REPORT OF INVESTIGATIONS NO. 78

ARSENIC IN GROUND WATER IN THE COASTAL PLAIN AQUIFERS OF MARYLAND

by

David D. Drummond
and
David W. Bolton

ABBREVIATIONS USED IN THIS REPORT

DHMH	Maryland Department of Health and Mental Hygiene
DMA	dimethylarsinic acid
E	estimated
ft	foot
ICPMS	inductively coupled plasma-mass spectroscopy
L	liter
MCL	Maximum Contaminant Level
MDE	Maryland Department of the Environment
mgd	million gallons per day
MGS	Maryland Geological Survey
mg/L	milligrams per liter
mi	mile
ml	milliliter
MMA	monomethylarsonate
NWIS	National Water Information System
NWQL	National Water Quality Laboratory
ppb	parts per billion
ppm	parts per million
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
μg/L	micrograms per liter
μM	micromoles
μS/cm	microsiemens per centimeter at 25 degrees Celsius

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KEY RESULTS

A study was conducted to determine the extent and range of arsenic in the major aquifers of the Maryland Coastal Plain, and to identify possible hydrochemical controls on arsenic distribution in these aquifers. This study was undertaken in response to a lowering of the U.S. Environmental Protection Agency's Maximum Contaminant Level for arsenic from 50 to 10 micrograms per liter.

Arsenic data from more than 4,200 wells were evaluated to determine the geographic distribution of arsenic in the Coastal Plain aquifers of Maryland. These data indicate that the Aquia and Piney Point aquifers are the only Coastal Plain aquifers with water that exceeds the Maximum Contaminant Level of 10 micrograms per liter on a widespread basis. There were no exceedances of the Maximum Contaminant Level in the Potomac, Magothy, or Columbia aquifers, and only one well in the Miocene aquifers exceeded the Maximum Contaminant Level. Arsenic concentrations in the Aquia aquifer range from below detection limits (generally 2 micrograms per liter) to 131 micrograms per liter (in Anne Arundel County). Arsenic concentrations in the Piney Point aquifer range from below detection limits to 33 micrograms per liter (in Dorchester County). The lack of elevated arsenic concentrations in the shallow aquifers, the age of water in the Aquia and Piney Point aquifers, and the distribution of arsenic in the Aquia and Piney Point aquifers indicate that the overall arsenic occurrence is a natural phenomenon, and is not caused by anthropogenic contamination.

Elevated arsenic concentrations (those that exceed 10 micrograms per liter) in the Aquia aquifer form a band that approximately parallels strike (northeastern/southwestern trend), and extends from the Eastern Shore, beneath the Chesapeake Bay, and into Southern Maryland. An additional area of high arsenic concentrations was identified on the Mayo Peninsula in Anne Arundel County, about 10 miles northwest of the main area of elevated arsenic concentrations. No evidence indicates vertical variation of arsenic concentrations in the main band in the Aquia aquifer, although insufficient data on vertical zonation are available. However, in Anne Arundel County, elevated arsenic concentrations appear to be restricted to the depth interval of 70 to 100 feet below land surface. In this area, the aquifer is unconfined, and surface contamination cannot be ruled out at this location.

Elevated arsenic concentrations in the Piney Point aquifer form a band similar to the one in the Aquia aquifer, only narrower and farther to the southeast. It also extends from the Eastern Shore, beneath the Chesapeake Bay, and into Southern Maryland. Additional smaller areas of elevated arsenic concentrations occur north of the main band in Talbot and Queen Anne's Counties. As in the Aquia aquifer, there is no evidence of widespread vertical zonation of arsenic concentrations in the Piney Point aquifer, although more data are needed to confirm this.

Speciation analyses indicate that arsenite is generally the dominant dissolved arsenic species, with about 80 percent of total arsenic as averaged for samples from the Aquia aquifer and about 70 percent for samples from the Piney Point aquifer. The organic methylated arsenic compounds monomethylarsonate and dimethylarsinate ranged from below detection limits (0.1 micrograms per liter for both) to 0.2 and 0.6 micrograms per liter (as arsenic), respectively, in the Aquia aquifer, and from below detection limits to 0.2 micrograms per liter (as arsenic) for both species in the Piney Point aquifer.

The lack of correlation of arsenic concentrations with most other solutes and a lack of data on the geochemistry of aquifer material preclude the development of a unique hydrochemical model that fully explains arsenic distribution in the Aquia and Piney Point aquifers. Arsenic distribution in ground water may be controlled by distribution of lithologic components in the aquifer material, by mobilization mechanisms, or a combination of

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both. The area of elevated arsenic roughly coincides with the highest percentages of medium to coarse sand in the Aquia aquifer. Possible aquifer components that could provide a source for arsenic in the Aquia and Piney Point aquifers include calcareous shell material and cement, glauconite grains, phosphate pellets, goethite pellets, and iron oxyhydroxide coatings on mineral grains. However, insufficient data are available on the distribution of these components within the aquifers and arsenic composition of these materials to identify lithologic controls on arsenic distribution.

