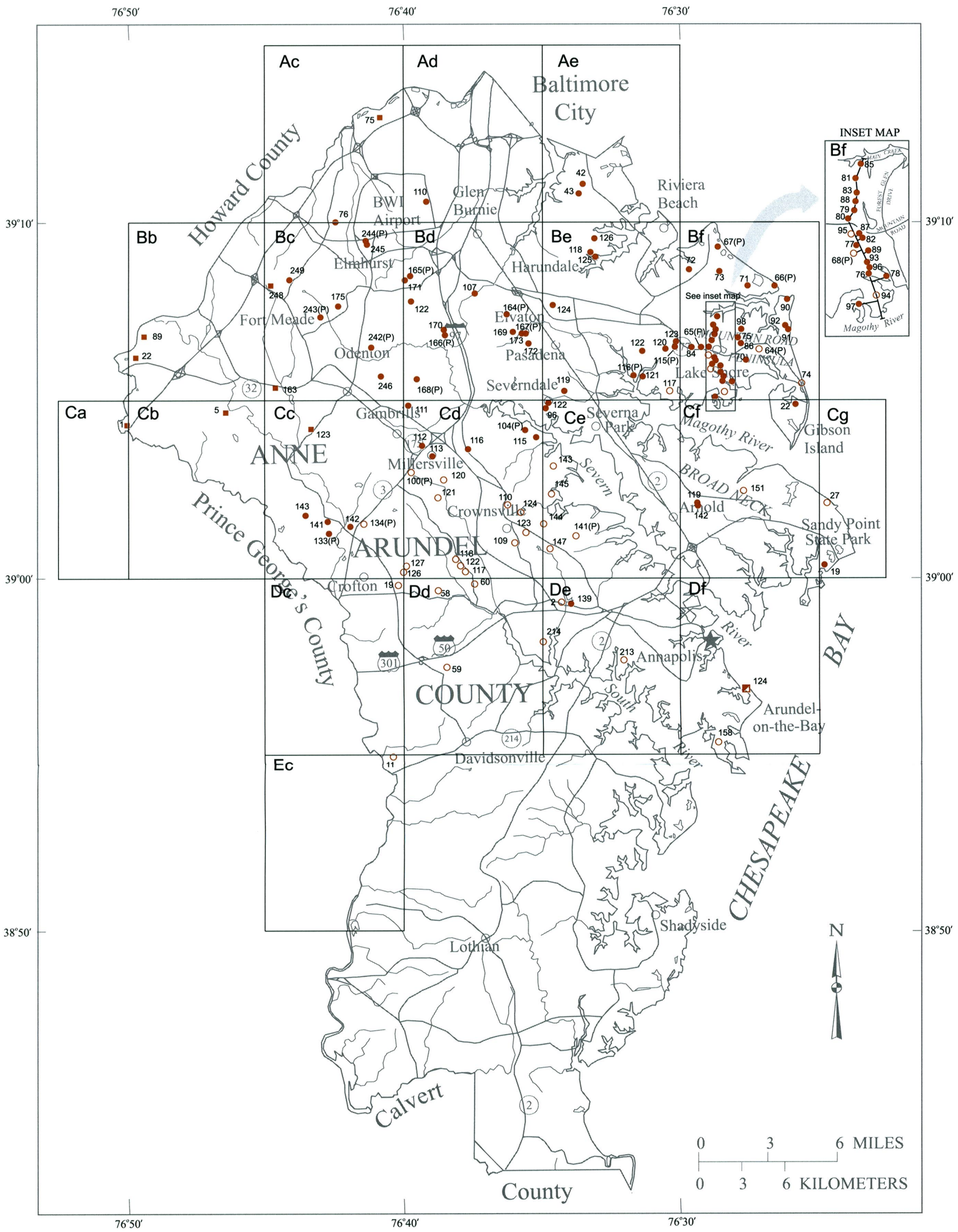
Well name	Date sampled	Iron (unfiltered) (µg/L)	Iron (filtered) (µg/L)	Manganese (unfiltered) (µg/L)	Manganese (filtered) (µg/L)	Silica (mg/L as SiO_2)	Fluoride (mg/L)	Total dissolved solids (ROE) (mg/L)	Bromide (mg/L)
AA Ae 42	10-26-98	--	--	--	--	--	--	--	--
AA Ae 43	11-02-98	--	--	--	--	--	--	--	--
AA Bb 89	11-09-98	--	--	--	--	--	--	--	--
AA Bc 163	11-04-98	--	--	--	--	--	--	--	--
AA Bc 246	06-24-98	100	<10	<10	<4.0	6.8	<0.10	16	--
AA Bc 248	11-18-98	--	--	--	--	--	--	--	--
AA Bd 107	06-15-98	<10	<10	14	24	7.6	<0.10	39	--
AA Bd 170	06-10-98	30	<10	<10	9.5	9.2	<0.10	20	--
AA Bd 172	10-21-98	--	--	--	--	--	--	--	--
AA Bd 173	11-18-98	--	--	--	--	--	--	--	--
AA Be 119	06-24-98	170	<10	15	17	7.0	<0.10	48	--
AA Be 120	06-18-98	10	<10	<10	<4.0	9.4	<0.10	21	--
AA Be 123	10-20-98	--	--	--	--	--	--	--	--
AA Be 124	06-24-98	370	45	74	90	7.2	<0.10	152	--
AA Be 125	11-02-98	--	--	--	--	--	--	--	--
AA Be 126	11-04-98	--	--	--	--	--	--	--	--
AA Bf 70	06-25-98	10,000	6,700	21	28	13	<0.10	74	--
AA Bf 74	06-25-98	16,000	8,500	130	152	11	<0.10	36	--
AA Bf 76	10-11-98	--	--	--	--	--	--	--	--
AA Bf 77	10-20-98	--	--	--	--	--	--	--	--
AA Bf 78	10-13-98	--	--	--	--	--	--	--	--
AA Bf 79	10-14-98	--	--	--	--	--	--	--	--
AA Bf 80	10-26-98	--	--	--	--	--	--	--	--
AA Bf 81	10-14-98	--	--	--	--	--	--	--	--
AA Bf 82	10-28-98	--	--	--	--	--	--	--	--
AA Bf 83	10-19-98	--	--	--	--	--	--	--	--
AA Bf 84	10-19-98	--	--	--	--	--	--	--	--
AA Bf 85	10-14-98	--	--	--	--	--	--	--	--
AA Bf 86	10-20-98	--	--	--	--	--	--	--	--
AA Bf 87	10-19-98	--	--	--	--	--	--	--	--
AA Bf 88	10-19-98	--	--	--	--	--	--	--	--
AA Bf 89	10-20-98	--	--	--	--	--	--	--	--
AA Bf 90	10-21-98	--	--	--	--	--	--	--	--
AA Bf 91	10-21-98	--	--	--	--	--	--	--	--
AA Bf 92	10-26-98	--	--	--	--	--	--	--	--
AA Bf 93	10-28-98	--	--	--	--	--	--	--	--
AA Bf 94	10-26-98	--	--	--	--	--	--	--	--
AA Bf 95	11-02-98	--	--	--	--	--	--	--	--
AA Bf 96	11-02-98	--	--	--	--	--	--	--	--
AA Bf 97	11-02-98	--	--	--	--	--	--	--	--
AA Bf 98	11-18-98	--	--	--	--	--	--	--	--
AA Ca 1	11-09-98	--	--	--	--	--	--	--	--
AA Cc 123	11-04-98	--	--	--	--	--	--	--	--

