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PILOT STUDY OF CARCINOGENS IN WELL WATER
IN ANNE ARUNDEL COUNTY, MARYLAND

by

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The Anne Arundel County Health Department
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Geological Survey
and
The U.S. Environmental Protection Agency

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PILOT STUDY OF CARCINOGENS IN WELL WATER IN ANNE ARUNDEL COUNTY, MARYLAND

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EXECUTIVE SUMMARY

BACKGROUND

A pilot study of carcinogens in domestic well water in Anne Arundel County was conducted by the Maryland Geological Survey (MGS) in cooperation with the U.S. Geological Survey (USGS), the U.S. Environmental Protection Agency (USEPA), the Anne Arundel County Health Department (AAHD), and the Anne Arundel County Department of Public Works. This study resulted from the recommendation of the Environmental Risks Subcommittee of the Anne Arundel County Advisory Task Force on Cancer Control.

Untreated water samples were collected from wells in areas where ground water is potentially at risk for the presence of carcinogens. Three areas were targeted: (1) areas of commercial and industrial land use or high-density residential development that are located in the general outcrop areas of the Patapsco, Magothy, and Aquia Formations, where well water may be susceptible to contamination by volatile organic compounds (VOCs) (referred to as VOC-targeted areas); (2) areas near current and former cropland in the general outcrop areas of the Patapsco, Magothy, and Aquia Formations, where well water may be susceptible to contamination by pesticides ("pesticide-targeted areas"); and (3) areas throughout Anne Arundel County (particularly in the Aquia Formation in southern part of the county), where few data were available on radon and other naturally occurring radionuclides and trace elements that may be dissolved in the water ("radon-targeted areas"). Areas potentially at risk were identified by use of a Geographic Information Systems (GIS) approach, which employed land-use and other digital coverages to generate maps of the targeted areas. Prioritized areas were visited to verify land use, interview residents about their wells, and obtain permission to sample. Because of the targeted selection process, the data from the study are not considered representative of all domestic wells in the county.

Untreated ("raw water") samples were collected from 47 wells (20 wells in each of the VOC- and pesticide-targeted areas and 7 wells in the radon-targeted area). Samples were collected from September through December 1997, and were analyzed for major ions (including iron, manganese, nitrate, and ammonia), the herbicides atrazine and metolachlor, radionuclides (uranium, radium-226, radium-228, radon, gross alpha- and gross beta-particle activity), arsenic, beryllium, lead, *E. coli*, total coliform bacteria, and a suite of volatile organic compounds. Because the radium concentrations from most of the wells from the Magothy and Patapsco Formations exceeded federal drinking water standards, resampling of selected wells took place in March 1998; samples were analyzed for radium-226, radium-228, radium-224 and short-term (measured within 3 days of sampling) and long-term (measured at about 30 days) gross alpha- and gross beta-particle activity.

SUMMARY OF KEY FINDINGS

- **Radium-226 plus radium-228 concentrations** exceeded the Maximum Contaminant Level (MCL) of 5 picocuries per liter (pCi/L) in 15 of 20 wells in the Magothy and Patapsco Formations in central and northern Anne Arundel County. The high radium values, which are believed to be from natural sources, were closely associated with acidic ground water (pH values less than 5.0); the highest **radium-226 plus radium-228 concentrations** (66 pCi/L) were in acidic water with relatively high (greater than 450 milligrams per liter, or mg/L) total dissolved-solids (TDS) content. Six samples exceeded the MCL of 15 pCi/L for **gross alpha-particle activity**, which reflects the high radium levels in the samples. **Radon concentrations** were all below 1,000 pCi/L, and tended to be higher in samples from wells in the Aquia Formation than from wells in the Magothy and Patapsco Formations. **Radium, radon, and gross alpha-particle activity** are classified as human carcinogens (cancer group A).
- **Radium-224** appears to comprise a major proportion of total radium and gross alpha-particle activity in the study area. Because radium-224 has a half-life of 3.64 days, **samples should be analyzed within three days of sample collection** in order to accurately assess total radium and gross alpha-particle activity.
- Most of the other constituents in cancer groups A, B2 (probable human carcinogens), and C (possible human carcinogens) were either not detected or were detected at low concentrations. **Arsenic** (cancer group A) and **chloroform** (cancer group B2) were detected in separate wells at concentrations above their current or proposed MCLs (respectively); other constituents in cancer group A, B2, or C that were analyzed in the study (including **uranium, beryllium, lead, and several VOCs**) did not exceed their respective current or proposed MCLs.
- There were no laboratory-confirmed detections of the herbicides **atrazine or metolachlor** (although there was one false-positive metolachlor detection by immunoassay).
- Water samples were generally low in **TDS** (median: 113 mg/L). Samples from the Patapsco and Magothy Formations had lower median values of **TDS, pH, calcium, alkalinity (bicarbonate), silica, iron, and manganese**, and higher median values of **sodium, chloride, nitrate, and dissolved oxygen** compared to samples from the Aquia Formation. Values of **pH** less than 4.0 were recorded in three Magothy wells and one Patapsco well, possibly as a result of pyrite oxidation. **Iron** was a major component in many wells; samples from 21 of 47 wells had iron concentrations exceeding the secondary MCL of 300 micrograms per liter ($\mu\text{g/L}$). **Nitrate** concentrations in three wells exceeded the MCL of 10 mg/L. **Chloride** concentrations exceeded 250 mg/L (the secondary MCL) in samples from two wells. Twenty-one wells tested positive for **total coliform bacteria**; one well tested positive for *E. coli*.

INTRODUCTION

In 1994, the Anne Arundel County Council established the Anne Arundel County Advisory Task Force on Cancer Control to review available information on factors contributing to the county's disproportionately high cancer death rate (compared to both the State of Maryland and the United States), and to recommend preventive measures. During the course of the Advisory Task Force's work, the Environmental Risks Subcommittee of the Advisory Task Force found that few data were available concerning carcinogens in domestic well water (Anne Arundel County Advisory Task Force on Cancer Control, 1996). To provide this information, a pilot study of carcinogens in domestic well water was conducted. The pilot study focused on areas that were considered to have the greatest potential for contamination by carcinogens. If high detection rates or concentrations of known or suspected carcinogens in domestic well water were found, a more detailed well-water-quality study, either at the county-wide level or in targeted areas, would be planned.

PURPOSE AND SCOPE

This pilot study was conducted to provide information on the occurrence and distribution of carcinogens and other chemical constituents in domestic well water in selected areas of Anne Arundel County. In this report, the hydrogeologic setting is discussed and a description of the study design is presented (including well selection, chemical constituents, and sampling and analytical methods). The occurrence and distribution of carcinogens in selected areas of the Patapsco, Magothy, and Aquia Formations in the county are discussed. Water-quality and well-construction data are included as Appendixes to this report.

ACKNOWLEDGMENTS

The study was a cooperatively funded project between the Anne Arundel County Health Department, the Anne Arundel County Department of Public Works, the U.S. Environmental Protection Agency, the U.S. Geological Survey, and the Maryland Geological Survey, which is part of the Resource Assessment Service of the Maryland Department of Natural Resources. Robert Weber and John Simpson (AAHD) and Harry Hansen (MGS) provided overall guidance for the project. William Deck and Brian Chew (AAHD) were indispensable in performing field reconnaissance and securing permission to sample wells. Thomas Pheiffer, Richard Kutz, and Joseph Slayton (USEPA), Richard Dixon (Anne Arundel County Water Operations Board), and Robert Shedlock (USGS) participated in discussions during project design. Andrew LaMotte of the USGS prepared GIS coverages. Lisa Olsen of the USGS provided assistance and materials for the preparation of VOC-free water for use in quality-control sampling. VOC sample preparation and analysis was facilitated by Susan Warner and Arnold Turner of the USEPA Region III Laboratory. Ann Mullin of the USGS National Water Quality Laboratory (NWQL) provided much useful information on radionuclides. L. Joseph Bachman (USGS) and Stephen R. Kraemer (USEPA) provided helpful comments as colleague reviewers. Figures were prepared by Cynthia Lang-Bachur, Timothy Auer (USGS), and Andrew LaMotte (USGS). Donajean Appel (MGS) did the manuscript layout. The authors gratefully acknowledge the well owners who granted permission to sample their wells.

WELL-NUMBERING SYSTEM

Wells in this report are identified by an alphanumeric system. The first two letters, both capitalized, indicate the county where the site is located (AA for Anne Arundel County). The next two letters (the first letter capitalized, the second letter 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 were numbered sequentially as they were inventoried. Thus, well AA Bf 68 refers to the sixty-eighth well inventoried in the block located at the intersection of row "B" and column "f" in Anne Arundel County. Because all wells sampled for this project were in Anne Arundel County, the "AA" has been dropped from the beginning of the well number when referring to specific wells in the text of this report.

HYDROGEOLOGIC SETTING

Anne Arundel County, located in the Coastal Plain Physiographic Province (fig. 1), is underlain by a southeastwardly-dipping sequence of unconsolidated sands, gravels, silts, and clays ranging in thickness from less than 100 feet (ft) in the northwestern part of the county to about 2,600 ft thick in the southeastern part (Hansen and Edwards, 1986). The unconsolidated sediments generally overlie crystalline rocks, which are not a significant source of water in the county. The basement rocks encountered in test wells in the county include microcline-bearing gneisses in the north-central part of the county, and sediments tentatively identified as the (Triassic) Newark Group at Sandy Point State Park on the Broadneck Peninsula (Hansen and Edwards, 1986).

In the northern part of the county, most domestic well water is derived from unconfined or semiconfined sands and gravels in the outcrop areas of the Potomac Group (including the

Patuxent and Patapsco Formations), the Magothy Formation, and the Aquia Formation (fig. 2). The Patapsco Formation consists of interbedded silt, clay, and argillaceous, quartzose sand deposited in a fluvial and paludal (swampy) environment. The Magothy Formation, which was deposited in a fluvio-marine environment, consists of medium- to coarse-grained quartzose sand and fine gravel interbedded with dark gray silts and clays, and lignite and pyrite (FeS_2) as important accessory minerals (Hansen, 1972). The Aquia Formation, however, was deposited in a marine environment and consists of fine- to coarse-grained sand interbedded with silts, clays, and indurated calcite-cemented sands and fossil beds; glauconite (a hydrous potassium iron silicate) and goethite (FeOOH) comprise between 20 and 70 percent of the formation (Hansen, 1972). The aquifers become progressively deeper to the south and east (fig. 3), and are overlain by relatively impermeable layers that result in confined ground-water conditions. The confined aquifers are replenished by infiltrating water in the recharge (outcrop) areas to the north and west, and to a lesser degree from water entering from the relatively impermeable layers above and below the aquifers. The confined aquifers are considered to be less susceptible to surface contamination than the unconfined aquifers. Most wells in the southern part of the county are completed in the Aquia Formation.

STUDY DESIGN

Well selection

This study focused on wells that are potentially at risk for the presence of carcinogens (tab. 1). These included: (1) wells near areas of commercial and industrial land use or dense residential development located in the general outcrop areas of the Patapsco, Magothy, and Aquia Formations, where well water may be susceptible to VOC contamination from commercial, industrial, or domestic (septic)

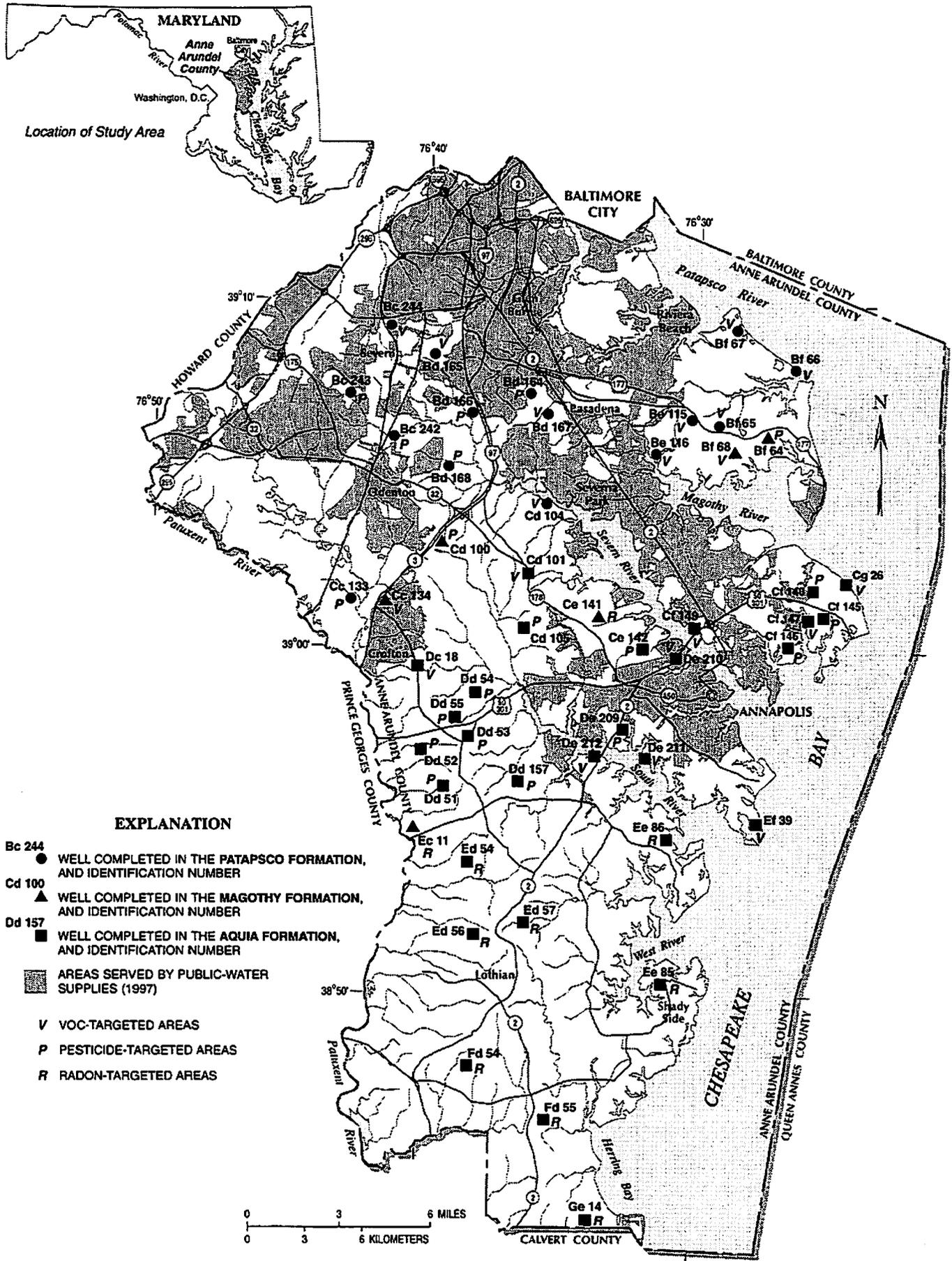


Figure 1. Map of Anne Arundel County showing well locations and areas served by public-water supplies. Source of data for public-water areas: Anne Arundel County Department of Planning and Code Enforcement.

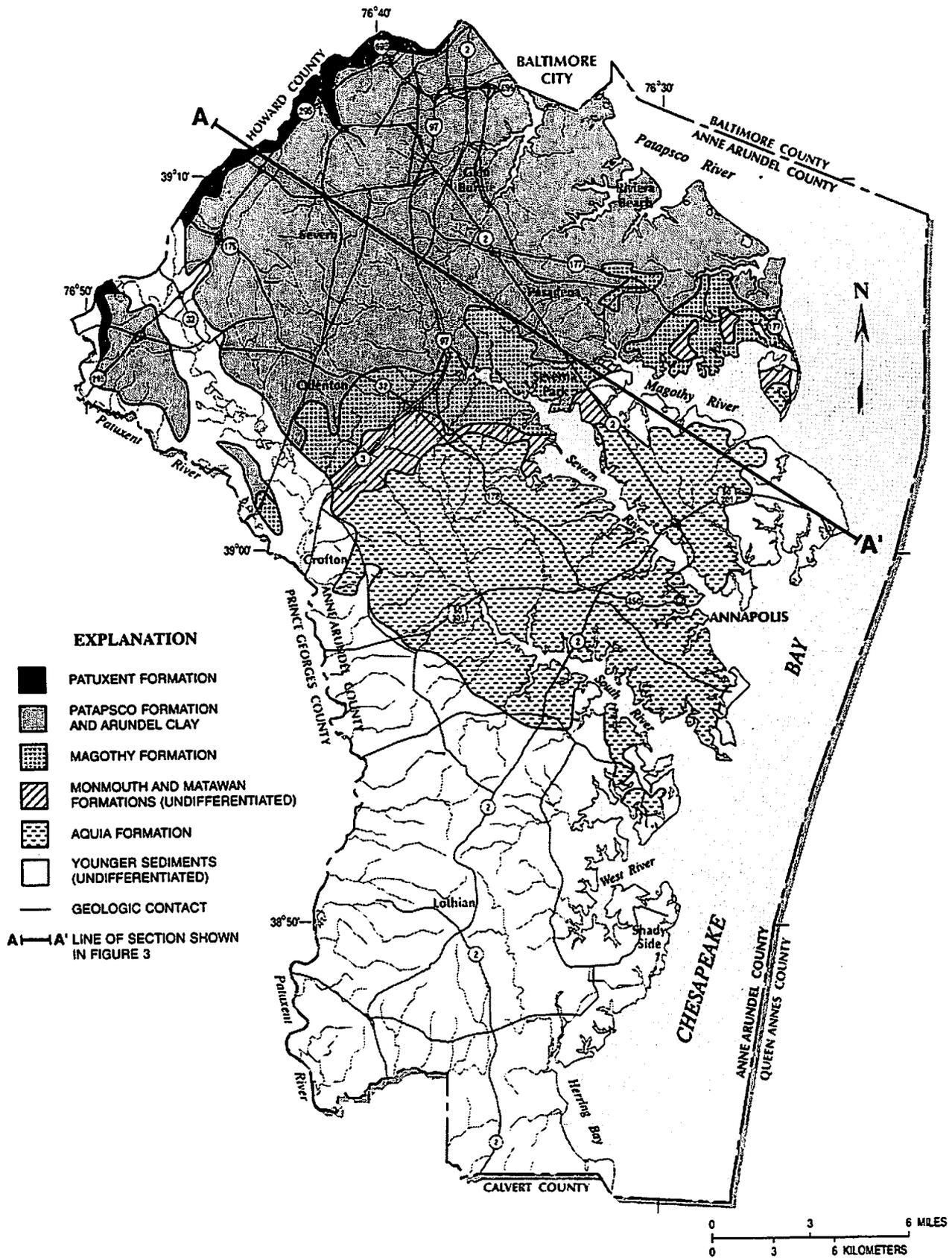


Figure 2. Map showing generalized outcrop areas of geologic formations in Anne Arundel County (Modified from Glaser, 1976).

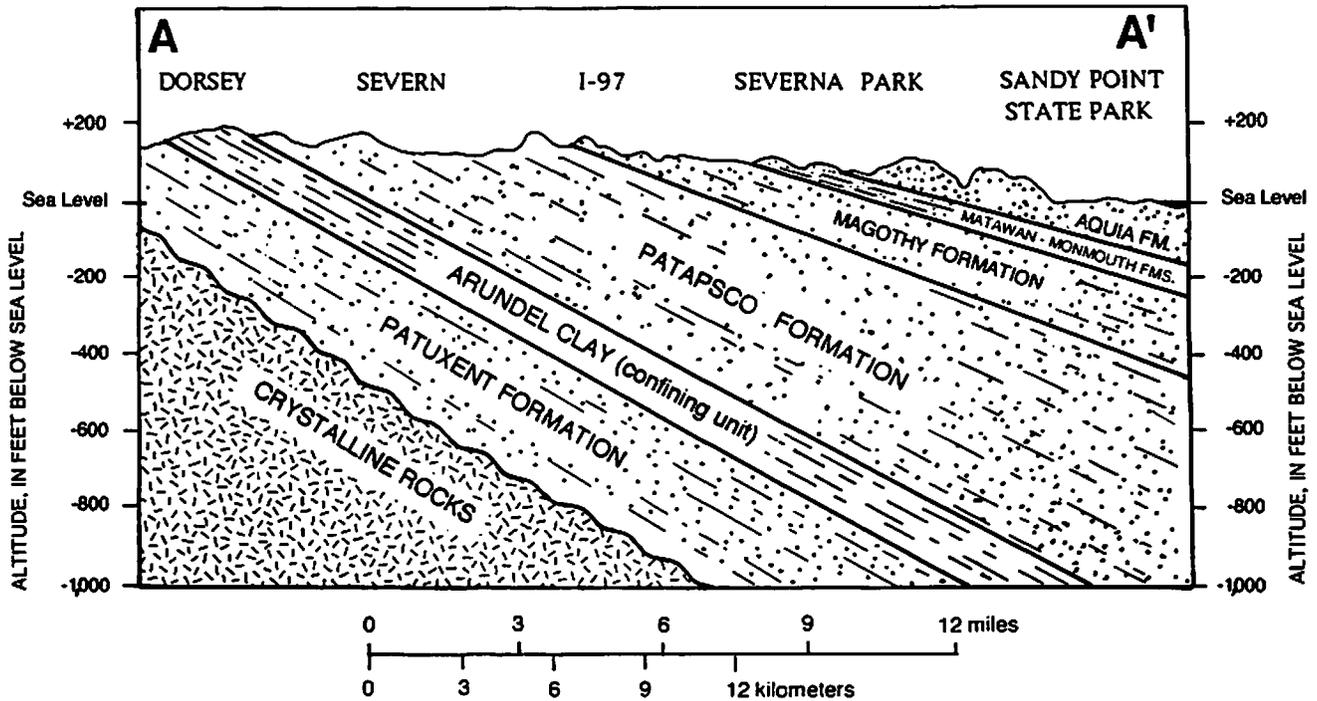


Figure 3. Generalized geologic section across Anne Arundel County. (Location of section is shown in Figure 2.)

effluent; (2) wells located near current and former cropland in the general outcrop areas of the Patapsco, Magothy, and Aquia Formations, where well water may be susceptible to contamination by pesticides; and (3) wells throughout Anne Arundel County (particularly in the Aquia Formation in the southern part of the county) where few data were available on radon and other naturally occurring radionuclides and trace elements that may be dissolved in ground water. These areas are referred to as VOC-targeted areas, pesticide-targeted areas, and radon-targeted areas, respectively. Within these targeted areas, the candidate population of wells consisted of all domestic water-supply wells (including dug wells and wells without construction documentation). Public-supply wells were excluded because they are already routinely tested for contaminants.

The VOC- and pesticide-targeted areas were

delineated using a Geographic Information Systems approach. Pesticide-targeted areas were identified by generating 1:24,000-scale maps showing all residential land not served by public water ("non-public water" areas) within 2,000 ft of current and former cropland. VOC-targeted areas were delineated by generating 1:24,000-scale maps showing all non-public water residential land within 2,000 ft of commercial or industrial land-use areas; densely populated residential subdivisions were also considered. Sub-areas within each of the targeted areas were identified and prioritized on the basis of groundwater flow direction (as inferred from potentiometric and topographic maps and other data). The prioritized sub-areas were visited to verify land use, interview residents about their wells, and obtain permission to sample. Wells completed in unconfined and semiconfined aquifers were given priority over confined-

Table 1. Summary of targeted areas for the Anne Arundel County pilot study of well-water quality

Potential carcinogenic risk in ground water	Targeted settings	Rationale
Volatile organic compounds	Outcrop areas of the Patapsco, Magothy, and Aquia Formations in or near commercial/industrial land use and densely populated residential areas ("VOC-targeted areas").	Volatile organic compounds may be present due to releases from commercial/industrial activity or septic effluent; unlikely to be a widespread problem in confined aquifers or in rural settings.
Pesticides	Outcrop areas of the Patapsco, Magothy, and Aquia Formations near areas of current or former cropland ("pesticide-targeted areas").	Atrazine and metolachlor were the most commonly detected pesticides in Baltimore County, which has similar land use.
Radon and other radionuclides	Confined and unconfined areas of the Patapsco, Magothy, and Aquia Formations throughout the county ("radon-targeted areas").	Few data are available concerning radionuclide concentrations and distribution in Maryland Coastal Plain aquifers.

aquifer wells. Shallow (less than 100 ft deep) wells were given preference. The wells in the radon-targeted areas were selected to achieve a broad spatial distribution in the confined part of the Aquia Formation in the southern part of the county. Fifty domestic wells were selected for sampling (48 drilled and 2 dug wells; fig. 1), including 20 wells in the VOC-targeted areas, 20 wells in the pesticide-targeted areas, and 10 wells in the radon-targeted areas. Wells in the pesticide- and VOC-targeted areas tended to be shallower than wells in the radon-targeted area (tab. 2).

Chemical Constituents

Samples were analyzed for a suite of VOCs, the herbicides atrazine and metolachlor, radionuclides, *Escherichia coli* (*E. coli*) and total coliform bacteria, major ions, nitrate, ammonia, and trace elements (app. C1). All the samples were analyzed for the same constituents rather than analyzing for particular constituents in each targeted area. Specific conductance, pH, dissolved oxygen, alkalinity, and water temperature were also measured at each site.

The radionuclides and most of the VOCs belong to cancer groups A (human carcinogens), B2 (probable human carcinogens), or C (possible human carcinogens). (See appendix C for definitions of cancer groups.) The major ions

Table 2. Summary of well depths from the Anne Arundel County pilot study in relation to aquifers and targeted areas

Well-group categories	Well depth (ft below land surface)			Number of wells
	Median	Minimum	Maximum	
All wells	82	30	371	47
Magothy and Patapsco wells	83	57	205	20
Aquia wells	82	30	371	27
Pesticide-targeted wells	83	30	135	20
VOC-targeted wells	73	30	130	20
Radon-targeted wells	275	43	371	7

and field data were measured primarily to identify the hydrochemical characteristics of the principal aquifers in the county.

VOCs include industrial chemicals such as chloroform, vinyl chloride, and other known or suspected carcinogens. Atrazine and metolachlor were analyzed because they are possible human carcinogens, and they were the two of the most frequently detected pesticides in a recent water-quality study in Baltimore County (Bolton, 1998). Confirmation samples from four wells were analyzed for atrazine, metolachlor, and 22 additional pesticides by use of gas chromatography/mass spectrometry (GC/MS) at the NWQL to confirm the immunoassay results. Radionuclides selected for analysis included radon-222 (hereafter referred to as radon), radium-226, radium-228, uranium, and gross alpha- and gross beta-particle activity¹. These constituents are all in cancer group A. Arsenic, beryllium, and lead were analyzed because they are either known or probable human carcinogens.

Fifty wells were sampled from September through December 1997 (Phase 1 sampling). Samples from three of the ten wells in the radon-targeted areas were determined to have been treated by water-softening systems; the data from these wells are not discussed in this report. A second phase of sampling was conducted in March 1998 in response to the high concentrations of radium and gross alpha- and gross beta-particle activity. Selected wells that had been sampled in Phase 1 were resampled and analyzed for radium-226, radium-228, radium-224, and long-term and short-term gross alpha-particle activity.

¹ Gross alpha- and gross beta-particle activities were measured approximately 30 days after sampling, and are referred to as "long-term" gross alpha- and gross beta-particle activities in order to distinguish them from "short-term" (measured approximately 3 days after sampling) gross alpha-particle activity, which was analyzed in the second sampling phase of the pilot study.

Sampling Methods

Sampling methods are briefly described here; they are discussed in greater detail in the quality-assurance (QA) project plan that was prepared for this project.² Water samples were collected and processed in a consistent manner in order to minimize variability between sampling sites and to maximize data comparability. Each type of sample was collected and processed in accordance with the established protocols of the laboratory analyzing that sample type. All samples were collected by the same personnel using the same field vehicle (a dedicated van equipped specifically for water-quality sampling). Prior to the sample-collection phase of the study, sampling personnel completed a Maryland Department of the Environment certification program for the collection of drinking-water samples.

The sample-collection process included calibration of field equipment, well purging, monitoring field parameters, sample collection, treatment, storage, and transport. The specific conductance, pH, and dissolved-oxygen meters were calibrated at the beginning of each sampling day in accordance with manufacturers' instructions. Once the field equipment had been calibrated, the well purging began. A hose was attached to the nearest "raw water" (untreated) spigot closest to the well. For most houses, this was an outside tap; when possible, the pressure-tank spigot was used. The water was allowed to run at a rate of approximately 2 gallons per minute (gpm). Specific conductance, pH, dissolved oxygen, and water temperature measurements were recorded at 5-minute intervals until the following stabilization criteria were met over three consecutive readings: pH, ± 0.05 pH units; specific conductance, ± 5 percent (if specific conductance was greater than 100 microsiemens per centimeter [$\mu\text{S}/\text{cm}$] or

² The QA project plan is on file at the Maryland Geological Survey, 2300 St. Paul St., Baltimore, Maryland 21218.

$\pm 5 \mu\text{S}/\text{cm}$ (if specific conductance was less than $100 \mu\text{S}/\text{cm}$); temperature, ± 0.5 degrees Celsius. Dissolved oxygen was not used as a purge criteria because a dissolved-oxygen probe was not always available (in which case dissolved oxygen was measured by titration). Wells were not purged of a pre-determined volume of water (such as three casing volumes) because the wells were assumed to be used daily.

Samples were collected once the stabilization criteria had been met. Sample containers, preservatives, and treatments are specified in appendixes C1 and C2. Unfiltered samples were collected directly from the sample spigot. To obtain water for filtered samples, a 5-liter (L) precleaned amber glass bottle (or bottles) was double-rinsed with sample water, filled, and brought into the sampling vehicle where the water was filtered. Samples were filtered through disposable 0.45-micron Gelman³ capsule filters using a peristaltic pump. Radon samples were collected from the end of the discharge hose because of the impracticality of sampling directly from the pressure-tank spigot. To avoid exposing the radon sample to air, samples were collected by inserting a syringe through a teflon diaphragm, filling it under positive pressure, injecting a 10-cubic centimeter sample into mineral oil, and shaking for 30 seconds to dissolve the radon gas in the oil. After samples had been processed (filtered and/or preservatives added as necessary), alkalinity was determined by digital titration with sulfuric acid (0.1600N or 1.600N, depending upon the pH and specific conductance).

Analytical Methods

Analytical procedures for all constituents are referenced in appendix C1. Major ions, trace elements, gross alpha- and gross beta-particle activity, and pesticide confirmation samples were

analyzed by the USGS NWQL in Arvada, Colorado. VOCs were analyzed by the USEPA Region III Office of Analytical Services and Quality Assurance (Annapolis, Maryland). Atrazine and metolachlor were analyzed at the MGS laboratory using an immunosorbent assay method (Lawruk and others, 1993; Hayes and others, 1996). Bacteria and nutrient samples were analyzed by the Maryland Department of Health and Mental Hygiene Laboratory Administration (Baltimore, Maryland). Radium-226 and radium-228 analyses were performed by Quanterra Environmental Services (Richland, Washington) under contract to the NWQL. Radium-224 analyses for samples collected in Phase 2 were performed by the Radioanalytical Services section of the New Jersey Department of Health and Senior Services (Trenton, New Jersey), and by the USGS radiochemistry laboratory in Reston, Virginia. Documentation, reagent preparation, instrument calibration and maintenance, and other quality-assurance measures of the NWQL are presented in Pritt and Raese (1995). Data validation for VOCs analyzed by the USEPA laboratory are described in U.S. Environmental Protection Agency (1994).

Quality Assurance

The QA project plan describes quality-assurance and quality-control elements of the project, including: experimental design features; project responsibilities; communications procedures; site selection, documentation, and sampling-related procedures; quality-assurance objectives; data reduction, validation, and reporting; and corrective actions. Quality-control samples were collected to measure bias and variability of the sampling and analytical methods, and to identify and correct any problems that arose during the sampling period. These data are summarized in Appendix D.

³ The use of trade names is meant for identification purposes only and does not constitute endorsement.

WATER QUALITY

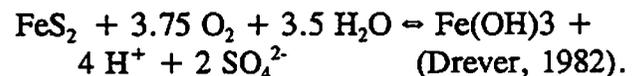
INORGANIC WATER QUALITY

This section discusses aspects of inorganic water quality from 47 untreated water samples collected during this study. (Samples from three radon-targeted wells [Ec 11, Ed 56, and Ed 85] were determined to have been treated by water-softening systems thought to have been bypassed at the time of sampling. The data from these wells are not included in this discussion but are included in the data tables in appendix A.) Because of the targeted selection process, this discussion applies only to the target population of wells and may not apply to any larger population of wells. Statistical tests were not performed on the water-quality data because the wells were selected from specifically targeted areas and do not represent a random sample of wells in the county.

Water samples were generally low in TDS (median: 113 mg/L), but contained chemical differences related to the aquifers. Samples from wells in the Patapsco and Magothy Formations had lower median values of TDS, pH, calcium, alkalinity (bicarbonate), silica, iron, and manganese, and higher median values of sodium, chloride, nitrate, and dissolved oxygen than samples from wells in the Aquia Formation (tab. 3). These differences generally reflect the lithologic and hydrogeologic characteristics of the aquifers. The Patapsco and Magothy Formations consist of siliciclastic sands, silts, and clays, which are composed of relatively unreactive minerals such as quartz. The Aquia Formation, however, contains abundant calcite-cemented sands and fossil beds. Calcium carbonate dissolution results in generally higher pH, alkalinity, calcium, and TDS in samples from the Aquia Formation as compared to samples from the Magothy and Patapsco Formations. Although there are iron-bearing minerals in all of the aquifers sampled, ground-water iron concentrations are controlled by the

dissolved-oxygen content of the ground water. Samples from the relatively deep wells and wells in the confined aquifers tend to be anoxic (indicated for this study by dissolved oxygen concentrations of less than 1 mg/L), which facilitates high iron concentrations. Samples from the shallow wells in the unconfined parts of the aquifers tend to be oxygenated and cannot support iron in solution. The chemical compositions of samples from selected wells are shown in figure 4.

Three wells in the Magothy Formation had pH values below 4.0. This is below the pH of precipitation as measured in Carroll County and Queen Anne's County, which was about 4.1 to 4.3 (National Atmospheric Deposition Program/National Trends Network, 1996). The Magothy Formation is generally lacking in reactive minerals, such as feldspars, that consume acid during the weathering process. Hydrogen ions made up more than 15 percent of cation milliequivalents per liter in three wells (Bf 64, completed in the Magothy Formation, and Bf 65 and Cc 133, both completed in the Patapsco Formation). Pyrite oxidation is a mechanism for generating acidic ground water, as shown by the following generalized reaction:



Iron comprised more than 10 percent of cation milliequivalents in nine wells (eight Aquia wells and one Magothy well). Iron concentrations ranged from < 10 to 42,000 $\mu\text{g/L}$ (median value: 220 $\mu\text{g/L}$). Twenty-one of the 47 wells had iron concentrations greater than 300 $\mu\text{g/L}$ (the secondary MCL for iron); 17 of these exceeded 1,000 $\mu\text{g/L}$. All seven wells with iron concentrations greater than 10,000 $\mu\text{g/L}$ were completed in the Aquia Formation.

(Text continued on p. 20.)

Table 3. Summary of pilot study water-quality data in relation to aquifers and targeted areas

[$\mu\text{S/cm}$, microsiemens per centimeter; mg/L , milligrams per liter; μ , microns; $\mu\text{g/L}$, micrograms per liter; pCi/L , picocuries per liter]

Chemical constituent and well-group categories	Median	Minimum	Maximum	Number of samples
Specific conductance ($\mu\text{S/cm}$ at 25° Celsius)				
All wells	217	26	1,290	47
Magothy and Patapsco wells	170	26	1,290	20
Aquia wells	240	58	65	27
Pesticide-targeted wells	190	26	1,020	20
VOC-targeted wells	179	58	1,290	20
Radon-targeted wells	313	100	578	7
Total dissolved solids (residue on evaporation) (mg/L at 180° Celsius)				
All wells	113	15	493	46
Magothy and Patapsco wells	92	15	493	19
Aquia wells	153	30	355	27
Pesticide-targeted wells	93	15	493	20
VOC-targeted wells	113	30	353	19
Radon-targeted wells	189	103	355	7
pH				
All wells	4.9	3.5	7.7	47
Magothy and Patapsco wells	4.3	3.5	5.9	20
Aquia wells	5.9	4.1	7.7	27
Pesticide-targeted wells	4.9	3.5	7.3	20
VOC-targeted wells	4.6	3.7	6.8	20
Radon-targeted wells	7.2	5.9	7.7	7
Alkalinity (mg/L as CaCO_3)				
All wells	6	<1	200	47
Magothy and Patapsco wells	<1	<1	23	20
Aquia wells	46	<1	200	27
Pesticide-targeted wells	4.5	<1	94	20
VOC-targeted wells	1.5	<1	192	20
Radon-targeted wells	176	23	200	7
Dissolved oxygen (mg/L)				
All wells	2.8	<1	9.3	47
Magothy and Patapsco wells	7.25	<1	9.3	20
Aquia wells	<1	<1	8.6	27
Pesticide-targeted wells	3.55	<1	9.3	20
VOC-targeted wells	4.8	<1	8.4	20
Radon-targeted wells	<1	<1	<1	7

Table 3. Summary of pilot study water-quality data in relation to aquifers and targeted areas
 -- Continued

[μ S/cm, microsiemens per centimeter; mg/L, milligrams per liter; μ , microns;
 μ g/L, micrograms per liter; pCi/L, picocuries per liter]