Well number	Date sampled	Specific conductance (µS/cm)	pH	Dissolved oxygen (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)
AA Cc 143	10-28-98	48	3.9	<1.0	--	--	--	--
AA Cd 113	06-23-98	33	5.3	--	0.76	0.26	1.2	0.59
AA Cd 117	10-27-98	119	4.0	<1.0	--	--	--	--
AA Cd 118	10-27-98	91	3.9	<1.0	--	--	--	--
AA Cd 120	10-27-98	121	3.3	6.4	--	--	--	--
AA Cd 121	10-27-98	200	3.9	7.0	--	--	--	--
AA Cd 122	11-04-98	99	4.0	0.2	--	--	--	--
AA Cd 123	11-09-98	79	5.2	0.2	--	--	--	--
AA Cd 124	11-09-98	211	3.9	0.3	--	--	--	--
AA Cd 126	11-04-98	123	4.1	0.2	--	--	--	--
AA Cd 127	11-16-98	129	4.1	0.3	--	--	--	--
AA Ce 96	06-15-98	74	3.0	7.5	1.3	0.88	4.3	0.78
AA Ce 122	06-15-98	53	4.4	1.3	0.44	0.24	0.75	0.49
AA Ce 144	10-28-98	90	4.0	<1.0	--	--	--	--
AA Ce 145	10-28-98	135	3.7	<1.0	--	--	--	--
AA Ce 147	11-04-98	63	4.3	0.2	--	--	--	--
AA Cf 22	06-15-98	77	5.2	1.0	1.3	0.81	0.74	1.0
AA Cf 119	06-16-98	115	4.7	1.2	2.2	1.2	0.83	1.3
AA Cf 142	06-16-98	79	5.4	1.7	3.8	2.1	1.0	1.5
AA Cg 19	06-30-98	148	5.8	1.1	5.1	3.0	1.2	1.7
AA Cg 27	06-25-98	190	6.0	1.1	5.3	2.8	4.8	2.1
AA Dc 19	11-16-98	95	4.4	0.2	--	--	--	--
AA Dd 60	10-27-98	75	5.4	<1.0	--	--	--	--
AA De 2	06-22-98	96	5.8	1.1	7.8	1.9	1.4	1.9
AA De 139	06-22-98	83	6.1	0.9	2.8	1.4	0.91	1.4
AA De 213	06-22-98	180	6.1	1.1	17	6.1	1.5	2.9
AA Df 124	11-16-98	338	5.1	0.4	--	--	--	--
AA Df 158	06-29-98	204	6.0	1.0	15	5.1	1.5	3.2
KE Ac 20	09-08-98	1,980	6.7	0.7	55	31	219	9.7
KE Eb 14	09-24-98	144	6.5	--	10	3.6	2.0	3.3