Chemical constituent and well-group categories	Median	Minimum	Maximum	Number of samples
Calcium (mg/L)				
All wells	8	0.36	94	47
Magothy and Patapsco wells	5.65	0.36	22	20
Aquia wells	14	0.88	94	27
Pesticide-targeted wells	7.5	0.36	48	20
VOC-targeted wells	6.35	0.88	78	20
Radon-targeted wells	45	5.9	94	7
Magnesium (mg/L)				
All wells	3.4	0.15	17	47
Magothy and Patapsco wells	3.4	0.15	15	20
Aquia wells	3.1	0.75	17	27
Pesticide-targeted wells	2.8	0.15	15	20
VOC-targeted wells	3.2	1.1	17	20
Radon-targeted wells	8	2.1	11	7
Sodium (mg/L)				
All wells	5.1	0.97	187	47
Magothy and Patapsco wells	13.5	1	187	20
Aquia wells	2.9	0.97	39	27
Pesticide-targeted wells	3.45	0.97	130	20
VOC-targeted wells	15.5	1.2	187	20
Radon-targeted wells	2.9	2.1	9	7
Potassium (mg/L)				
All wells	3.3	0.4	9.4	47
Magothy and Patapsco wells	2.2	0.4	8.7	20
Aquia wells	3.8	1.5	9.4	27
Pesticide-targeted wells	3.2	0.4	8.7	20
VOC-targeted wells	2.75	1.1	7.8	20
Radon-targeted wells	4.4	3.1	9.4	7
Chloride (mg/L)				
All wells	16	0.14	310	46
Magothy and Patapsco wells	21	1.3	310	19
Aquia wells	7.1	0.14	180	27
Pesticide-targeted wells	10.55	0.14	290	20
VOC-targeted wells	27	1.6	310	19
Radon-targeted wells	1.6	0.61	75	7

Table 3. Summary of pilot study water-quality data in relation to aquifers and targeted areas
 -- Continued

[μ S/cm, microsiemens per centimeter; mg/L, milligrams per liter; μ , microns;
 μ g/L, micrograms per liter; pCi/L, picocuries per liter]

Chemical constituent and well-group categories	Median	Minimum	Maximum	Number of samples
Sulfate (mg/L)				
All wells	11.5	<0.10	110	46
Magothy and Patapsco wells	13	0.19	110	19
Aquia wells	9.1	<0.10	40	27
Pesticide-targeted wells	9.25	<0.10	46	20
VOC-targeted wells	12	0.58	110	19
Radon-targeted wells	13	5.7	40	7
Fluoride (mg/L)				
All wells	<0.10	<0.10	0.61	47
Magothy and Patapsco wells	<0.10	<0.10	0.30	20
Aquia wells	0.14	<0.10	0.61	27
Pesticide-targeted wells	<0.10	<0.10	0.61	20
VOC-targeted wells	<0.10	<0.10	0.31	20
Radon-targeted wells	0.19	0.11	0.30	7
Silica (mg/L as SiO₂)				
All wells	17	6	51	47
Magothy and Patapsco wells	9.15	6	51	20
Aquia wells	22	14	46	27
Pesticide-targeted wells	18	6.3	46	20
VOC-targeted wells	12.5	6	41	20
Radon-targeted wells	18	14	51	7
Color (platinum-cobalt units)				
All wells	2	<1	160	47
Magothy and Patapsco wells	<1	<1	110	20
Aquia wells	3	<1	160	27
Pesticide-targeted wells	2.5	<1	160	20
VOC-targeted wells	<1	<1	100	20
Radon-targeted wells	3	1	110	7
Iron (0.45μ-filtered) (μg/L)				
All wells	140	<3	41,300	47
Magothy and Patapsco wells	13.5	<3	9,000	20
Aquia wells	610	<10	41,300	27
Pesticide-targeted wells	375	<3	41,300	20
VOC-targeted wells	55	<3	17,000	20
Radon-targeted wells	270	56	9,000	7

Table 3. Summary of pilot study water-quality data in relation to aquifers and targeted areas
-- Continued

[μ S/cm, microsiemens per centimeter; mg/L, milligrams per liter; μ , microns;
 μ g/L, micrograms per liter; pCi/L, picocuries per liter]

Chemical constituent and well-group categories	Median	Minimum	Maximum	Number of samples
Iron (unfiltered) (μg/L)				
All wells	220	<10	42,000	47
Magothy and Patapsco wells	20	<10	7,800	20
Aquia wells	690	<10	42,000	27
Pesticide-targeted wells	505	<10	42,000	20
VOC-targeted wells	65	<10	17,000	20
Radon-targeted wells	300	60	7,800	7
Manganese (0.45μ-filtered) (μg/L)				
All wells	37	4.2	488	47
Magothy and Patapsco wells	27.5	4.2	448	20
Aquia wells	53	5.8	488	27
Pesticide-targeted wells	82.5	4.2	488	20
VOC-targeted wells	36	15	378	20
Radon-targeted wells	30	5.8	161	7
Manganese (unfiltered) (μg/L)				
All wells	39	<10	510	47
Magothy and Patapsco wells	29.5	<10	460	20
Aquia wells	53	<10	510	27
Pesticide-targeted wells	82	<10	510	20
VOC-targeted wells	34	<10	350	20
Radon-targeted wells	28	<10	97	7
Lead (μg/L)				
All wells	<1	<1	12	47
Magothy and Patapsco wells	1	<1	8	20
Aquia wells	<1	<1	12	27
Pesticide-targeted wells	<1	<1	8	20
VOC-targeted wells	1	<1	12	20
Radon-targeted wells	<1	<1	<1	7
Arsenic (μg/L)				
All wells	<1	<1	110	47
Magothy and Patapsco wells	<1	<1	110	20
Aquia wells	<1	<1	1	27
Pesticide-targeted wells	<1	<1	4	20
VOC-targeted wells	<1	<1	110	20
Radon-targeted wells	<1	<1	1	7

Table 3. Summary of pilot study water-quality data in relation to aquifers and targeted areas
 -- Continued

[μ S/cm, microsiemens per centimeter; mg/L, milligrams per liter; μ , microns;
 μ g/L, micrograms per liter; pCi/L, picocuries per liter]

Chemical constituent and well-group categories	Median	Minimum	Maximum	Number of samples
Beryllium (μg/L)				
All wells	<2	<2	3.1	47
Magothy and Patapsco wells	<2	<2	3.1	20
Aquia wells	<2	<2	3	27
Pesticide-targeted wells	<2	<2	2.6	20
VOC-targeted wells	<2	<2	3.1	20
Radon-targeted wells	<2	<2	3	7
Nitrate-plus-nitrite (mg/L as N)				
All wells	0.5	<0.2	20.5	47
Magothy and Patapsco wells	2.65	<0.2	13	20
Aquia wells	<0.2	<0.2	20.5	27
Pesticide-targeted wells	0.45	<0.2	20.5	20
VOC-targeted wells	2.25	<0.2	11.4	20
Radon-targeted wells	<0.2	<0.2	6.3	7
Ammonium (mg/L as N)				
All wells	<0.2	<0.2	3.2	47
Magothy and Patapsco wells	<0.2	<0.2	3.2	20
Aquia wells	<0.2	<0.2	0.3	27
Pesticide-targeted wells	<0.2	<0.2	0.3	20
VOC-targeted wells	<0.2	<0.2	3.2	20
Radon-targeted wells	<0.2	<0.2	<0.2	7
Total Coliform bacteria				
All wells	26 negative, 21 positive			47
Magothy and Patapsco wells	15 negative, 5 positive			20
Aquia wells	11 negative, 16 positive			27
Pesticide-targeted wells	7 negative, 13 positive			20
VOC-targeted wells	14 negative, 6 positive			20
Radon-targeted wells	5 negative, 2 positive			7
<i>Escherichia coli</i> (<i>E. coli</i>)				
All wells	46 negative, 1 positive			47
Magothy and Patapsco wells	20 negative, 0 positive			20
Aquia wells	26 negative, 1 positive			27
Pesticide-targeted wells	20 negative, 0 positive			20
VOC-targeted wells	19 negative, 1 positive			20
Radon-targeted wells	7 negative, 0 positive			7

Table 3. Summary of pilot study water-quality data in relation to aquifers and targeted areas
-- Continued

[μ S/cm, microsiemens per centimeter; mg/L, milligrams per liter; μ , microns;
 μ g/L, micrograms per liter; pCi/L, picocuries per liter]

Chemical constituent and well-group categories	Median	Minimum	Maximum	Number of samples
Atrazine (μg/L)				
All wells	<0.1	<0.1	<0.1	47
Magothy and Patapsco wells	<0.1	<0.1	<0.1	20
Aquia wells	<0.1	<0.1	<0.1	27
Pesticide-targeted wells	<0.1	<0.1	<0.1	20
VOC-targeted wells	<0.1	<0.1	<0.1	20
Radon-targeted wells	<0.1	<0.1	<0.1	10
Metolachlor (μg/L)				
All wells	<0.1	<0.1	0.2 ¹	47
Magothy and Patapsco wells	<0.1	<0.1	0.2 ¹	20
Aquia wells	<0.1	<0.1	<0.1	27
Pesticide-targeted wells	<0.1	<0.1	0.2 ¹	20
VOC-targeted wells	<0.1	<0.1	<0.1	20
Radon-targeted wells	<0.1	<0.1	<0.1	7
Radon (pCi/L)				
All wells	292	106	989	47
Magothy and Patapsco wells	180	106	436	20
Aquia wells	328	149	989	27
Pesticide-targeted wells	280.5	106	726	20
VOC-targeted wells	286.5	110	989	20
Radon-targeted wells	299	228	486	7
Gross alpha-particle activity (pCi/L)				
All wells	<3	<3	110	47
Magothy and Patapsco wells	10.55	<3	110	20
Aquia wells	<3	<3	5.5	27
Pesticide-targeted wells	<3	<3	79	20
VOC-targeted wells	7.35	<3	110	20
Radon-targeted wells	<3	<3	4.9	7
Gross beta-particle activity (pCi/L)				
All wells	5.9	<4	88	47
Magothy and Patapsco wells	22	<4	88	20
Aquia wells	5	<4	10	27
Pesticide-targeted wells	4.8	<4	80	20
VOC-targeted wells	11	<4	88	20
Radon-targeted wells	6.2	<4	10	7

Table 3. Summary of pilot study water-quality data in relation to aquifers and targeted areas
 -- Continued

[μ S/cm, microsiemens per centimeter; mg/L, milligrams per liter; μ , microns;
 μ g/L, micrograms per liter; pCi/L, picocuries per liter]

Chemical constituent and well-group categories	Median	Minimum	Maximum	Number of samples
Radium-226 (pCi/L)				
All wells	0.1	<0.1	33	47
Magothy and Patapsco wells	4.8	<0.1	33	20
Aquia wells	<0.1	<0.1	1.1	27
Pesticide-targeted wells	<0.1	<0.1	31	20
VOC-targeted wells	2.7	<0.1	33	20
Radon-targeted wells	<0.1	<0.1	0.3	7
Radium-228 (pCi/L)				
All wells	<1	<1	35	47
Magothy and Patapsco wells	8.7	<1	35	20
Aquia wells	<1	<1	1.1	27
Pesticide-targeted wells	<1	<1	35	20
VOC-targeted wells	4.85	<1	33	20
Radon-targeted wells	<1	<1	<1	7
Uranium (μg/L)				
All wells	<1	<1	14	47
Magothy and Patapsco wells	<1	<1	14	20
Aquia wells	<1	<1	<1	27
Pesticide-targeted wells	<1	<1	<1	20
VOC-targeted wells	<1	<1	14	20
Radon-targeted wells	<1	<1	<1	7

¹ Metolachlor not detected in the same sample when analyzed by gas chromatography/mass spectrometry

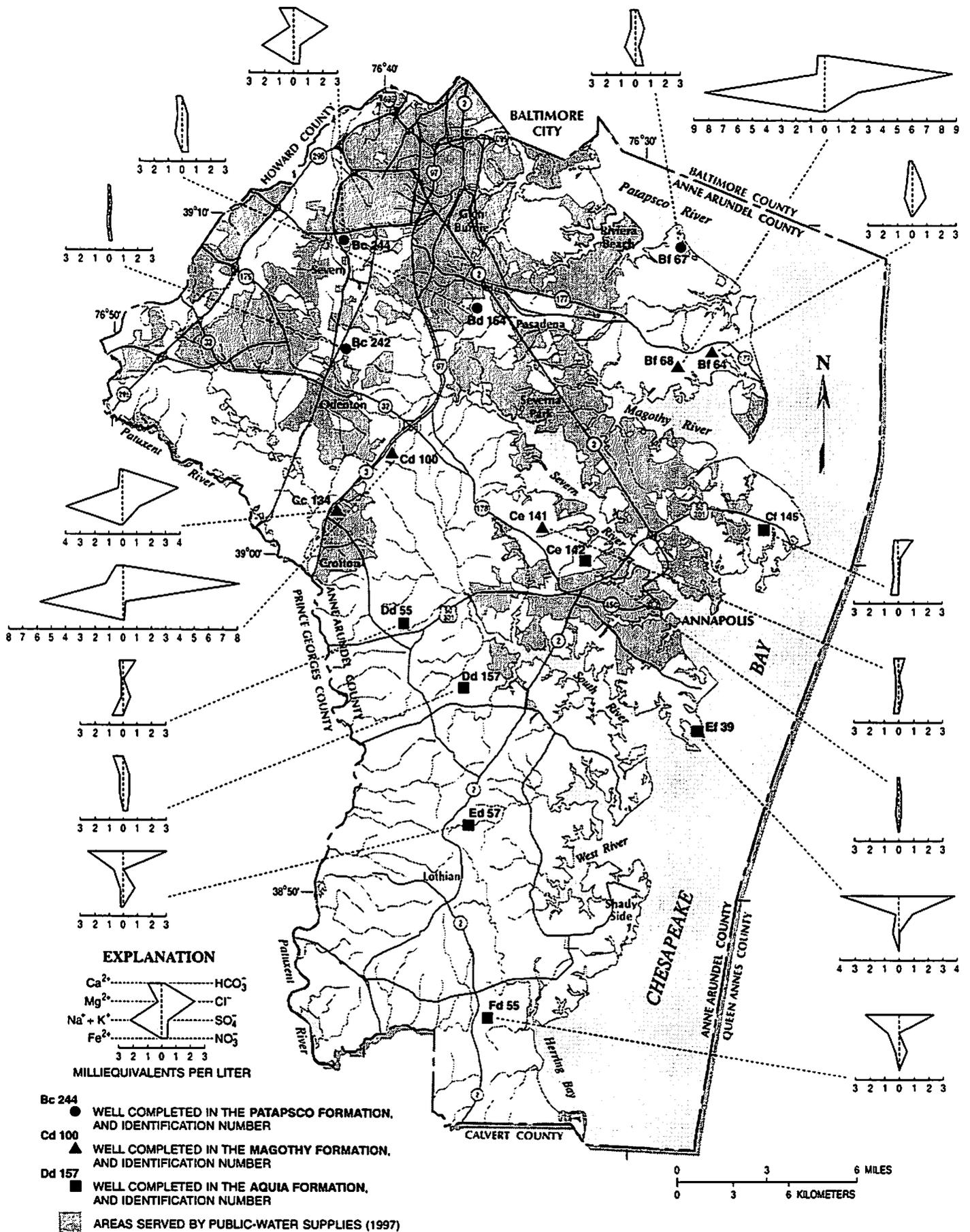
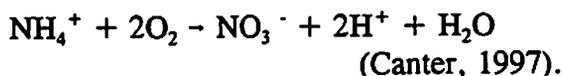


Figure 4. Map showing Stiff diagrams of selected wells in the Patapsco, Magothy, and Aquia Formations in Anne Arundel County, Maryland. Source of data for public-water areas: Anne Arundel County Department of Planning and Code Enforcement.

Nitrate concentrations ranged from less than 0.2 to 20.5 mg/L as nitrogen (median: 0.5 mg/L). (Samples were analyzed for nitrate-plus-nitrite; in this report, nitrate refers to the nitrate-plus-nitrite analyses because nitrite concentrations are assumed to be negligible. All nitrate and ammonia analyses are reported as nitrogen.) Detectable amounts (>0.2 mg/L) of nitrate were present in 27 of the 47 untreated samples. Samples from three wells exceeded 10 mg/L (the MCL for nitrate). Two of these wells (Bd 166 and Be 116) are less than 75 ft deep and are located in densely populated residential developments; the third (Cd 105) is a dug well located within an enclosed dog kennel. Detectable amounts (>0.2 mg/L) of ammonium were present in samples from 9 of 47 wells (range: 0.2–3.2 mg/L). At the pH range encountered in this study, any ammonia nitrogen in solution is assumed to be in the form of the ammonium ion (NH₄⁺) (Hem, 1985).

High concentrations of nitrate have been associated with methemoglobinemia ("blue baby syndrome") in infants, in which the blood's capacity to transport oxygen is diminished (Canter, 1997). Sources of nitrate to ground water include nitrogen in precipitation, organic matter in soils, fertilizers, and human and animal wastes. Virtually all nitrate in ground water is produced by the bacterially mediated oxidation of ammonium (NH₄⁺) to nitrite (NO₂⁻) and then to nitrate (NO₃⁻) (Hallberg and Keeney, 1993). This nitrification process can be shown by the overall reaction:



Nitrate is generally absent in anoxic waters, presumably due to denitrification (the process by which nitrate is reduced to gaseous nitrogen [either N₂ or N₂O]). Only one of the 17 anoxic water samples (from well Ee 86) had detectable nitrate. Five of these 17 wells had chloride concentrations above 15 mg/L, which suggests that the ground-water quality has been affected

by human activity. Therefore, the lack of nitrate indicates that either there has been a lack of nitrogen inputs or that the hydrochemical conditions are favorable to denitrification.

Concentrations of chloride ranged from 0.14 to 310 mg/L (median: 16 mg/L). Chloride concentrations above approximately 250 mg/L cause water to taste salty and can be corrosive to well pumps, appliances, and other plumbing fixtures. The chloride concentrations exceeded 250 mg/L (the secondary MCL for chloride) in only two wells (Bf 68, 310 mg/L; Cd 100, 290 mg/L). Potential sources of ground-water chloride in the study area include deicing salts, septic-system effluent, brine from rejuvenation of water-treatment systems, and agricultural activities. Precipitation probably contributes very little to chloride in ground water in the study area; a three-fold concentration by evapotranspiration would result in chloride of less than 1 mg/L. Salt- or brackish-water intrusion from overpumping of aquifers has resulted in increased chlorides in some coastal and tidal areas in Anne Arundel County and elsewhere in Maryland (Drummond, 1988; Hiortdahl, 1990; Fleck, Andreasen, and Smith, 1996); however, the four wells with chloride concentrations greater than 100 mg/L are not close enough to the Chesapeake Bay or its tributaries to have been affected by brackish-water intrusion. There are no evaporite minerals such as halite (NaCl) in the aquifers in the study area.

Chloride concentrations tended to be higher in the Magothy and Patapsco wells than in the Aquia wells. This is probably related to the different hydrogeologic settings of the targeted areas: many of the Aquia wells are located in the southern part of the county, where the Aquia Formation is a confined aquifer and is therefore better protected from surface contamination. Most of the wells completed in the Magothy and Patapsco Formations are in unconfined or semiconfined aquifers in the central and northern areas of the county, where ground water is more susceptible to contamination.

Arsenic (cancer group A; human carcinogen) was detected in six samples (range: 1-110 µg/L). Only one arsenic sample (well Cc 134, near Crofton) exceeded the MCL of 50 µg/L. (The well was resampled, with similar results). The source of the arsenic is not known. Arsenic is produced as a byproduct of industrial applications, pesticide production and application, and burning of fossil fuels (U.S. Environmental Protection Agency, 1992a). It is present in chromated copper arsenate, a widely used wood preservative in Maryland (Maryland Department of Agriculture, 1996). It can form metal arsenides and sulfides (Hem, 1985). Beryllium (cancer group B2; probable human carcinogen) was detected in five samples (range: 2-3.1 µg/L). None of the detections exceeded the MCL of 4 µg/L. Beryllium is uncommon in sedimentary deposits and is relatively immobile in ground water. The major source of beryllium to the environment is combustion of coal and fuel oil (Hem, 1985; U.S. Environmental Protection Agency, 1992b). Lead (cancer group B2) was detected in 20 samples (range: 1-12 µg/L). None of the detections exceeded 15 µg/L (the USEPA's action level for lead). Detections were prevalent among samples with pH values below 5. Lead is relatively immobile in the environment due to solubility of lead hydroxy carbonates, adsorption, and coprecipitation (Hem, 1985), and many of the lead detections may have been derived from household plumbing fixtures, particularly older pipe joints containing lead solder.

SYNTHETIC ORGANIC COMPOUNDS

Volatile Organic Compounds

Three VOCs were detected at concentrations above minimum reporting limits (MRLs). Chloroform (cancer group B2) was detected in seven wells (range: 1-95 µg/L). Six of the seven detections were less than 4 µg/L; the seventh detection (95 µg/L) was from a dug well

(Cf 148) that the owner reported had been chlorinated several weeks prior to sampling. The concentration exceeded the proposed MCL of 80 µg/L total for all trihalomethanes. Bromodichloromethane (cancer group B2) also was detected in this well (3.3 µg/L). Both chloroform and bromodichloromethane have been detected in septic effluent and in regional studies (Viraraghavan and Hashem, 1986; Daly and Lindsey, 1996). VOCs did not exceed MCLs in any of the other wells. Methyl *tert*-butyl ether (MTBE; tentative cancer group C) was detected in well Be 115 at 6.2 µg/L. MTBE is an octane booster in gasoline that has been frequently detected in ground water (Squillace and others, 1995; Daly and Lindsey, 1996). The well is located near a commercial area along Mountain Road.

Atrazine and Metolachlor

Metolachlor was detected in well Bd 166 (0.2 µg/L) by immunoassay; however, it was not detected (<0.2 µg/L) in a confirmation sample analyzed by GC/MS at the NWQL. The GC/MS analysis is considered to be more reliable than the immunoassay test for quantitative analysis, and the immunoassay detection is considered to be a false-positive test. All other immunoassay tests for atrazine and metolachlor were below MRLs.

RADIONUCLIDES

The radionuclides tested in this study are human carcinogens (cancer group A). Radionuclide concentrations are usually reported in terms of the number of disintegrations per second per volume of water. In this report, concentrations are reported in picocuries per liter, where one picocurie equals 3.7×10^{-2} disintegrations per second. Uranium is reported in µg/L.

Radium-226, Radium-228, and Gross Alpha- and Gross Beta-Particle Activity

Radium-226 is one of the intermediate disintegration products in the uranium-238 decay series (fig. 5). Radium-228 is one of the intermediate products in the thorium-232 decay series. Radium-226 has a half-life of 1,622 years; the half-life of radium-228 is 5.7 years. (The half-life of a radionuclide is the time it takes for the original concentration to be reduced by one-half). Radium-226 emits an alpha particle and radium-228 emits a beta particle when they undergo radioactive decay. An alpha particle consists of two protons and two neutrons; beta particles are identical to electrons, but are emitted from the nucleus. Gross alpha- and gross beta-particle activity are thus used to screen for the presence of alpha- and beta-emitting radionuclides. The USEPA has established MCLs for gross alpha-particle activity (15 pCi/L) and radium-226 plus radium-228 (5 pCi/L). The MCL for gross beta-particle activity, 4 millirems (mrem) per year, is a dosage rather than a concentration; the amount needed to produce this dosage varies among beta-emitting isotopes.

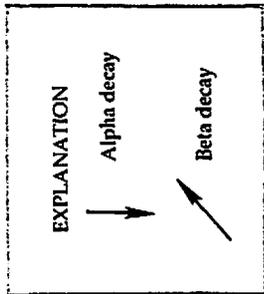
Radium-226 concentrations from all samples ranged from less than 0.1 to 33 pCi/L (median value: 0.1 pCi/L); radium-228 concentrations ranged from less than 1 to 35 pCi/L (median value: less than 1 pCi/L) (tab. 3). Radium concentrations were higher in samples from the Magothy and Patapsco Formations than in samples from the Aquia Formation (figs. 6 and 7). Fifteen of the 20 wells in the Magothy and Patapsco Formations had radium-226 plus radium-228 concentrations exceeding the MCL of 5 pCi/L. Wells Bf 68 and Cd 100 had the maximum combined radium values (66 pCi/L in both wells). The maximum radium-226 plus radium-228 concentration from the Aquia Formation was 1.1 pCi/L. Gross alpha- and gross beta-particle activities, which correlate strongly with radium-226 and radium-228 respectively (figs. 8 and 9), were also higher in

samples from wells in the Magothy and Patapsco Formations than in samples from wells in the Aquia Formation. Gross alpha- and gross beta-particle activities ranged from <3 to 110 pCi/L and <4 to 88 pCi/L, respectively.

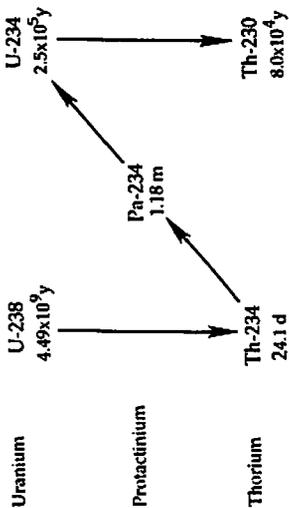
The high concentrations of radium in Anne Arundel County occur in acidic ground water as indicated by the sharp increase in radium concentrations from samples with pH values less than 5 (fig. 10). Radium, a divalent cation (Ra^{2+}) whose chemical behavior is similar to that of calcium, has been shown to be strongly influenced by sorption and ion exchange processes that are often pH-dependent (Langmuir and Riese, 1982; Beneš and others, 1984; Webster and others, 1995). The surface charge on metal oxyhydroxides is strongly pH-dependent: the net charge is positive at low pH values and negative at higher pH values (Langmuir, 1997). At lower pH values, the oxyhydroxides are protonated and may have a positive surface charge that is not conducive to sorbing divalent cations such as Ra^{2+} . At higher pH values, the surface charge becomes negative and cations are able to sorb. The pH at which the net surface charge changes from negative to positive due to absorption of H^+ or OH^- ions is called the point of zero net proton charge (PZNPC). Materials whose surface charge is pH-dependent include quartz (PZNPC: 1-3), amorphous silica (3.5), feldspars (5.2-6.8 [estimated]), kaolinite ($\leq 2-4.6$), α -hematite (natural hematite; 4.2-6.9), goethite (5.9-6.7), and amorphous $Fe(OH)_3$ (8.5-8.8) (Langmuir, 1997). Radium is strongly adsorbed onto quartz, kaolinite, and ferric oxyhydroxides (Beneš and others, 1984; Ames and others, 1983a, 1983b). Iron oxides and oxyhydroxides are common in the Potomac and Magothy Formations (Otton, 1955; Glaser, 1969), and provide a sorbing surface for radium.

Radium concentrations in the Magothy and Patapsco Formations were positively correlated ($r=0.749$) with TDS (fig. 11). The highest radium-226, radium-228, and gross alpha- and gross beta-particle activity values were from two

Radioactive Decay Series



Uranium-238



↑ INCREASING ATOMIC NUMBER

Thorium-232

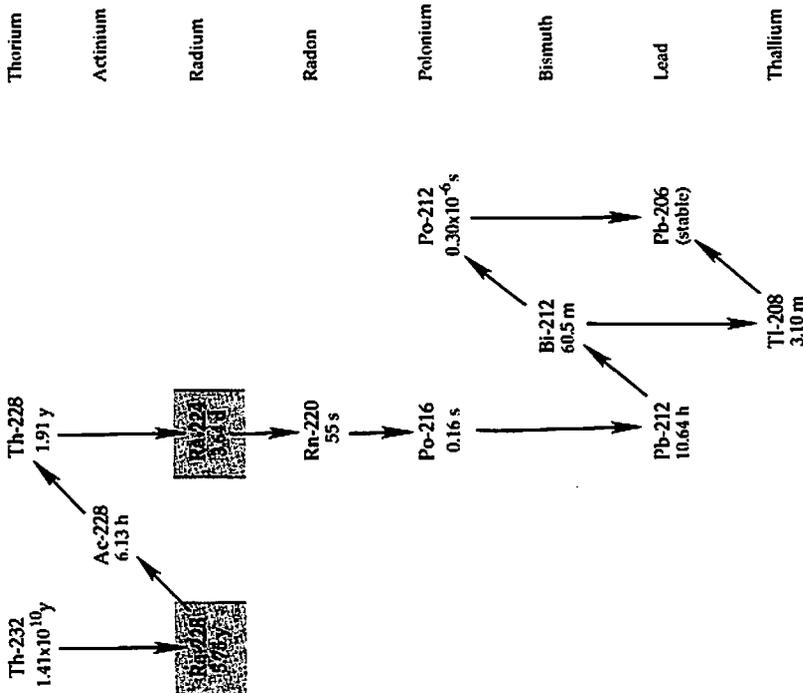


Figure 5. Uranium-238 and thorium-232 radioactive decay series. Shaded isotopes were analyzed in the pilot study. Isotope half-lives are given in years (y), days (d), hours (h), minutes (m), and seconds (s). Modified from Kozinski and others (1995).

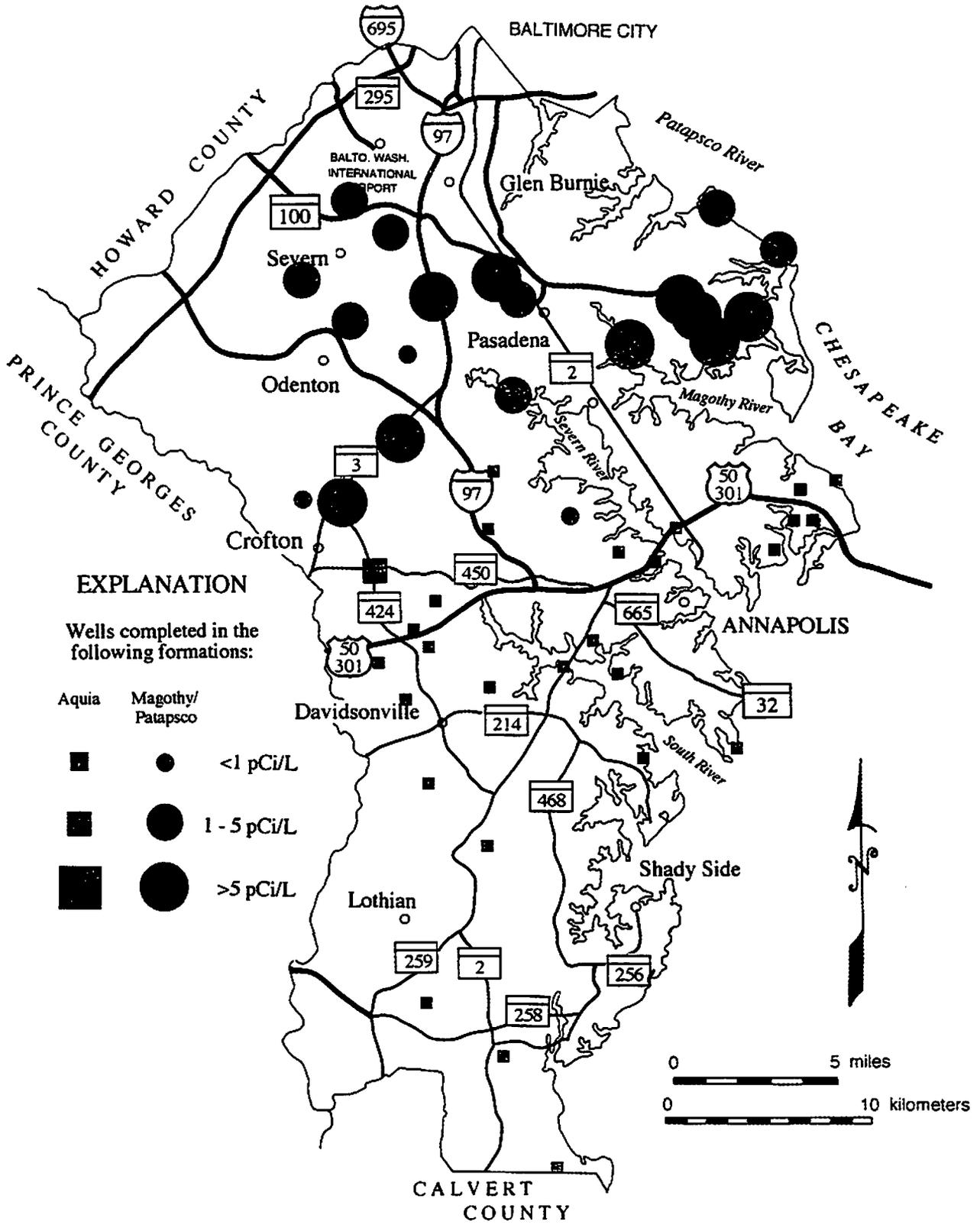


Figure 6. Distribution of radium-226 in well water in Anne Arundel County. pCi/L, picocuries per liter.

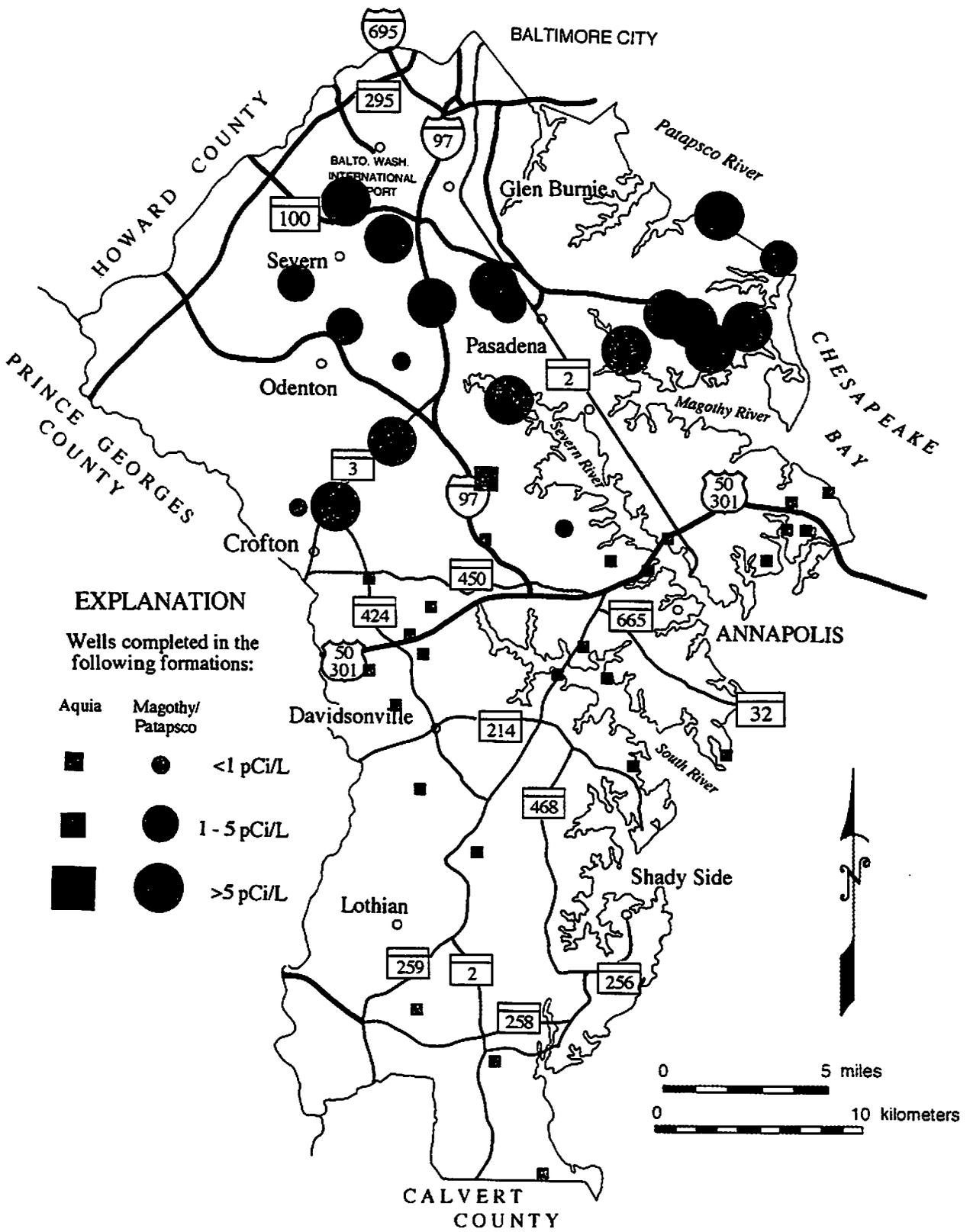


Figure 7. Distribution of radium-228 in well water in Anne Arundel County. pCi/L, picocuries per liter.

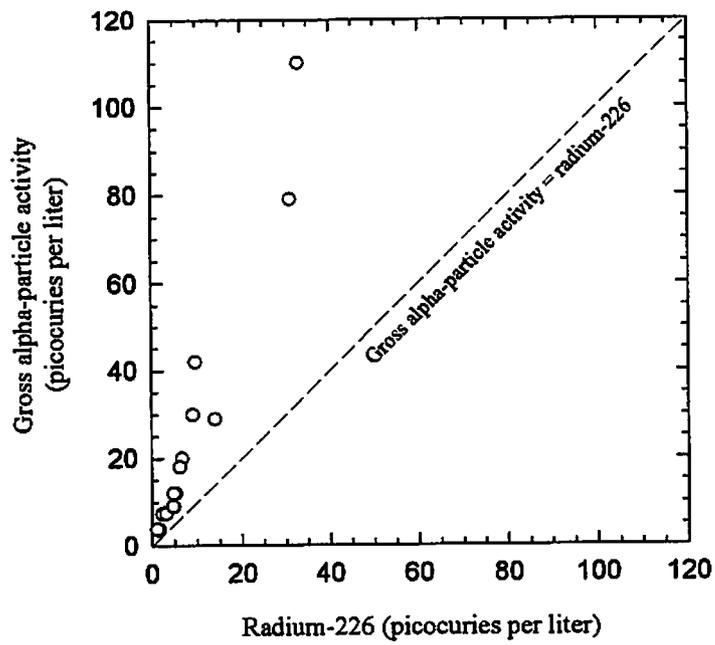


Figure 8. Relationship between gross alpha-particle activity and radium-226 concentration.