Appendix C2. Major ions and field water-quality data from well-water samples in the upper Chesapeake Bay area, Maryland -- Continued

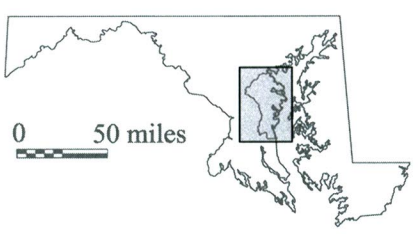
Well name	Date sampled	Alkalinity (mg/L as $CaCO_3$)	Chloride (mg/L)	Sulfate (mg/L)	Nitrate plus nitrite (mg/L as N)	Nitrite (mg/L as N)	Ammonium (mg/L as N)	Phosphorus (mg/L)	Ortho phosphorus (mg/L)
AA Cc 143	10-28-98	--	<10	--	<0.2	--	--	--	--
AA Cd 113	06-23-98	--	2.4	0.19	0.61	<.010	0.078	<.010	<.010
AA Cd 117	10-27-98	--	<10	--	<0.2	--	--	--	--
AA Cd 118	10-27-98	--	<10	--	<0.2	--	--	--	--
AA Cd 120	10-27-98	--	<10	--	0.4	--	--	--	--
AA Cd 121	10-27-98	--	30	--	3.4	--	--	--	--
AA Cd 122	11-04-98	--	<10	--	<0.2	--	--	--	--
AA Cd 123	11-09-98	--	<10	--	<0.2	--	--	--	--
AA Cd 124	11-09-98	--	<10	--	<0.2	--	--	--	--
AA Cd 126	11-04-98	--	<10	--	<0.2	--	--	--	--
AA Cd 127	11-16-98	--	<10	--	<0.2	--	--	--	--
AA Ce 96	06-15-98	--	8.4	5.0	1.53	<.010	0.033	<.010	<.010
AA Ce 122	06-15-98	--	1.4	9.6	<.050	0.193	0.029	<.010	<.010
AA Ce 144	10-28-98	--	<10	--	<0.2	--	--	--	--
AA Ce 145	10-28-98	--	<10	--	<0.2	--	--	--	--
AA Ce 147	11-04-98	--	<10	--	<0.2	--	--	--	--
AA Cf 22	06-15-98	--	0.73	19	<.050	<.010	0.105	0.063	0.069
AA Cf 119	06-16-98	4.0	2.6	10	<.050	<.010	0.056	0.027	0.036
AA Cf 142	06-16-98	12	2.0	33	<.050	<.010	0.066	--	0.048
AA Cg 19	06-30-98	2.0	4.4	44	<.050	<.010	0.023	<.010	<.010
AA Cg 27	06-25-98	41	0.94	40	<.050	0.012	0.071	0.041	0.036
AA Dc 19	11-16-98	--	<10	--	<0.2	--	--	--	--
AA Dd 60	10-27-98	--	<10	--	<0.2	--	--	--	--
AA De 2	06-22-98	24	1.9	13	<.050	<.010	0.034	0.593	0.485
AA De 139	06-22-98	27	1.1	10	<.050	<.010	<.020	0.082	<.010
AA De 213	06-22-98	63	3.2	31	<.050	<.010	0.065	0.277	<.010
AA Df 124	11-16-98	--	86	--	4.4	--	--	--	--
AA Df 158	06-29-98	52	1.3	47	<.050	0.01	0.068	<.010	<.010
KE Ac 20	09-08-98	--	560	0.65	<.050	0.02	0.259	<.010	0.02
KE Eb 14	09-24-98	--	1.1	22	0.066	0.013	0.066	0.029	0.081