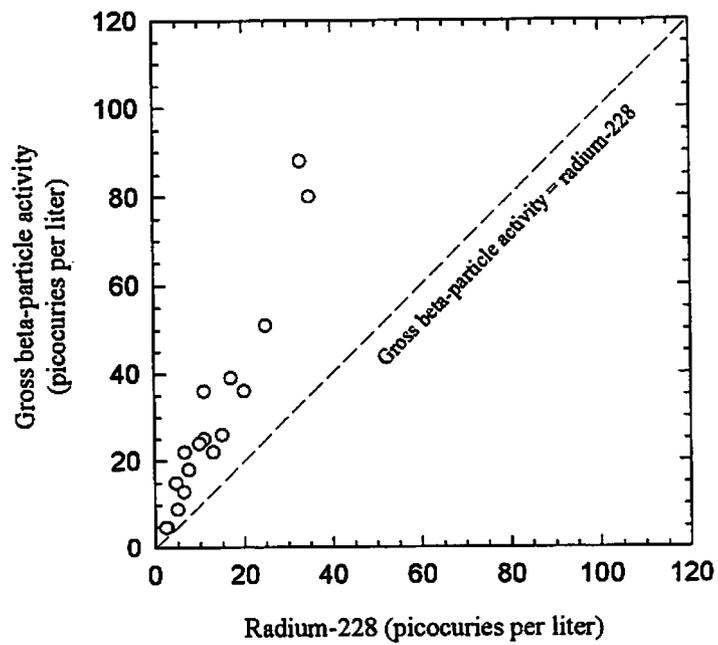


Figure 9. Relationship between gross beta-particle activity and radium-228 concentration.

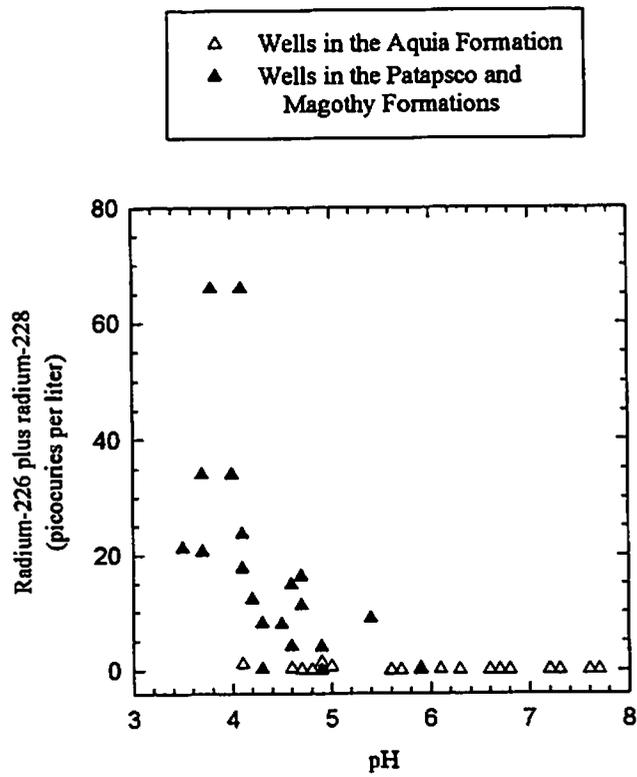


Figure 10. Relationship between radium-226 plus radium-228 and pH.

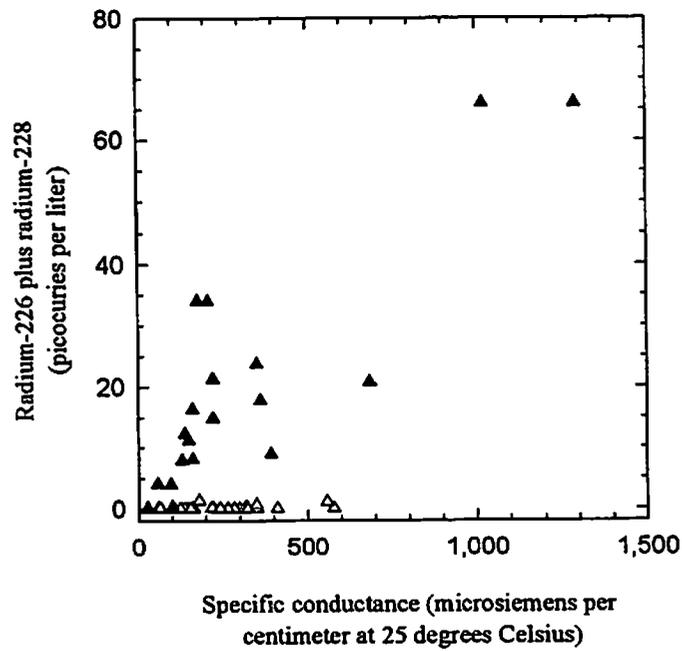


Figure 11. Relationship between radium-226 plus radium-228 and specific conductance.

wells (Bf 68 and Cd 100) that had the highest chloride and TDS values of all wells sampled. The mechanism is assumed to be ion exchange whereby the cations, particularly the divalent cations such as Ca^{2+} and Mg^{2+} exchange for the Ra^{2+} ions on the sediment surfaces. Radium was shown by Tanner (1964) to be most mobile in chloride-rich reducing ground water with high TDS content. Radium desorption from sediment has been found to increase with increasing dissolved-solids content of the water (Li and others, 1977; Webster and others, 1995). An increase in calcium and magnesium inputs into the ground-water system resulting from agricultural practices was proposed as a factor in increased radium concentrations in ground water in southern New Jersey (Szabo and others, 1997). Although TDS content was positively correlated and pH was negatively correlated with radium concentrations in the Magothy and Patapsco Formations in this study, the individual effects of these components on radium concentrations could not be evaluated because the samples with high specific conductance values also had low pH values.

The source of the radium in the samples is believed to be naturally occurring uranium and thorium in the Patapsco and Magothy Formations. Radium-226 is in the uranium-238 radioactive decay series, and radium-228 and radium-224 are both in the thorium-232 decay series (fig. 5). Uranium- and thorium-bearing minerals are the suspected sources of high concentrations of radium in ground water in other areas of the Atlantic Coastal Plain, including South Carolina (Michel and Moore, 1980), New Jersey (Kozinski and others, 1995; Szabo and others, 1997), and Georgia (Cline and others, 1983).

Radium-224 and Short-Term Gross Alpha-Particle Activity

In March 1998, 23 wells with radium detections were resampled to confirm the high

concentrations of radium-226, radium-228 and gross alpha- and gross beta-particle activity. In addition, some wells were analyzed for radium-224 and both long-term (measured after about 30 days) and short-term (measured within three days) gross alpha-particle activity. Radium-224 is an alpha-emitting radionuclide in the thorium-232 decay series with a half-life of 3.64 days (fig. 5). The radium-226 and radium-228 concentrations from the Phase 1 samples (collected from September through December 1997) were similar to those collected during Phase 2 (March 1998). However, the short-term gross alpha-particle activities were much higher than the long-term gross alpha-particle activities: the average reduction in gross alpha-particle activity for the ten samples tested was 67 percent (range: 40 to 89 percent), indicating the presence of one or more short-lived alpha-emitting radionuclides (tab. 4). Short-term gross alpha-particle activities ranged from 25 to 919 pCi/L in untreated water samples. Radium-224 was detected in all six water samples in which it was analyzed (range: 0.65 to 30.2 pCi/L). In all six wells, the radium-224 concentration was greater than either the radium-226 or radium-228 concentration. Furthermore, radium-224 in three of the samples exceeded 5 pCi/L (the MCL for radium-226 plus radium-228). These data strongly suggest that radium-224 is a major component of total radium in ground water in the Magothy and Patapsco Formations in the central and northern parts of Anne Arundel County. Radium-224 was found to be a significant radium isotope in well water in southern New Jersey (New Jersey Department of Environmental Protection, 1997). The USEPA has not established drinking-water regulations for radium-224; this policy is currently under review (D. Huber, U.S. Environmental Protection Agency, 1998, oral commun.).

Radon

Radon concentrations ranged from 106 to 989 pCi/L (median value: 292 pCi/L) (fig. 10).

Table 4. Short-term and long-term gross alpha-particle activity and radium concentrations from Phase 2 sampling, and comparison to radium concentrations from Phase 1 sampling

[LTGA, long-term gross alpha-particle activity; STGA, short-term gross alpha-particle activity; pCi/L, picocuries per liter; --, not tested; NA, not applicable]

Well	Phase 1 LTGA ¹ (pCi/L)	Phase 2 STGA ² (pCi/L)	Phase 2 LTGA ² (pCi/L)	Percent reduction in STGA	Phase 1 radium-226 ¹ (pCi/L)	Phase 2 radium-226 ¹ (pCi/L)	Phase 1 radium-228 ¹ (pCi/L)	Phase 2 radium-228 ¹ (pCi/L)	Phase 2 radium-224 ³ (pCi/L)	Phase 2 radium-224 ⁴ (pCi/L)
AA Bc 242	3.6	--	--	NA	1.4	1.7	2.7	2.6	3.1	--
AA Bd 165	12	58	13	78	4.9	4.9	9.9	12	--	--
AA Bd 166	20	264	30	89	6.7	6.4	17	17	--	--
AA Be 115	12	25	7.0	72	4.8	4.4	7.5	6.5	--	--
AA Be 116	29	101 ⁵	23 ⁵	77	14	12	20	17	--	--
AA Bf 64	18	110	36	67	6.2	6.5	15	16	30.2	--
AA Bf 64 ⁶	--	2.0	<1	NA	--	<0.1	--	<1	1.1	--
AA Bf 65	30	155	41	74	9.1	7.2	25	25	--	--
AA Bf 66	7.4	27	7.0	74	3.1	3.4	5.0	5.1	8.2	--
AA Bf 68	110	919 ⁵	530 ⁵	42	33	31	33	29	--	--
AA Bf 68 ⁶	--	9.0	<8	NA	--	<0.1	--	<1	--	--
AA Cc 134	42	140	84	40	9.7	7.6	11	11	18.9	18
AA Cd 100	79	472	186	61	31	33	35	32	--	--
AA De 211	<3.0	--	--	NA	<0.1	0.26	<1.0	1.3	0.65	--

¹ Analyzed by Quanterra Environmental Services (Richland, Washington).

² Analyzed by Maryland Department of Health and Mental Hygiene Radiation Laboratory (Baltimore, Maryland).

³ Analyzed by New Jersey Department of Health and Senior Services Radioanalytical Services Laboratory (Trenton, New Jersey).

⁴ Analyzed by U.S. Geological Survey Research Laboratory (Reston, Virginia).

⁵ Average of duplicate samples.

⁶ Sample was collected after well water had passed through water softener.

Radon tended to be higher in samples from wells in the Aquia Formation (median value: 328 pCi/L) than in samples from wells in the Magothy and Patapsco Formations (median value: 180 pCi/L) (fig. 12). Within the Aquia Formation, radon concentrations tended to be lowest in the southern part of the county, where the Aquia Formation contains a higher sand percentage than in central Anne Arundel County (Hansen, 1974, p. 20). Radon is the daughter product of radium-226 and has a half-life of 3.8 days. As is the case with almost all ground water (Wanty and Nordstrom, 1993), the radon

concentrations from these samples are too high to have been generated solely by the decay of radium-226 dissolved in ground water, and most of the radon is assumed to have been derived from the decay of radium-226 located near the mineral surfaces (either sorbed or part of the crystal lattice). There is currently no proposed MCL for radon; a proposed MCL of 300 pCi/L was withdrawn in 1997. The American Water Works Association has recommended that utilities keep radon levels in finished water below 4,000 pCi/L (American Water Works Association, written commun., 1997).

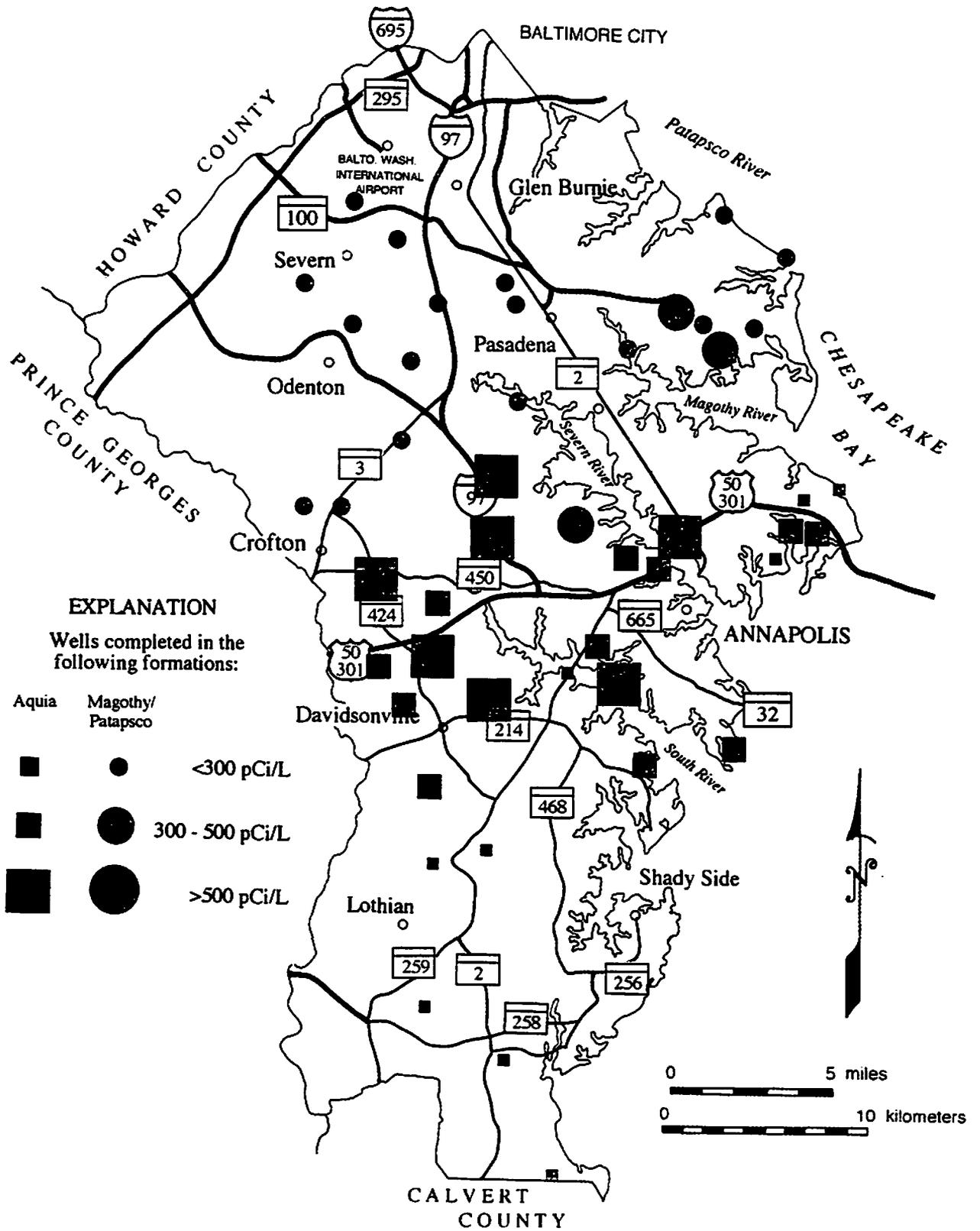


Figure 12. Distribution of radon in well water in Anne Arundel County. pCi/L, picocuries per liter.

Uranium

Uranium was detected in two wells in the Magothy Formation (2.4 and 14 $\mu\text{g/L}$) and one well in the Patapsco Formation (1.1 $\mu\text{g/L}$). Uranium is in cancer group A (human carcinogen) and has a proposed MCL of 20 $\mu\text{g/L}$. All three wells had pH values less than 4.0, and two had specific conductance values greater than 1,000 $\mu\text{S/cm}$. Most natural waters contain uranium in concentrations between 0.1 and 10 $\mu\text{g/L}$ (Hem, 1985). Uranium mobility is enhanced under oxidizing conditions and in carbonate-rich ground water. Bicarbonate (alkalinity) is abundant in ground water in the confined Aquia Formation in the southern part of the county, but most Aquia samples were anoxic, which would reduce uranium mobility. Conversely, many samples from the unconfined aquifers in the central and northern parts of the county were oxic, but had low alkalinities.

BACTERIA

Samples were analyzed for total coliform bacteria and *E. coli*. Twenty-one wells tested positive for total coliform bacteria; only one well (Cd 101, a dug well) tested positive for *E. coli*. Sixteen of the 27 wells in the Aquia Formation tested positive for total coliform bacteria; 5 of

the 20 wells in the Magothy and Patapsco Formations tested positive. Coliform bacteria have been widely used as an indicator of contamination from human sewage and are present in septic effluent (Yates and Yates, 1993). A higher proportion of positive detections of total coliform bacteria appear to be associated with the pesticide-targeted areas (13 of 20 samples positive) than with the VOC-targeted (6 of 20 samples positive) or radon-targeted areas (2 of 7 samples positive).

WATER-QUALITY DATA IN RELATION TO CANCER GROUPS

Water-quality data for constituents in cancer groups A (human carcinogens), B2 (probable human carcinogens), and C (possible human carcinogens) are summarized in table 5. Radium-226 plus radium-228 and gross alpha-particle activity were the most widespread carcinogens detected in the study. The only non-radionuclide constituents detected in cancer groups A, B2, and C were arsenic and chloroform, which were detected only in isolated cases. Constituents in cancer group D ("not classifiable; inadequate or no human and animal evidence of carcinogenicity," U.S. Environmental Protection Agency, 1996), are not included in table 5.

Table 5. Summary of chemical constituents in cancer groups A, B2, and C

[None of the pilot study constituents was classified in cancer group B1. MCL, Maximum Contaminant Level; pCi/L, picocuries per liter; mrem/yr, millirems per year; $\mu\text{g/L}$, micrograms per liter; na, not applicable. Source of cancer group and MCL data: U.S. Environmental Protection Agency (1996)]

Constituent	MCL	Number of wells exceeding MCL (47 samples total)	Comments
CANCER GROUP A: HUMAN CARCINOGENS			
Radium-226 plus radium-228	5 pCi/L	15	Highest concentrations found in low pH (<5) well water in the Magothy and Patapsco Formations.
Gross alpha-particle activity	15 pCi/L	6	Highest concentrations found in low pH (<5) well water in the Magothy and Patapsco Formations.
Beta-particle and photon activity (formerly man-made radionuclides)	4 mrem/yr	-- ⁵	Highest concentrations found in low pH (<5) well water in the Magothy and Patapsco Formations.
Uranium	20 $\mu\text{g/L}$ ¹	0	
Radon	Not established	na	All samples less than 1,000 pCi/L.
Benzene	5 $\mu\text{g/L}$	0	
Vinyl chloride	2 $\mu\text{g/L}$	0	
Arsenic	50 $\mu\text{g/L}$ ³	1	Detection confirmed in second sample; source of arsenic not identified.
CANCER GROUP B2: PROBABLE HUMAN CARCINOGENS			
Bromodichloromethane	100/80 ^{1,2} $\mu\text{g/L}$	0	
Bromoform	100/80 ^{1,2} $\mu\text{g/L}$	0	
Carbon tetrachloride	5 $\mu\text{g/L}$	0	
Chloroform	100/80 ^{1,2} $\mu\text{g/L}$	1	Well had been recently chlorinated.
1,2-dichloroethane	5 $\mu\text{g/L}$	0	
1,2-dichloropropane	5 $\mu\text{g/L}$	0	
Methylene chloride (dichloromethane)	5 $\mu\text{g/L}$	0	
Trichloroethylene	5 $\mu\text{g/L}$	0	
Beryllium	4 $\mu\text{g/L}$	0	
Lead	15 $\mu\text{g/L}$ ⁴	0	

Table 5. Summary of chemical constituents in cancer groups A, B2, and C -- Continued

Constituent	MCL	Number of wells exceeding MCL (47 samples total)	Comments
CANCER GROUP C: POSSIBLE HUMAN CARCINOGENS			
Chlorodibromomethane	100/80 ^{1,2} µg/L	0	
1,1-dichloroethylene	7 µg/L	0	
1,4-dichlorobenzene	75 µg/L	0	
Methyl <i>tert</i> -butyl ether (MTBE) ⁶	not established	na	
Atrazine	3 µg/L	0	
Metolachlor	not established	na	One immunoassay detection; not detected in laboratory confirmation sample
Styrene	100 µg/L	0	

¹ Proposed MCL.

² Total for all trihalomethanes cannot exceed 80 µg/L.

³ Under review.

⁴ Action level.

⁵ MCL is a dosage that corresponds to different concentrations for different beta-emitting isotopes.

⁶ Assignment to cancer group C is tentative.

SUMMARY AND CONCLUSIONS

A pilot study of carcinogens in well water was conducted in Anne Arundel County, Maryland. The study focused on wells that are potentially at risk from carcinogens in well water, including: (1) wells near areas of commercial and industrial land use or dense residential development that are in the general outcrop areas of the Patapsco, Magothy, and Aquia Formations, where well water may be susceptible to contamination by VOCs; (2) wells

near current and former cropland in the general outcrop areas of the Patapsco, Magothy, and Aquia Formations, where well water may be susceptible to contamination by pesticides; and (3) wells throughout Anne Arundel County (particularly in the confined Aquia Formation in the southern part of the county), where few data were available on radon and other naturally occurring radionuclides and trace elements that may be dissolved in the water. Untreated

samples were collected from September through December 1997 from 47 wells, including 20 wells sampled in each of the VOC- and pesticide-targeted areas, and 7 wells in the radon-targeted area of the confined Aquia Formation. All samples were analyzed for a suite of VOCs, radium-226, radium-228, uranium, gross alpha- and gross beta-particle activity, atrazine, metolachlor, arsenic, beryllium, lead, major ions, nutrients, and field parameters (pH, specific conductance, and dissolved oxygen).

Water samples were generally low in TDS (median: 113 mg/L). Samples from the Patapsco and Magothy Formations had lower median values of TDS, pH, calcium, alkalinity (bicarbonate), silica, iron, and manganese, and higher median values of sodium, chloride, nitrate, and dissolved oxygen compared to samples from the Aquia Formation. Three wells in the Magothy Formation and one well in the Patapsco Formation had pH values below 4.0, possibly as a result of pyrite oxidation. Nitrate concentrations exceeded 10 mg/L (the MCL) in 3 of the 47 samples. Anoxic conditions probably inhibit elevated nitrate concentrations. Chloride concentrations exceeded 250 mg/L (the secondary MCL for chloride) in samples from two wells. Iron concentrations exceeded 300 $\mu\text{g/L}$ (the secondary MCL) in 21 of 47 wells; 17 wells had more than 1,000 $\mu\text{g/L}$ iron.

There were several low-level detections of arsenic, beryllium, and lead; only one detection (arsenic; 110 $\mu\text{g/L}$) exceeded the MCL. Three VOCs were detected (chloroform, detected in seven wells; bromodichloromethane and MTBE, each detected in one well); the chloroform detection exceeded the proposed MCL. Metolachlor was detected by immunoassay in one sample, but was not confirmed by GC/MS analysis; atrazine was undetected in all samples. Twenty-one wells tested positive for total coliform bacteria; only one well (a dug well) tested positive for *E. coli*.

Radium isotopes were the most commonly detected carcinogens in the study. Radium-226 plus radium-228 concentrations exceeded the

MCL of 5 pCi/L in 15 of 20 samples in the Magothy and Patapsco Formations. There were no radium MCL exceedances in samples from the Aquia Formation. The high radium values from wells in the Magothy and Patapsco Formations were associated with low (<5) pH values; the highest values were from low-pH, high-TDS samples. Comparison of short-term (analyzed within 3 days of sampling) and long-term (analyzed approximately 30 days after sampling) gross alpha-particle activities from 10 samples indicated an average reduction in gross alpha values of 67 percent (range: 40-89 percent). Radium-224 was analyzed in six of these samples, and was detected in all six in concentrations greater than either radium-226 or radium-228. In conjunction with the short-term and long-term gross alpha-particle activity measurements, this strongly suggests that radium-224 is a major component of total radium in ground water in these aquifers. Radon concentrations ranged from 106 to 989 pCi/L (median: 292 pCi/L). Radon tended to be higher in samples from the Aquia Formation (median value: 328 pCi/L) than in samples from the Magothy and Patapsco Formations (median value: 180 pCi/L). Uranium was detected in samples from three wells (range of detections: 1.1-14 $\mu\text{g/L}$); none exceeded the proposed MCL of 20 $\mu\text{g/L}$.

Radium is the only carcinogen analyzed in this study that exceeded the MCL over a widespread area of Anne Arundel County. The data are insufficient to determine the lateral and vertical extent of the high concentrations of radium, which are attributed to radioactive decay of naturally occurring uranium and thorium in the Patapsco and Magothy Formations. Furthermore, the data are not sufficient to determine all factors associated with the high radium values. Additional data are needed to investigate: (1) the lateral and vertical extent of radium contamination in ground water in the Patapsco and Magothy Formations in Anne Arundel County and the upper Chesapeake Bay region of Maryland; (2) the relationship between

well depth and radium concentration; (3) geochemical factors affecting the occurrence and distribution of radium in ground water; and (4) the extent to which radium-224 and other short-lived isotopes are present in the Patapsco and

Magothy Formations. A larger-scale study of the occurrence and distribution of radium in the Maryland Coastal Plain is currently (August 1998) being conducted to address these questions.

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APPENDIXES

APPENDIX A

WATER-QUALITY DATA FROM WELLS SAMPLED IN THIS STUDY

Appendix A includes all water-quality data from Phase 1 of the pilot study except the VOC data. VOC detections are discussed in the "Volatile Organic Compounds" section of the report. All other VOC analyses were below the minimum reporting levels in appendix C1. The samples from wells AA Ec 11, AA Ed 56, and AA Ee 85 were determined to have passed through water-softening systems.

Abbreviations for unit concentrations:

mg/L	milligrams per liter
µg/L	micrograms per liter
µS/cm	microsiemens per centimeter at 25° Celsius
p-c units	platinum-cobalt units
pCi/L	picocuries per liter
2 sigma	total propagated error
CaCO ₃	calcium carbonate
SiO ₂	silica
N	nitrogen

Abbreviations for targeted areas:

P	Pesticide-targeted area
V	VOC-targeted area
R	Radon-targeted area

Abbreviations for bacteriological tests (*Escherichia coli* and total coliform bacteria):

pos	positive test
neg	negative test

Appendix A. Water-quality data from wells sampled in this study

Well	Date sampled	Targeted area	Geologic formation	Specific conductance ($\mu\text{S}/\text{cm}$)	Total dissolved solids (residue at 180°C) (mg/L)	pH	Alkalinity (mg/L as CaCO_3)
AA Bc 242	10-Sep-97	P	Patapsco	57	32	4.6	1
AA Bc 243	12-Nov-97	P	Patapsco	97	63	4.9	3
AA Bc 244	17-Dec-97	V	Patapsco	393	222	5.4	11
AA Bd 164	10-Sep-97	P	Patapsco	162	92	4.7	1
AA Bd 165	01-Oct-97	V	Patapsco	222	128	4.6	4
AA Bd 166	12-Nov-97	P	Patapsco	352	192	4.1	<1
AA Bd 167	20-Nov-97	V	Patapsco	130	56	4.5	<1
AA Bd 168	16-Dec-97	P	Patapsco	26	15	4.9	2
AA Be 115	08-Oct-97	V	Patapsco	139	74	4.2	3
AA Be 116	08-Oct-97	V	Patapsco	209	113	4.0	<1
AA Bf 64	09-Sep-97	P	Magothy	222	94	3.5	<1
AA Bf 65	30-Sep-97	V	Patapsco	178	74	3.7	<1
AA Bf 66	08-Oct-97	V	Patapsco	162	80	4.3	<1
AA Bf 67	19-Nov-97	V	Patapsco	150	84	4.7	9
AA Bf 68	17-Dec-97	V	Magothy	1290	—	3.8	<1
AA Cc 133	16-Sep-97	P	Patapsco	26	22	4.3	1
AA Cc 134	23-Oct-97	V	Magothy	686	320	3.7	<1
AA Cd 100	16-Sep-97	P	Magothy	1020	493	4.1	<1
AA Cd 101	02-Dec-97	V	Aquia	180	121	4.9	16
AA Cd 104	03-Dec-97	V	Patapsco	362	190	4.1	<1
AA Cd 105	15-Dec-97	P	Aquia	349	263	5.0	13
AA Ce 141	04-Nov-97	R	Magothy	100	103	5.9	23
AA Ce 142	16-Dec-97	P	Aquia	65	52	4.8	3
AA Cf 145	30-Sep-97	P	Aquia	136	62	6.3	52
AA Cf 146	01-Oct-97	P	Aquia	263	122	5.9	46
AA Cf 147	21-Oct-97	V	Aquia	145	108	5.7	36
AA Cf 148	19-Nov-97	P	Aquia	138	88	5.6	16
AA Cf 149	03-Dec-97	V	Aquia	63	84	4.7	<1
AA Cg 26	21-Oct-97	V	Aquia	155	87	5.9	25
AA Dc 18	10-Dec-97	V	Aquia	558	353	4.1	<1
AA Dd 51	30-Sep-97	P	Aquia	240	194	7.3	93
AA Dd 52	17-Sep-97	P	Aquia	241	164	7.2	94
AA Dd 53	22-Sep-97	P	Aquia	217	158	6.1	34
AA Dd 54	17-Sep-97	P	Aquia	106	76	5.9	47
AA Dd 55	22-Sep-97	P	Aquia	124	70	6.3	47
AA Dd 57	25-Sep-97	P	Aquia	162	111	4.8	2
AA De 209	25-Sep-97	P	Aquia	221	113	4.9	6
AA De 210	20-Nov-97	V	Aquia	58	30	4.7	<1
AA De 211	11-Dec-97	V	Aquia	319	207	4.6	5
AA De 212	02-Dec-97	V	Aquia	164	153	6.6	126
AA Ec 11 ¹	23-Oct-97	R	Magothy	279	191	6.8	119
AA Ed 54	13-Nov-97	R	Aquia	350	238	7.2	176
AA Ed 56 ¹	27-Oct-97	R	Aquia	409	271	7.5	168
AA Ed 57	04-Nov-97	R	Aquia	322	200	6.8	157
AA Ee 85 ¹	27-Oct-97	R	Aquia	337	217	7.6	184
AA Ee 86	04-Nov-97	R	Aquia	578	355	6.7	199
AA Ef 39	22-Dec-97	V	Aquia	411	301	6.8	192
AA Fd 54	03-Nov-97	R	Aquia	298	179	7.7	191
AA Fd 55	28-Oct-97	R	Aquia	313	189	7.6	121
AA Ge 14	03-Nov-97	R	Aquia	282	159	7.7	200

¹ Treated sample.

Appendix A. Water-quality data from wells sampled in this study -- Continued

Well	Dissolved oxygen (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Chloride (mg/L)	Sulfate (mg/L)
AA Bc 242	7.8	2.1	0.97	2.7	1.2	5.4	0.97
AA Bc 243	8.1	3.0	2.8	6.5	1.6	14	5.0
AA Bc 244	8.0	19	2.9	46	6.6	82	22
AA Bd 164	7.0	8.0	3.7	6.5	7.7	15	18
AA Bd 165	7.9	11	2.9	19	2.8	34	20
AA Bd 166	9.3	22	6.7	16	8.7	34	46
AA Bd 167	8.3	5.5	3.0	9.0	1.1	—	—
AA Bd 168	8.1	0.96	0.39	1.3	0.45	3.2	0.19
AA Be 115	5.6	3.0	4.0	11	1.3	20	17
AA Be 116	4.3	6.5	3.4	16	2.2	19	9.1
AA Bf 64	1.0	3.3	3.8	10	2.3	20	44
AA Bf 65	5.8	0.97	2.6	12	1.4	21	38
AA Bf 66	2.8	2.9	3.4	16	1.3	33	3.4
AA Bf 67	7.5	6.5	3.5	15	2.2	21	11
AA Bf 68	1.4	9.4	6.9	187	6.5	310	110
AA Cc 133	0.7	0.36	0.15	1.0	0.4	1.3	5.7
AA Cc 134	0.4	3.5	3.4	89	4.8	140	58
AA Cd 100	9.2	8.9	15	130	5.4	290	9.3
AA Cd 101	5.3	8.6	3.5	20	2.3	27	22
AA Cd 104	8.1	5.8	4.5	55	1.8	94	13
AA Cd 105	8.6	24	9.6	25	5.2	57	1.1
AA Ce 141	0.3	5.9	2.1	2.1	3.1	2.2	13
AA Ce 142	3.0	2.0	1.1	2.4	3.7	6.6	9.2
AA Cf 145	<1.0	5.1	4.5	4.2	5.3	6.1	2.8
AA Cf 146	0.5	12	4.5	5.1	3.1	43	14
AA Cf 147	0.6	4.2	2.2	5.0	3.1	16	9.1
AA Cf 148	5.4	12	2.8	12	1.5	16	15
AA Cf 149	6.6	1.7	1.5	2.4	3.8	7.7	8.2
AA Cg 26	0.5	6.2	2.7	3.3	2.4	19	18
AA Dc 18	8.4	32	17	39	7.8	180	0.58
AA Dd 51	0.6	48	1.2	2.0	3.6	4.3	21
AA Dd 52	0.5	45	0.75	0.97	1.8	7.1	22
AA Dd 53	<1.0	5.2	1.6	2.9	3.3	0.14	<0.10
AA Dd 54	1.3	7.0	2.3	1.2	3.1	4.7	1.6
AA Dd 55	0.5	5.0	1.3	1.4	2.8	2.7	26
AA Dd 57	8.6	14	3.1	2.7	5.5	16	22
AA De 209	4.1	12	3.4	4.0	6.2	32	2.4
AA De 210	1.7	0.88	1.1	2.4	3.3	4.0	12
AA De 211	4.1	17	6.2	20	6.2	78	1.2
AA De 212	1.0	30	1.1	1.2	2.7	1.6	8.1
AA Ec 11 ¹	0.4	0.4	0.056	63	0.78	2.3	14
AA Ed 54	0.4	61	5.3	2.6	3.9	3.0	8.0
AA Ed 56 ¹	0.4	0.55	0.071	97	0.29	2.0	24
AA Ed 57	0.3	50	8.0	2.3	3.9	1.6	40
AA Ee 85 ¹	0.4	0.025	<0.01	77	0.45	1.1	48
AA Ee 86	0.8	94	3.5	9.0	4.4	75	5.7
AA Ef 39	2.8	78	2.4	6.5	4.5	31	1.4
AA Fd 54	0.3	43	8.3	2.9	5.1	1.0	29
AA Fd 55	0.5	45	9.1	2.9	5.4	0.61	26
AA Ge 14	0.3	37	11	3.8	9.4	0.75	5.9

¹ Treated sample.

Appendix A. Water-quality data from wells sampled in this study -- Continued

Well	Fluoride (mg/L)	Silica (mg/L as SiO ₂)	Color (p-c units)	Iron (filtered) (µg/L)	Iron (unfiltered) (µg/L)	Manganese (filtered) (µg/L)	Manganese (unfiltered) (µg/L)
AA Bc 242	<0.10	7.4	<1	<3.0	<10	15	18
AA Bc 243	<0.10	7.5	<1	<3.0	<10	17	14
AA Bc 244	<0.10	6.0	2	<10	30	25	26
AA Bd 164	<0.10	7.5	<1	<10	10	90	92
AA Bd 165	<0.10	7.1	1	<10	20	64	66
AA Bd 166	0.24	6.3	<1	120	160	263	250
AA Bd 167	<0.10	6.9	<1	<3.0	<10	19	13
AA Bd 168	<0.10	8.2	1	<10	<10	4.2	<10
AA Be 115	<0.10	10	<1	35	40	36	31
AA Be 116	0.18	11	<1	14	20	15	13
AA Bf 64	<0.10	16	1	1700	1700	29	42
AA Bf 65	<0.10	14	<1	88	70	17	<10
AA Bf 66	<0.10	10	<1	3.2	10	80	72
AA Bf 67	<0.10	7.4	<1	<3.0	<10	73	68
AA Bf 68	<0.10	11	4	7400	7700	105	100
AA Cc 133	<0.10	9.9	8	1500	1400	7.6	14
AA Cc 134	<0.10	9.3	2	2800	2900	25	23
AA Cd 100	0.11	13	10	13	10	448	460
AA Cd 101	<0.10	22	2	55	140	28	29
AA Cd 104	<0.10	9	<1	29	20	26	28
AA Cd 105	0.23	17	1	<10	<10	75	72
AA Ce 141	0.30	51	110	9000	7800	161	97
AA Ce 142	<0.10	23	10	1100	1900	73	60
AA Cf 145	0.61	27	160	14700	14000	112	94
AA Cf 146	0.28	21	4	30900	33000	488	510
AA Cf 147	0.14	31	100	17000	17000	173	140
AA Cf 148	<0.10	17	1	18	70	34	30
AA Cf 149	<0.10	21	13	1000	1800	36	34
AA Cg 26	0.11	26	25	15700	17000	378	350
AA Dc 18	0.31	20	<1	12	60	95	96
AA Dd 51	0.12	46	10	790	850	15	15
AA Dd 52	<0.10	25	4	610	690	11	17
AA Dd 53	0.13	25	10	41300	42000	359	280
AA Dd 54	0.33	19	12	11200	12000	329	330
AA Dd 55	0.32	23	20	21600	23000	145	120
AA Dd 57	<0.10	20	1	11	320	234	220
AA De 209	0.14	22	<1	140	150	173	170
AA De 210	<0.10	20	<1	1100	1200	152	93
AA De 211	<0.10	41	<1	55	60	53	53
AA De 212	0.30	30	55	3200	3600	30	34
AA Ec 11 ¹	0.36	29	1	74	80	2.3	<10
AA Ed 54	0.18	37	2	380	550	37	34
AA Ed 56 ¹	0.19	27	1	8.3	10	<1.0	<10
AA Ed 57	0.15	18	7	4500	4400	38	39
AA Ee 85 ¹	0.22	20	1	8.3	20	<1.0	<10
AA Ee 86	0.11	18	1	56	60	8.9	10
AA Ef 39	0.16	40	2	120	130	15	14
AA Fd 54	0.19	14	3	210	220	8	<10
AA Fd 55	0.25	17	3	270	300	30	28
AA Ge 14	0.28	14	3	260	280	5.8	<10

¹ Treated sample.