Well name	Date sampled	Iron (unfiltered) (µg/L)	Iron (filtered) (µg/L)	Manganese (unfiltered) (µg/L)	Manganese (filtered) (µg/L)	Silica (mg/L as SiO_2)	Fluoride (mg/L)	Total dissolved solids (ROE) (mg/L)	Bromide (mg/L)
AA Cc 143	10-28-98	--	--	--	--	--	--	--	--
AA Cd 113	06-23-98	20	13	<10	<4.0	6.7	<0.10	20	--
AA Cd 117	10-27-98	--	--	--	--	--	--	--	--
AA Cd 118	10-27-98	--	--	--	--	--	--	--	--
AA Cd 120	10-27-98	--	--	--	--	--	--	--	--
AA Cd 121	10-27-98	--	--	--	--	--	--	--	--
AA Cd 122	11-04-98	--	--	--	--	--	--	--	--
AA Cd 123	11-09-98	--	--	--	--	--	--	--	--
AA Cd 124	11-09-98	--	--	--	--	--	--	--	--
AA Cd 126	11-04-98	--	--	--	--	--	--	--	--
AA Cd 127	11-16-98	--	--	--	--	--	--	--	--
AA Ce 96	06-15-98	20	20	<10	9.5	8.2	<0.10	35	--
AA Ce 122	06-15-98	290	900	<10	22	10	<0.10	24	--
AA Ce 144	10-28-98	--	--	--	--	--	--	--	--
AA Ce 145	10-28-98	--	--	--	--	--	--	--	--
AA Ce 147	11-04-98	--	--	--	--	--	--	--	--
AA Cf 22	06-15-98	9,800	9,800	68	79	7.7	<0.10	45	--
AA Cf 119	06-16-98	8,200	7,900	200	226	8.3	<0.10	35	--
AA Cf 142	06-16-98	11,000	10,400	210	224	7.3	--	68	--
AA Cg 19	06-30-98	30,000	26,400	330	362	7.5	<0.10	78	--
AA Cg 27	06-25-98	43,000	28,400	260	292	6.9	<0.10	78	--
AA Dc 19	11-16-98	--	--	--	--	--	--	--	--
AA Dd 60	10-27-98	--	--	--	--	--	--	--	--
AA De 2	06-22-98	17,000	6,700	92	100	11	0.23	53	--
AA De 139	06-22-98	13,000	12,700	460	514	8.1	<0.10	31	--
AA De 213	06-22-98	14,000	14,200	240	257	10	0.31	101	--
AA Df 124	11-16-98	--	--	--	--	--	--	--	--
AA Df 158	06-29-98	29,000	25,200	310	332	8.7	0.28	108	--
KE Ac 20	09-08-98	44,000	42,900	1,600	1,510	5.0	<0.10	1,010	2.8
KE Eb 14	09-24-98	11,000	11,500	180	178	7.6	0.24	83	0.067