Appendix A. Water-quality data from wells sampled in this study -- Continued

Well	Lead ($\mu\text{g/L}$)	Arsenic ($\mu\text{g/L}$)	Beryllium ($\mu\text{g/L}$)	$\text{NO}_3 + \text{NO}_2$ (mg/L as N)	Ammonia (mg/L as N)	Total Coliforms	<i>Escherichia coli</i>
AA Bc 242	<1	<1	<2.0	3.0	<0.2	pos	neg
AA Bc 243	2	<1	<2.0	2.9	<0.2	neg	neg
AA Bc 244	2	<1	<2.0	5.7	<0.2	neg	neg
AA Bd 164	6	<1	<2.0	6.4	<0.2	pos	neg
AA Bd 165	<1	<1	<2.0	6.3	0.2	pos	neg
AA Bd 166	3	<1	2.6	13	<0.2	neg	neg
AA Bd 167	2	<1	<2.0	7.0	<0.2	neg	neg
AA Bd 168	8	<1	<2.0	0.3	<0.2	pos	neg
AA Be 115	<1	<1	<2.0	2.2	0.2	neg	neg
AA Be 116	5	<1	<2.0	11.4	<0.2	neg	neg
AA Bf 64	<1	4	<2.0	<0.2	<0.2	neg	neg
AA Bf 65	1	<1	<2.0	0.4	0.2	neg	neg
AA Bf 66	2	<1	<2.0	2.4	<0.2	neg	neg
AA Bf 67	1	<1	3.1	6.8	<0.2	neg	neg
AA Bf 68	2	46	<2.0	2.3	0.7	neg	neg
AA Cc 133	1	<1	<2.0	<0.2	<0.2	neg	neg
AA Cc 134	<1	110	<2.0	<0.2	3.2	neg	neg
AA Cd 100	<1	<1	<2.0	1.4	<0.2	pos	neg
AA Cd 101	1	<1	2.0	3.6	<0.2	pos	pos
AA Cd 104	<1	<1	<2.0	4.2	<0.2	neg	neg
AA Cd 105	<1	<1	<2.0	20.5	<0.2	pos	neg
AA Ce 141	<1	<1	2.1	<0.2	<0.2	neg	neg
AA Ce 142	4	<1	<2.0	0.6	<0.2	neg	neg
AA Cf 145	<1	1	<2.0	<0.2	0.3	pos	neg
AA Cf 146	<1	<1	<2.0	<0.2	<0.2	pos	neg
AA Cf 147	<1	<1	<2.0	<0.2	<0.2	pos	neg
AA Cf 148	<1	<1	<2.0	2.9	<0.2	neg	neg
AA Cf 149	4	<1	<2.0	0.3	<0.2	neg	neg
AA Cg 26	<1	1	<2.0	<0.2	<0.2	pos	neg
AA Dc 18	12	<1	<2.0	1.2	<0.2	neg	neg
AA Dd 51	<1	<1	<2.0	<0.2	<0.2	pos	neg
AA Dd 52	<1	<1	<2.0	<0.2	<0.2	pos	neg
AA Dd 53	<1	<1	<2.0	<0.2	0.3	pos	neg
AA Dd 54	<1	<1	<2.0	<0.2	<0.2	pos	neg
AA Dd 55	<1	<1	<2.0	<0.2	0.2	pos	neg
AA Dd 57	2	<1	<2.0	4.1	0.2	neg	neg
AA De 209	2	<1	<2.0	2.3	<0.2	pos	neg
AA De 210	2	<1	<2.0	0.5	<0.2	pos	neg
AA De 211	4	<1	<2.0	2.4	<0.2	neg	neg
AA De 212	<1	<1	<2.0	<0.2	<0.2	pos	neg
AA Ee 11 ¹	<1	<1	<2.0	<0.2	<0.2	pos	neg
AA Ed 54	<1	<1	<2.0	<0.2	<0.2	pos	neg
AA Ed 56 ¹	<1	<1	<2.0	<0.2	<0.2	neg	neg
AA Ed 57	<1	<1	<2.0	<0.2	<0.2	neg	neg
AA Ee 85 ¹	<1	<1	2.4	<0.2	<0.2	neg	neg
AA Ee 86	<1	<1	3.0	6.3	<0.2	pos	neg
AA Ef 39	<1	<1	<2.0	<0.2	<0.2	neg	neg
AA Fd 54	<1	<1	<2.0	<0.2	<0.2	neg	neg
AA Fd 55	<1	<1	<2.0	<0.2	<0.2	neg	neg
AA Gc 14	<1	1	<2.0	<0.2	<0.2	neg	neg

¹ Treated sample.

Appendix A. Water-quality data from wells sampled in this study -- Continued

Well	Atrazine (µg/L)	Metolachlor (µg/L)	Radon (pCi/L)	Radon 2 sigma (pCi/L)	Gross alpha- particle activity (pCi/L)	Gross alpha 2 sigma (pCi/L)	Gross beta- particle activity (pCi/L)	Gross beta 2 sigma (pCi/L)
AA Bc 242	<0.05	<0.05	136	19	3.6	2.0	4.8	3.7
AA Bc 243	<0.05	<0.05	290	21	3.8	2.0	4.8	3.8
AA Bc 244	<0.05	<0.05	128	17	7.3	2.9	22	4.6
AA Bd 164	<0.05	<0.05	237	22	12	3.4	25	4.6
AA Bd 165	<0.05	<0.05	164	18	12	3.4	24	4.6
AA Bd 166	<0.05	0.2	168	19	20	4.4	39	5.2
AA Bd 167	<0.05	<0.05	187	19	7.6	2.7	15	4.2
AA Bd 168	<0.05	<0.05	135	18	<3.0	1.4	<4.0	3.5
AA Be 115	<0.05	<0.05	305	22	12	3.5	18	4.4
AA Be 116	<0.05	<0.05	193	19	29	5.2	36	5.1
AA Bf 64	<0.05	<0.05	210	20	18	4.0	26	4.7
AA Bf 65	<0.05	<0.05	172	20	30	5.1	51	5.6
AA Bf 66	<0.05	<0.05	110	18	7.4	2.9	9.0	4.0
AA Bf 67	<0.05	<0.05	173	19	9.0	2.9	13	4.2
AA Bf 68	<0.05	<0.05	436	23	110	14	88	7.1
AA Cc 133	<0.05	<0.05	106	17	<3.0	1.1	<4.0	3.6
AA Cc 134	<0.05	<0.05	206	20	42	5.6	36	3.3
AA Cd 100	<0.05	<0.05	217	19	79	10	80	6.8
AA Cd 101	<0.05	<0.05	590	25	<3.0	1.6	<4.0	3.7
AA Cd 104	<0.05	<0.05	130	18	9.1	3.2	22	4.6
AA Cd 105	<0.05	<0.05	536	24	<3.0	1.9	<4.0	3.8
AA Ce 141	<0.05	<0.05	331	21	<3.0	1.5	4.3	3.8
AA Ce 142	<0.05	<0.05	396	23	<3.0	1.2	5.0	3.8
AA Cf 145	<0.05	<0.05	315	23	<3.0	1.3	6.9	3.9
AA Cf 146	<0.05	<0.05	237	20	<3.0	1.4	<4.0	3.7
AA Cf 147	<0.05	<0.05	328	21	<3.0	1.5	5.9	4.0
AA Cf 148	<0.05	<0.05	149	18	<3.0	1.2	4.0	3.7
AA Cf 149	<0.05	<0.05	512	24	<3.0	1.3	<4.0	3.7
AA Cg 26	<0.05	<0.05	292	21	<3.0	1.5	<4.0	3.7
AA Dc 18	<0.05	<0.05	989	31	3.8	2.5	8.7	4.1
AA Dd 51	<0.05	<0.05	311	22	<3.0	1.6	<4.0	3.7
AA Dd 52	<0.05	<0.05	361	23	<3.0	1.4	<4.0	3.7
AA Dd 53	<0.05	<0.05	687	28	<3.0	1.5	5.9	3.8
AA Dd 54	<0.05	<0.05	381	23	<3.0	1.6	<4.0	3.6
AA Dd 55	<0.05	<0.05	271	22	<3.0	1.6	4.2	3.7
AA Dd 57	<0.05	<0.05	726	27	<3.0	1.7	5.0	3.9
AA De 209	<0.05	<0.05	395	22	<3.0	1.9	8.0	4.0
AA De 210	<0.05	<0.05	463	24	<3.0	1.4	7.4	3.9
AA De 211	<0.05	<0.05	651	26	<3.0	1.9	5.3	3.9
AA De 212	<0.05	<0.05	281	20	<3.0	1.4	<4.0	3.7
AA Ec 11 ¹	<0.05	<0.05	194	20	<3.0	1.9	<4.0	3.9
AA Ed 54	<0.05	<0.05	486	38	4.9	2.6	9.5	4.1
AA Ed 56 ¹	<0.05	<0.05	277	20	<3.0	1.5	<4.0	3.8
AA Ed 57	<0.05	<0.05	228	20	<3.0	1.6	6.9	4.0
AA Ee 85 ¹	<0.05	<0.05	333	21	<3.0	1.5	<4.0	3.6
AA Ee 86	<0.05	<0.05	308	21	<3.0	1.9	6.2	4.0
AA Ef 39	<0.05	<0.05	312	21	5.5	3.3	4.2	4.1
AA Fd 54	<0.05	<0.05	293	21	<3.0	1.2	<4.0	3.8
AA Fd 55	<0.05	<0.05	299	21	<3.0	1.4	5.7	3.9
AA Ge 14	<0.05	<0.05	246	20	<3.0	1.5	10	4.1

¹ Treated sample.

Appendix A. Water-quality data from wells sampled in this study -- Continued

Well	Radium-226 (pCi/L)	Radium-226 2 sigma (pCi/L)	Radium-228 (pCi/L)	Radium-228 2 sigma (pCi/L)	Uranium (µg/L)	Uranium 2 sigma (µg/L)
AA Bc 242	1.4	0.421	2.7	0.8	<1.0	0.1
AA Bc 243	1.6	0.46	2.4	0.7	<1.0	0.1
AA Bc 244	2.3	0.654	6.6	1.6	<1.0	0.1
AA Bd 164	5.3	1.19	11	2.6	<1.0	0.1
AA Bd 165	4.9	1.08	9.9	2.3	<1.0	0.1
AA Bd 166	6.7	1.5	17	3.9	<1.0	0.3
AA Bd 167	3.2	0.848	4.7	1.2	<1.0	0.1
AA Bd 168	<0.1	0.031	<1.0	0.4	<1.0	0.1
AA Be 115	4.8	1.09	7.5	1.8	<1.0	0.2
AA Be 116	14	2.84	20	4.4	1.1	0.4
AA Bf 64	6.2	1.35	15	3.4	<1.0	0.1
AA Bf 65	9.1	1.92	25	5.5	<1.0	0.2
AA Bf 66	3.1	0.756	5.0	1.3	<1.0	0.2
AA Bf 67	4.8	1.14	6.4	1.6	<1.0	0.1
AA Bf 68	33	6.33	33	7.2	2.4	0.8
AA Cc 133	0.2	0.105	<1.0	0.3	<1.0	0.1
AA Cc 134	9.7	2.11	11	2.6	14	4.1
AA Cd 100	31	6.14	35	7.7	<1.0	0.1
AA Cd 101	0.2	0.156	1.1	0.5	<1.0	0.1
AA Cd 104	4.7	1.14	13	3.0	<1.0	0.1
AA Cd 105	0.6	0.261	<1.0	0.3	<1.0	0.1
AA Ce 141	0.3	0.19	<1.0	0.3	<1.0	0.1
AA Ce 142	<0.1	0.091	<1.0	0.3	<1.0	0.1
AA Cf 145	<0.1	0.076	<1.0	0.3	<1.0	0.1
AA Cf 146	<0.1	0.086	<1.0	0.3	<1.0	0.1
AA Cf 147	<0.1	0.108	<1.0	0.3	<1.0	0.1
AA Cf 148	<0.1	0.119	<1.0	0.2	<1.0	0.1
AA Cf 149	0.1	0.116	<1.0	0.3	<1.0	0.1
AA Cg 26	<0.1	0.1	<1.0	0.3	<1.0	0.1
AA Dc 18	1.1	0.351	<1.0	0.4	<1.0	0.2
AA Dd 51	<0.1	0.074	<1.0	0.3	<1.0	0.1
AA Dd 52	<0.1	0.057	<1.0	0.4	<1.0	0.1
AA Dd 53	0.1	0.112	<1.0	0.3	<1.0	0.1
AA Dd 54	<0.1	0.08	<1.0	0.2	<1.0	0.1
AA Dd 55	<0.1	0.082	<1.0	0.3	<1.0	0.1
AA Dd 57	<0.1	0.084	<1.0	0.2	<1.0	0.1
AA De 209	0.1	0.107	<1.0	0.3	<1.0	0.1
AA De 210	0.1	0.128	<1.0	0.3	<1.0	0.1
AA De 211	0.3	0.167	<1.0	0.3	<1.0	0.1
AA De 212	<0.1	0.085	<1.0	0.4	<1.0	0.1
AA Ec 11 ¹	<0.1	0.06	<1.0	0.2	<1.0	0.1
AA Ed 54	<0.1	0.094	<1.0	0.3	<1.0	0.1
AA Ed 56 ¹	<0.1	0.046	<1.0	0.2	<1.0	0.1
AA Ed 57	<0.1	0.092	<1.0	0.2	<1.0	0.1
AA Ee 85 ¹	<0.1	0.083	<1.0	0.3	<1.0	0.1
AA Ee 86	<0.1	0.069	<1.0	0.3	<1.0	0.4
AA Ef 39	<0.1	0.11	<1.0	0.2	<1.0	0.2
AA Fd 54	<0.1	0.076	<1.0	0.3	<1.0	0.1
AA Fd 55	<0.1	0.043	<1.0	0.3	<1.0	0.1
AA Ge 14	<0.1	0.082	<1.0	0.2	<1.0	0.1

¹ Treated sample.

Appendix B. Well-construction and well-location data from wells sampled in this study

[P, pesticide-targeted area; V, VOC-targeted area; R, radon-targeted area; dd, degrees; mm, minutes; ss, seconds; ft, feet]

Well number	Targeted area	Well permit number	Latitude (dd-mm-ss)	Longitude (dd-mm-ss)	USGS 7.5-minute quadrangle	Approximate elevation (ft)
AA Bc 242	P	AA-73-7963	39-06-12	76-41-13	ODENTON	100
AA Bc 243	P	AA-88-5039	39-07-19	76-42-49	ODENTON	160
AA Bc 244	V	AA-74-2218	39-09-29	76-41-16	RELAY	150
AA Bd 164	P	AA-73-1807	39-07-24	76-36-06	ROUND BAY	90
AA Bd 165	V	AA-74-1429	39-08-32	76-39-45	RELAY	120
AA Bd 166	P	AA-73-3615	39-06-50	76-38-19	ODENTON	90
AA Bd 167	V	AA-92-0901	39-06-51	76-35-34	ROUND BAY	120
AA Bd 168	P	AA-73-7136	39-05-16	76-39-11	ODENTON	130
AA Be 115	V	AA-81-3304	39-06-40	76-30-09	ROUND BAY	60
AA Be 116	V	AA-73-6932	39-05-41	76-31-37	ROUND BAY	20
AA Bf 64	P	AA-73-4906	39-06-22	76-27-27	GIBSON ISLAND	60
AA Bf 65	V	AA-72-0797	39-06-29	76-29-14	GIBSON ISLAND	50
AA Bf 66	V	AA-81-5605	39-08-13	76-26-28	SPARROWS POINT	10
AA Bf 67	V	AA-88-8420	39-09-21	76-28-36	SPARROWS POINT	5
AA Bf 68	V	AA-81-7413	39-05-51	76-28-39	GIBSON ISLAND	40
AA Cc 133	P	AA-92-1899	39-01-22	76-42-40	ODENTON	70
AA Cc 134	V	AA-88-1964	39-01-27	76-41-24	ODENTON	110
AA Cd 100	P	AA-81-1485	39-03-13	76-39-30	ODENTON	130
AA Cd 101	V	--	39-02-11	76-36-12	ROUND BAY	160
AA Cd 104	V	AA-81-2387	39-04-17	76-35-33	ROUND BAY	70
AA Cd 105	P	--	39-00-38	76-36-17	ROUND BAY	130
AA Ce 141	R	AA-74-1246	39-01-05	76-33-30	ROUND BAY	130
AA Ce 142	P	AA-81-6083	39-00-02	76-31-51	ROUND BAY	60
AA Cf 145	P	AA-81-6428	39-01-00	76-25-14	GIBSON ISLAND	10
AA Cf 146	P	AA-86-0325	39-00-11	76-26-33	GIBSON ISLAND	30
AA Cf 147	V	AA-73-3643	39-00-58	76-25-54	GIBSON ISLAND	10
AA Cf 148	P	--	39-01-49	76-25-42	GIBSON ISLAND	25
AA Cf 149	V	AA-94-0330	39-00-43	76-29-57	GIBSON ISLAND	50
AA Cg 26	V	AA-73-8262	39-02-03	76-24-28	GIBSON ISLAND	20
AA Dc 18	V	AA-93-0137	38-59-29	76-40-12	BOWIE	180
AA Dd 51	P	AA-81-4277	38-56-01	76-39-09	BOWIE	140
AA Dd 52	P	AA-73-3159	38-57-02	76-40-01	BOWIE	110
AA Dd 53	P	AA-74-3937	38-57-26	76-38-17	BOWIE	130
AA Dd 54	P	AA-73-8343	38-58-44	76-38-03	BOWIE	110
AA Dd 55	P	AA-81-1266	38-57-56	76-38-44	BOWIE	90
AA Dd 57	P	AA-94-1728	38-56-19	76-36-13	SOUTH RIVER	70
AA De 209	P	AA-88-8082	38-57-41	76-32-41	SOUTH RIVER	20
AA De 210	V	AA-88-2908	38-59-50	76-30-38	SOUTH RIVER	50
AA De 211	V	AA-94-1197	38-56-50	76-31-51	SOUTH RIVER	20
AA De 212	V	AA-88-1851	38-56-58	76-33-34	SOUTH RIVER	20
AA Ec 11	R	AA-73-7240	38-55-00	76-40-28	BOWIE	60
AA Ed 54	R	AA-81-1926	38-53-49	76-38-13	BOWIE	100
AA Ed 56	R	AA-81-1424	38-51-43	76-38-03	BRISTOL	180
AA Ed 57	R	AA-86-0287	38-52-08	76-36-10	DEALE	110
AA Ee 85	R	AA-81-2501	38-50-19	76-31-04	DEALE	5
AA Ee 86	R	AA-93-0710	38-54-32	76-30-55	SOUTH RIVER	5
AA Ef 39	V	AA-81-1224	38-54-54	76-27-46	ANNAPOLIS	5
AA Fd 54	R	AA-93-1481	38-47-54	76-38-08	BRISTOL	140
AA Fd 55	R	AA-93-0845	38-46-32	76-35-28	DEALE	120
AA Ge 14	R	AA-81-8969	38-43-28	76-33-40	NORTH BEACH	110