EXPLANATION

Map location

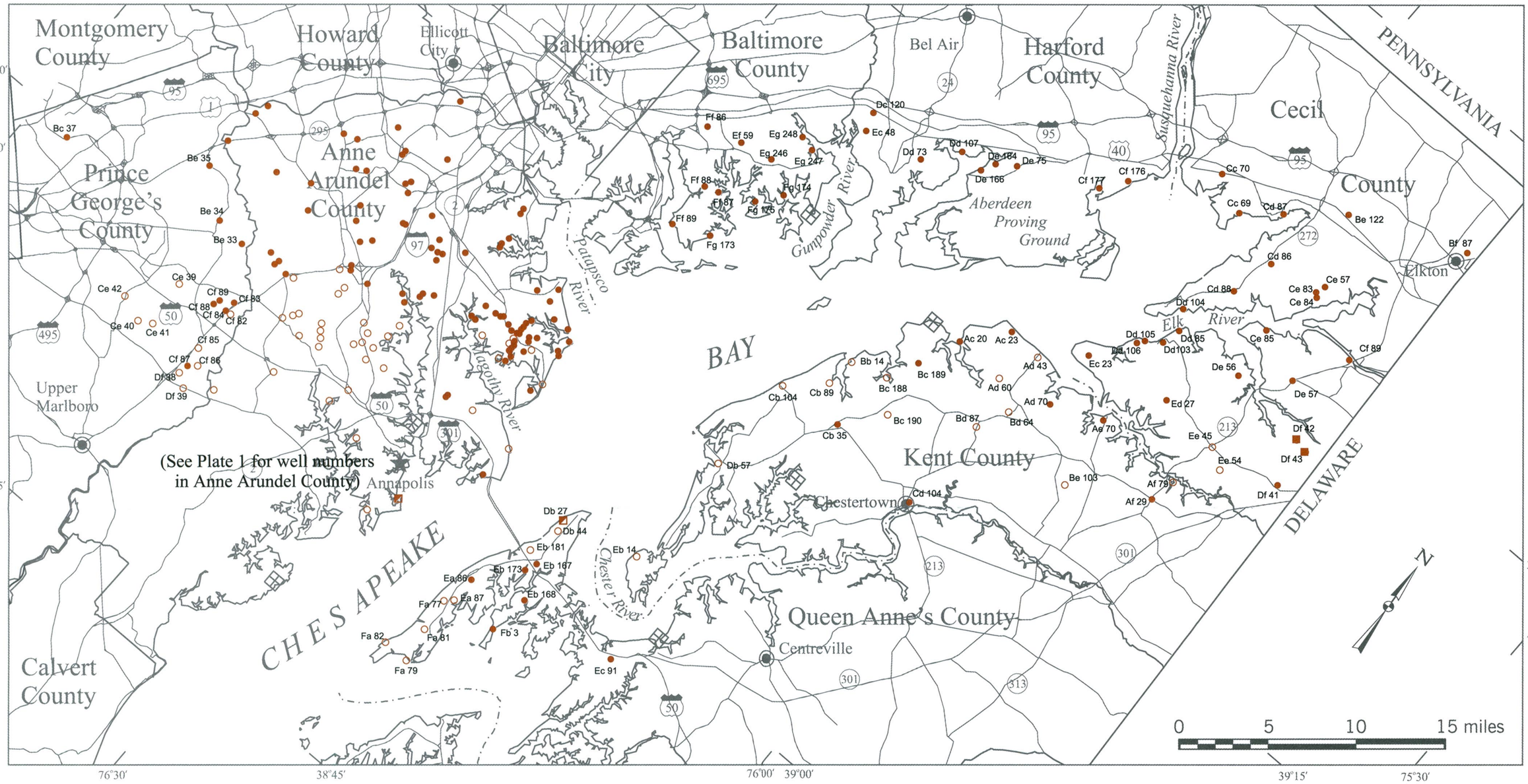


The full well designation is the well number listed next to the well symbol, preceded by AA (indicating Anne Arundel County). Thus, well number 122 in the Ce quad is AA Ce 122.

(P) after the number indicates that the well was sampled during the pilot study (Bolton and Hayes, 1999).

SYMBOL	AQUIFER
▪	Patuxent Formation
●	Patapsco Formation
○	Magothy Formation
◪	Aquia Formation

Plate 1. Locations of wells in Anne Arundel County that were sampled in this study and in the pilot study of carcinogens in Anne Arundel County well water (Bolton and Hayes, 1999).



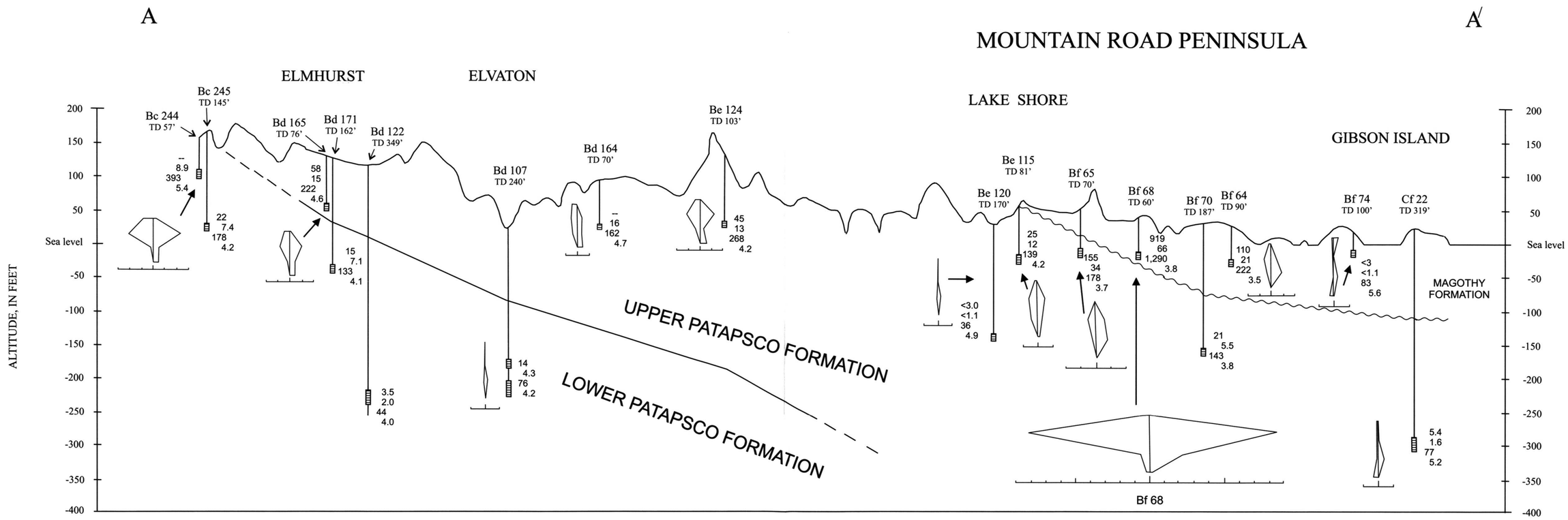
EXPLANATION

The full well designation is the well number listed next to the well symbol, preceded by the two-letter county abbreviation. County abbreviations have been omitted. Thus well number 190 in the Bc quad in Kent County is KE Bc 190.

BA: Baltimore County
CE: Cecil County
HA: Harford County
KE: Kent County
PG: Prince George's County
QA: Queen Anne's County

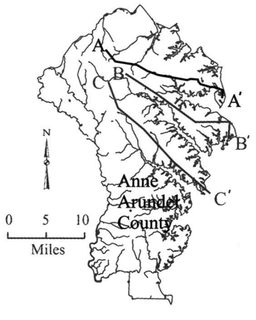
SYMBOL	AQUIFER
●	Potomac Group
○	Magothy Formation
■	Monmouth Formation
◪	Aquia Formation

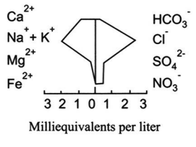
Plate 2. Locations of wells in the upper Chesapeake Bay area of Maryland that were sampled in this study and in the pilot study of carcinogens in Anne Arundel County well water (Bolton and Hayes, 1999).