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

[ft, feet]

Well number	Aquifer	Date of construction	Type of construction	Well depth (ft below land surface)	Top of open interval (ft below land surface)	Bottom of open interval (ft below land surface)
AA Bc 242	Patapsco	09-02-1977	Drilled	84	77	84
AA Bc 243	Patapsco	01-17-1991	Drilled	87	80	87
AA Bc 244	Patapsco	08-25-1980	Drilled	57	52	57
AA Bd 164	Patapsco	08-08-1973	Drilled	70	63	70
AA Bd 165	Patapsco	11-20-1979	Drilled	76	71	76
AA Bd 166	Patapsco	09-26-1974	Drilled	70	63	70
AA Bd 167	Patapsco	01-13-1994	Drilled	93	86	93
AA Bd 168	Patapsco	04-05-1977	Drilled	125	120	125
AA Be 115	Patapsco	06-08-1984	Drilled	81	74	81
AA Be 116	Patapsco	02-02-1977	Drilled	65	60	65
AA Bf 64	Magothy	08-14-1975	Drilled	90	83	90
AA Bf 65	Patapsco	01-13-1972	Drilled	70	60	70
AA Bf 66	Patapsco	11-15-1985	Drilled	66	59	66
AA Bf 67	Patapsco	08-28-1992	Drilled	92	85	92
AA Bf 68	Magothy	11-03-1986	Drilled	60	52	60
AA Cc 133	Patapsco	09-02-1994	Drilled	131	126	131
AA Cc 134	Magothy	02-06-1989	Drilled	104	99	104
AA Cd 100	Magothy	03-24-1983	Drilled	82	77	82
AA Cd 101	Aquia	-	Dug	30	0	30
AA Cd 104	Patapsco	11-01-1983	Drilled	90	70	90
AA Cd 105	Aquia	-	Dug	30	0	30
AA Ce 141	Magothy	10-09-1979	Drilled	205	198	205
AA Ce 142	Aquia	03-20-1986	Drilled	105	95	105
AA Cf 145	Aquia	07-15-1986	Drilled	120	113	120
AA Cf 146	Aquia	06-13-1988	Drilled	87	35	87
AA Cf 147	Aquia	11-15-1974	Drilled	67	60	67
AA Cf 148	Aquia	-	Dug	30	0	30
AA Cf 149	Aquia	04-09-1996	Drilled	105	98	105
AA Cg 26	Aquia	11-01-1977	Drilled	67	60	67
AA Dc 18	Aquia	11-29-1994	Drilled	79	74	79
AA Dd 51	Aquia	02-13-1985	Drilled	135	125	135
AA Dd 52	Aquia	09-04-1974	Drilled	90	78	90
AA Dd 53	Aquia	11-30-1981	Drilled	80	75	80
AA Dd 54	Aquia	11-15-1977	Drilled	80	73	80
AA Dd 55	Aquia	01-14-1983	Drilled	50	45	50
AA Dd 57	Aquia	07-26-1997	Drilled	46	36	46
AA De 209	Aquia	06-26-1992	Drilled	82	75	82
AA De 210	Aquia	06-30-1989	Drilled	130	120	130
AA De 211	Aquia	01-23-1997	Drilled	51	41	51
AA De 212	Aquia	01-09-1989	Drilled	92	84	92
AA Ec 11	Magothy	05-13-1977	Drilled	185	180	185
AA Ed 54	Aquia	07-09-1983	Drilled	165	158	165
AA Ed 56	Aquia	04-25-1983	Drilled	245	230	245
AA Ed 57	Aquia	08-12-1988	Drilled	275	268	275
AA Ee 85	Aquia	12-18-1983	Drilled	152	145	152
AA Ee 86	Aquia	05-15-1995	Drilled	43	36	43
AA Ef 39	Aquia	12-28-1982	Drilled	53	46	53
AA Fd 54	Aquia	12-06-1995	Drilled	315	308	315
AA Fd 55	Aquia	06-26-1995	Drilled	310	300	310
AA Ge 14	Aquia	09-19-1987	Drilled	371	361	371

APPENDIX C

WATER-QUALITY CONSTITUENTS AND SAMPLE CONTAINER DESCRIPTIONS, PRESERVATIONS, AND TREATMENTS

Appendix C1. Chemical and bacteriological constituents analyzed in this study

Appendix C2. Sample container designations, container descriptions, and sample preservation and treatment

Cancer group definitions:

- Cancer group A: Human carcinogen. Sufficient evidence in epidemiological studies to support causal association between exposure and cancer.
- Cancer group B: Probable human carcinogen. Limited evidence in epidemiological studies (group B1) and/or sufficient evidence from animal studies (group B2).
- Cancer group C: Possible human carcinogen. Limited evidence from animal studies and inadequate or no data in humans.
- Cancer group D: Not classifiable. Inadequate or no human or animal evidence of carcinogenicity.

[Source: U.S. Environmental Protection Agency, 1996]

Appendix C1. Chemical and bacteriological constituents analyzed in this study

[GC/MS, gas chromatography/mass spectrometry; $\mu\text{g/L}$, micrograms per liter; EPA, Environmental Protection Agency Region III Central Laboratory; --, not assigned to any cancer group. Sample container designations are described in appendix C2]

Constituent	Type of analysis	EPA method or reference	Reporting level ($\mu\text{g/L}$)	Laboratory	Sample container designation	Cancer group
VOLATILE ORGANIC COMPOUNDS:						
Benzene	GC/MS	524.2	1.0	EPA	GVC	A
Carbon tetrachloride	GC/MS	524.2	1.0	EPA	GVC	B2
Chlorodibromomethane	GC/MS	524.2	1.0	EPA	GVC	C
Bromodichloromethane	GC/MS	524.2	1.0	EPA	GVC	B2
1,1-dichloroethane	GC/MS	524.2	1.0	EPA	GVC	--
1,1-dichloroethylene	GC/MS	524.2	1.0	EPA	GVC	C
1,2-dichloropropane	GC/MS	524.2	1.0	EPA	GVC	B2
Methylene chloride (dichloromethane)	GC/MS	524.2	1.0	EPA	GVC	B2
Toluene	GC/MS	524.2	1.0	EPA	GVC	D
Trichloroethylene	GC/MS	524.2	1.0	EPA	GVC	B2
Vinyl chloride	GC/MS	524.2	1.0	EPA	GVC	A
1,3-dichlorobenzene	GC/MS	524.2	1.0	EPA	GVC	D
Styrene	GC/MS	524.2	1.0	EPA	GVC	C
<i>cis</i> -1,2-dichloroethene	GC/MS	524.2	1.0	EPA	GVC	D
Bromoform	GC/MS	524.2	1.0	EPA	GVC	B2
Chlorobenzene	GC/MS	524.2	1.0	EPA	GVC	--
Chloroform	GC/MS	524.2	1.0	EPA	GVC	B2
Dichlorodifluoromethane	GC/MS	524.2	1.0	EPA	GVC	D
1,2-dichloroethane	GC/MS	524.2	1.0	EPA	GVC	B2
1,2- <i>trans</i> -dichloroethene	GC/MS	524.2	1.0	EPA	GVC	D
Ethylbenzene	GC/MS	524.2	1.0	EPA	GVC	D
Tetrachloroethylene	GC/MS	524.2	1.0	EPA	GVC	--
1,1,1-trichloroethane	GC/MS	524.2	1.0	EPA	GVC	D

Appendix C1. Chemical and bacteriological constituents analyzed in this study --
Continued

[GC/MS, gas chromatography/mass spectrometry; $\mu\text{g/L}$, micrograms per liter; pCi/L, picocuries per liter; EPA, Environmental Protection Agency Region III Central Laboratory; MGS, Maryland Geological Survey; NWQL, U.S. Geological Survey National Water Quality Laboratory; Q, Quanterra Environmental Services; --, not assigned to any cancer group. Sample container designations are described in appendix C2]

Constituent	Type of analysis	EPA method or reference	Reporting level	Laboratory	Sample container designation	Cancer group
VOLATILE ORGANIC COMPOUNDS (continued):						
Trichlorofluoromethane	GC/MS	524.2	1.0 $\mu\text{g/L}$	EPA	GVC	--
1,2-dichlorobenzene	GC/MS	524.2	1.0 $\mu\text{g/L}$	EPA	GVC	D
1,4-dichlorobenzene	GC/MS	524.2	1.0 $\mu\text{g/L}$	EPA	GVC	C
Xylene	GC/MS	524.2	1.0 $\mu\text{g/L}$	EPA	GVC	D
Methyl <i>tert</i> -butyl ether (MTBE)	GC/MS	524.2	5 $\mu\text{g/L}$ (est.)	EPA	GVC	C (tentative)
Trichlorotrifluoroethane	GC/MS	524.2	1.0 $\mu\text{g/L}$	EPA	GVC	--
PESTICIDES:						
Atrazine	Immunoassay	Hayes and others (1996)	0.05 $\mu\text{g/L}$	MGS	LC0114	C
Metolachlor	Immunoassay	Lawruk and others (1993)	0.05 $\mu\text{g/L}$	MGS	LC0114	C
RADIONUCLIDES:						
Radon	Liquid scintillation	913.0 (draft)	80 pCi/L	NWQL	LC1369	A
Radium-226	Precipitation; planchet counting	903.0	0.1 pCi/L	Q	FAR	A
Radium-228	Radiochemical separation and beta counting	904.0	1.0 pCi/L	Q	FAR	A
Uranium	Fluorometry	908.1	1.0 $\mu\text{g/L}$	Q	FAR	A
Gross alpha-particle activity	Residue procedure	900.0	3.0 pCi/L	NWQL	FAR	A
Gross beta-particle activity	Residue procedure	900.0	4.0 pCi/L	NWQL	FAR	A

Appendix C1. Chemical and bacteriological constituents analyzed in this study --
Continued

[ICP, inductively-coupled plasma; AA, atomic absorption; IC, ion-exchange chromatography; $\mu\text{g/L}$, micrograms per liter; mg/L , milligrams per liter; CaCO_3 , calcium carbonate; NWQL, U.S. Geological Survey National Water Quality Laboratory; MDH, Maryland Department of Health and Mental Hygiene Laboratory; —, not assigned to any cancer group. Sample container designations are described in appendix C2]

Constituent	Type of analysis	EPA Method or reference	Reporting Level	Laboratory	Sample container designation	Cancer group
BACTERIOLOGICAL CONSTITUENTS:						
<i>Escherichia coli</i>	Colorimetric	Eaton, Clesceri, and Greenberg (1995)	presence/absence	MDH	B	--
Total coliform bacteria	Colorimetric	Eaton, Clesceri, and Greenberg (1995)	presence/absence	MDH	B	--
INORGANIC CONSTITUENTS AND INDICATORS:						
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	IC	Fishman (1993)	0.1 mg/L	NWQL	FU	--
Sulfate	IC	Fishman (1993)	0.1 mg/L	NWQL	FU	--
Alkalinity	Electrometric	Fishman and Friedman (1989)	1 mg/L as CaCO_3	NWQL ¹	FU	--
Fluoride	Colorimetric	Fishman and Friedman (1989)	0.1 mg/L	NWQL	FU	--
Iron (filtered)	ICP	Fishman (1993)	3 $\mu\text{g/L}$	NWQL	FA	--
Iron (unfiltered)	AA	Fishman and Friedman (1989)	10 $\mu\text{g/L}$	NWQL	RA	--
Manganese (filtered)	ICP	Fishman (1993)	1 $\mu\text{g/L}$	NWQL	FA	--
Manganese (unfiltered)	AA	Fishman and Friedman (1989)	10 $\mu\text{g/L}$	NWQL	RA	--
Silica	Colorimetric	Fishman and Friedman (1989)	0.1 mg/L as SiO_2	NWQL	FU	--
Residue at 180° Celsius	Gravimetric	Fishman and Friedman (1989)	1 mg/L	NWQL	FU	--

¹ Also measured in the field

Appendix C1. Chemical and bacteriological constituents analyzed in this study --
Continued

[GFAA, graphite furnace atomic absorption; ICP, inductively-coupled plasma; $\mu\text{g/L}$, micrograms per liter; mg/L , milligrams per liter; $\mu\text{S/cm}$, microsiemens per centimeter at 25° Celsius; NWQL, U.S. Geological Survey National Water Quality Laboratory; MDH, Maryland Department of Health and Mental Hygiene Laboratory; --, not assigned to any cancer group. Sample container designations are described in appendix C2]

Constituent	Type of analysis	EPA method or reference	Reporting level	Laboratory	Sample container designation	Cancer group
INORGANIC CONSTITUENTS AND INDICATORS (continued):						
pH	Electro-metric	Fishman and Friedman (1989)	--	NWQL ¹	RU	--
Specific conductance	Electro-metric	Fishman and Friedman (1989)	1 $\mu\text{S/cm}$	NWQL ¹	RU	--
Color	Electro-metric	Fishman and Friedman (1989)	1.0 color units	NWQL	RCB	--
Nitrate + nitrite (as nitrogen)	Colori-metric	353.2	0.2 mg/L	MDH	C	under review
Ammonia (as N)	Colori-metric	350.1	0.2 mg/L	MDH	C	D
Arsenic	GFAA	200.9	1.0 $\mu\text{g/L}$	NWQL	ERA	A
Beryllium	ICP	200.7	2.0 $\mu\text{g/L}$	NWQL	ERA	B2
Lead	ICP	200.9	1.0 $\mu\text{g/L}$	NWQL	ERA	B2
Dissolved oxygen (DO)	Titration or electro-metric	360.2 ² or 360.1 ³	0.1 mg/L	field	BOD	--

¹ Also measured in field.

² For DO measured by titration method.

³ For DO measured by electrometric method.

Appendix C2. Sample container designations, container descriptions, and sample preservation and treatment

[C, Centigrade; μ , micron]

Sample container designation	Container description	Sample preservation and treatment
GVC	Amber glass vial	Unfiltered, unrinsed, acidified with HCl to pH < 2; chilled and maintained at 4° C; delivered to lab within 24 hours.
LC0114	Amber glass bottle, baked at 450° C. by laboratory	Unfiltered, unrinsed, chilled and maintained at 4° C., shipped immediately.
LC1369	Glass bottle with mineral oil	Sample injected into oil and shaken; shipped same day via overnight courier.
FAR	Polyethylene bottle, acid-rinsed	0.45 μ -filtered, acidified with HNO ₃ to pH < 2.
FA	Polyethylene bottle, acid-rinsed	0.45 μ -filtered, rinsed with filtered sample, acidified with HNO ₃ to pH < 2.
FU	Polyethylene bottle	0.45 μ -filtered, rinsed with filtered sample.
RA	Polyethylene bottle, acid-rinsed	Unfiltered, rinsed with sample, acidified with HNO ₃ to pH < 2.
RU	Polyethylene bottle	Unfiltered, rinsed with sample.
RCB	Polyethylene bottle	Unfiltered, rinsed with sample, chilled and maintained to 4° C., shipped immediately.
C	Cubitainer (polyethylene container)	Unfiltered, acidified with H ₂ SO ₄ to pH < 2, chilled and maintained at 4° C., delivered to lab within 24 hours.
ERA	Polyethylene bottle, acid-rinsed	Unfiltered, acidified with HNO ₃ to pH < 2.
B	Polyethylene bottle	Unfiltered, unrinsed, chilled and maintained at 4° C; delivered to lab within 24 hours.
BOD	Glass-stoppered glass bottle	None (sample titrated immediately after collection).

APPENDIX D

SUMMARY OF QUALITY-ASSURANCE SAMPLE DATA

Quality-assurance samples were submitted to the laboratories throughout the sampling program in order to monitor for sample contamination and document analytical precision. QA data for this study consisted of analyses of trip blank samples, field blank samples, and duplicate samples. Most QA samples were collected early in the sampling program to ensure that any problems were identified and corrected. Both field blanks and trip blanks were submitted with selected VOC samples. Field blanks were submitted at selected times with all other critical-constituent samples except radon.

Blank samples. Blank samples were submitted to determine whether contamination occurred during sample collection, processing, or transport. Blank samples consisted of field blanks and trip blanks. Field blanks were sample bottles filled with inorganic- and organic-free water treated with the same procedures as were used when collecting the environmental samples. Trip blanks were sample bottles filled with organic-free water bottled under clean conditions and transported with the environmental samples. Sixteen field blank samples were collected, including four VOC blanks, three atrazine and metolachlor blanks, three radionuclide blanks, three nutrient blanks, and three trace-element (arsenic, beryllium, and lead) blanks. All field blanks except one were below reporting limits. The one exception was a nitrate blank (0.3 mg/L) which was slightly higher than the reporting limit (0.2 mg/L). VOC trip blanks were collected and submitted with each batch of VOC samples. VOC concentrations in all trip blanks were below MRLs.

Duplicate samples. Duplicate samples were submitted to document laboratory precision and variation in sample water during the collection process. Eighteen duplicate samples were collected, including 4 VOC duplicates, 4 radionuclide duplicates, 3 bacteria duplicates, 4 nutrient duplicates, and 3 trace-element duplicates. Duplicate immunoassay tests were conducted on all samples that were analyzed for atrazine and metolachlor. One set of duplicate radon samples (523 pCi/L and 651 pCi/L, respectively) exceeded the precision requirements specified in the QA project plan. Nitrate concentrations from a set of duplicate samples (3.5 mg/L and 5.0 mg/L) did not meet the precision requirements. Consultation with the project quality-assurance officer resulted in the decision to not resample the wells where the precision exceedances occurred. All other duplicate samples were within precision requirements.

Other quality-assurance samples. Nitrate and ammonium samples from two wells were analyzed by the NWQL to document comparability of the nutrient analyses analyzed by the Maryland Department of Health and Mental Hygiene Laboratory. Nitrate concentrations in the environmental and duplicate samples were within 0.1 mg/L of one another in each pair of samples; ammonium was not detected in any of the four samples.

No reference samples or other samples of known concentration were submitted for analysis for this study because there were no specific project accuracy requirements other than the internal requirements of the individual laboratories and for the pesticide immunoassay analyses. Percent-recovery data on VOCs from the USGS National Water-Quality Assessment

Program have indicated that there is little loss of volatiles in transport (J. Zogorski, U.S. Geological Survey, oral commun., 1997). Atrazine and metolachlor samples of known concentration were not submitted because the additional expenses for equipment, materials, and laboratory analysis were not considered to be justified for a pilot project of limited scope.

Samples from four wells were analyzed by GC/MS for a suite of 22 pesticides (including atrazine and metolachlor) and pesticide metabolites as a check on the immunoassay method. The wells tested included Bd 166, which had the only pesticide detection by immunoassay in the pilot study (metolachlor; 0.2 $\mu\text{g/L}$). The four wells were chosen on the basis of the perceived likelihood of having pesticide detections. None of the 22 pesticides was detected in any of the four wells, suggesting that the immunoassay detection in Bd 166 was a false-positive detection. False-positive detections are occasionally encountered in immunoassay techniques; false-negative detections have been shown to be very rare (Gruessner, Shambaugh, and Watzin, 1995; Maryland Geological Survey, unpublished data).

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