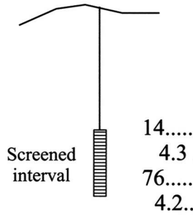


EXPLANATION

LOCATION OF TRANSECT





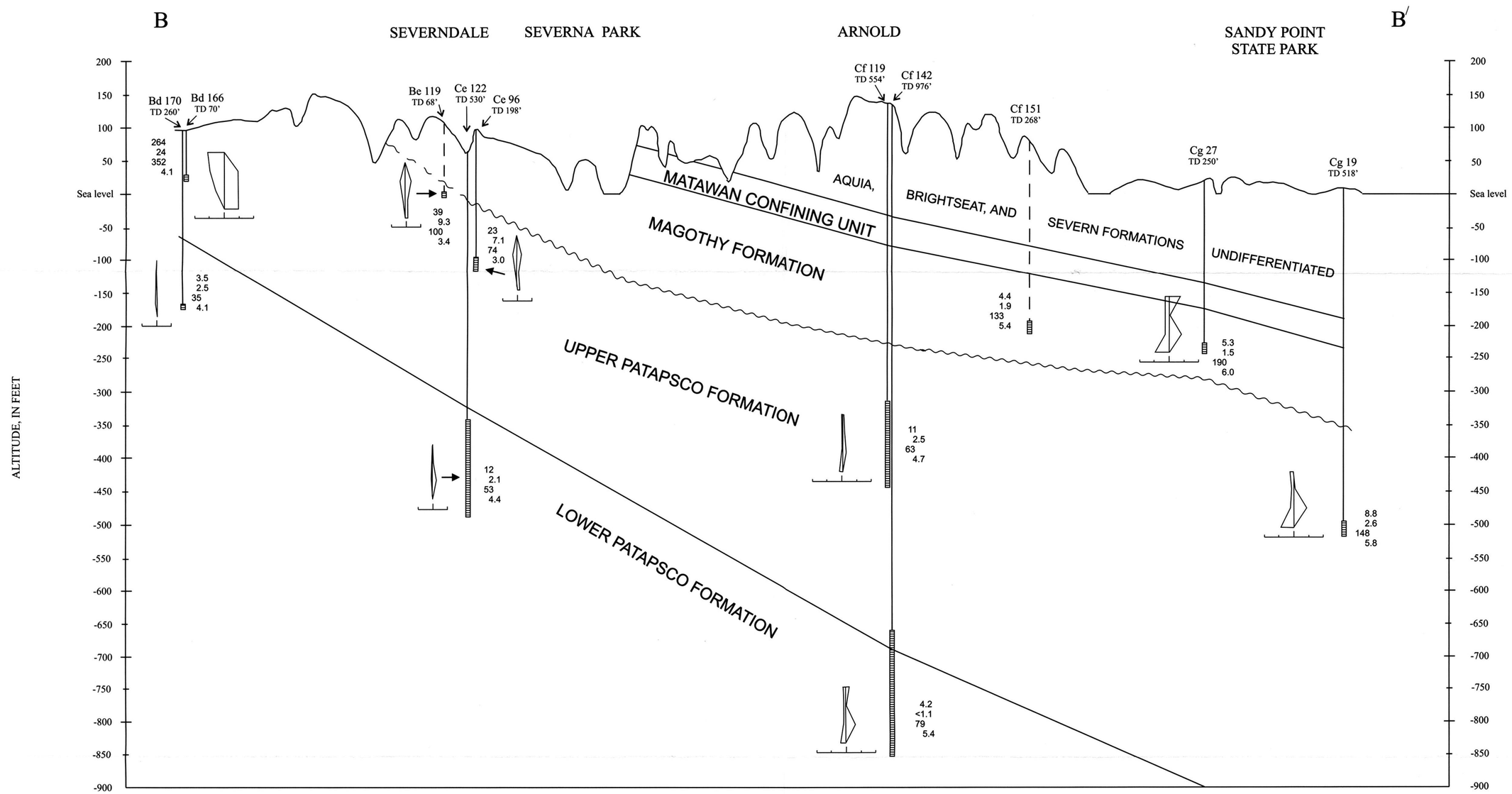


Bd 107.....Well number[1]
TD 240'.....Total depth of well

14.....Short-term gross alpha-particle activity (picocuries per liter)
4.3 .....Radium-226 plus radium-228 (picocuries per liter)
76.....Specific conductance (microsiemens per centimeter at 25 degrees Celsius)
4.2.....pH

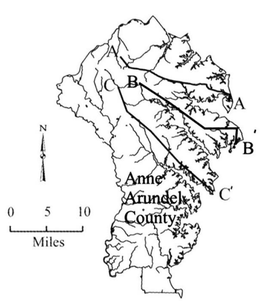
0 1 2 3 4 Miles

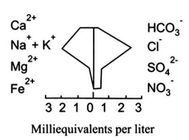
[1] All wells are in Anne Arundel County; the "AA" prefix has been omitted.

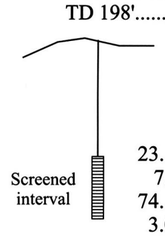


EXPLANATION

LOCATION OF TRANSECT





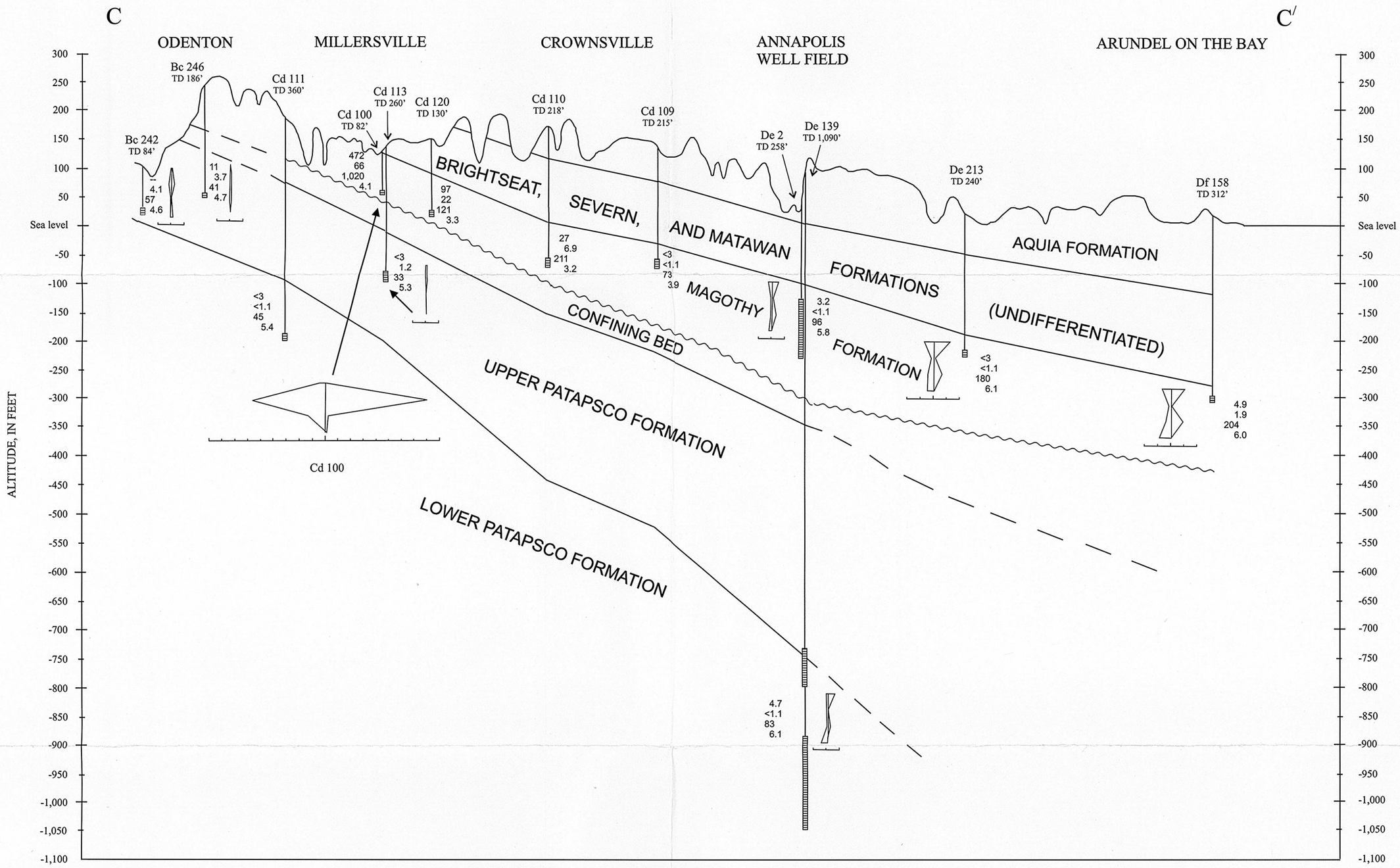


Ce 96.....Well number[1]
TD 198'.....Total depth of well

23.....Short-term gross alpha-particle activity (picocuries per liter)
7.1 .....Radium-226 plus radium-228 (picocuries per liter)
74.....Specific conductance (microsiemens per centimeter at 25 degrees Celsius)
3.0.....pH

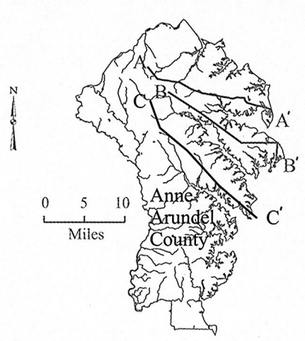
0 1 2 3 4 Miles

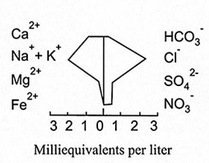
[1] All wells are in Anne Arundel County; the "AA" prefix has been omitted.

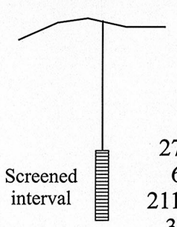


Cd 110.....Well number[1]
TD 218'.....Total depth of well

LOCATION OF TRANSECT







27.....Short-term gross alpha-particle activity (picocuries per liter)
6.9 .....Radium-226 plus radium-228 (picocuries per liter)
211.....Specific conductance (microsiemens per centimeter at 25 degrees Celsius)
3.2.....pH

0 1 2 3 4 Miles

[1] All wells are in Anne Arundel County; the "AA" prefix has been omitted.

Parris N. Glendening
Governor

Kathleen Kennedy Townsend
Lieutenant Governor

Sarah J. Taylor-Rogers
Secretary

Stanley K. Arthur
Deputy Secretary

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