Mobilization controls that could partially determine arsenic distribution in ground water include oxidation-reduction reactions, pH variations, adsorption/desorption reactions, reductive dissolution, sulfate reduction, and ionic competition (and enhancement). Reductive dissolution is a likely mechanism for the mobilization of arsenic. In reductive dissolution, an arsenic-bearing substrate (either incorporated in the mineral structure or adsorbed on the substrate surface) such as iron oxyhydroxide, is solubilized due to increasingly reducing conditions, and arsenic is mobilized into solution. Sulfate reduction may also play a role in arsenic mobilization. In the Aquia and Piney Point aquifers, the highest arsenic concentrations occur in wells where sulfate concentrations are below 10 milligrams per liter, indicating that sulfate-reducing bacteria may produce sulfide, which precipitates arsenic-bearing sulfide minerals, and limits arsenic mobility. Competition for adsorption sites with other solutes, such as phosphate, may mobilize arsenic in the Aquia and Piney Point aquifers, and enhancement of adsorption by solutes such as calcium and magnesium may demobilize arsenic. Chemical evolution of ground water and leakage of water from adjacent confining units may also influence arsenic distribution.

INTRODUCTION

In 2001, the Maryland Geological Survey (MGS), in cooperation with the Maryland Department of the Environment (MDE), began a study of arsenic in ground water in the major aquifers of the Maryland Coastal Plain, where ground water is the primary source of drinking water. This study was undertaken because the U.S. Environmental Protection Agency (USEPA) in 2001 lowered the Maximum Contaminant Level (MCL) for arsenic from 50 to 10 micrograms per liter (μg/L) (Federal Register, 2001). This new standard is applicable to community water systems and non-transient non-community water systems, but generally not to privately owned (domestic) water supplies (although state and county regulators may apply it in some circumstances). Public-water systems were required to be in compliance with the new MCL by January 23, 2006. From routine monitoring, several community water systems in Maryland, particularly in Southern Maryland and the Delmarva Peninsula, were known to have ground-water arsenic concentrations between 10 and 50 μg/L in the Aquia and Piney Point aquifers (J. Grace, Maryland Department of the Environment, written commun., 2000). However, there had been no systematic study of arsenic concentrations in these or any other aquifers in the Maryland Coastal Plain.

PURPOSE AND SCOPE

The purpose of this study was to (1) determine the distribution of ground-water arsenic concentrations in the major aquifers of the Maryland Coastal Plain, with emphasis on private water wells; and (2) identify factors that are associated with arsenic concentrations greater than 10 μg/L. This report describes study methods (including study design, sample collection and analysis, and data interpretation) and presents arsenic data from the major Coastal Plain aquifers of Maryland. Factors associated with elevated arsenic concentrations (defined for this report as arsenic greater than 10 μg/L) are discussed.

Sampling for this study was conducted in two phases. In Phase 1 (2001-03), samples from 284 water wells were collected and analyzed for arsenic. Additional data were compiled from MDE for public-supply wells, and from county health department databases to further evaluate the occurrence and range of concentrations of arsenic in

the major aquifers of the Maryland Coastal Plain. In Phase 2 (2002-03), approximately 60 of the Phase 1 wells were resampled and analyzed for major and minor ions to better define the geochemical environments associated with arsenic concentrations greater than 10 μg/L. Thirty-three of these samples (25 from the Aquia aquifer and 8 from the Piney Point aquifer) were also analyzed for individual inorganic and organic arsenic species. In order to evaluate the influence of pH and major ions on arsenic mobilization, the Phase 2 samples were supplemented with 359 analyses from the U.S. Geological Survey (USGS) National Water Information System (NWIS) database. The discussion on arsenic occurrence focuses on the Aquia and Piney Point aquifers because the MCL was exceeded in only one well screened in other aquifers.

LOCATION OF STUDY AREA

The study area includes the entire Coastal Plain province of Maryland, which is the part of Maryland southeast of the Fall Line that is underlain by unconsolidated sands, silts, gravels, and clays (fig. 1). In this report, the term "Southern Maryland" refers to the five counties south of Baltimore and west of the Chesapeake Bay; the term "Eastern Shore" refers to the area of Maryland east of the Chesapeake Bay.

HEALTH EFFECTS OF ARSENIC

Chronic ingestion of water containing elevated levels of arsenic can cause a variety of health problems, including skin, lung, bladder, and kidney cancer, and skin discoloration and thickening (World Health Organization, 2001). Increased mortality risks for bladder, kidney, lung, liver, and colon cancers were associated with exposure to inorganic arsenic in drinking water (Chen and others, 1985, as cited in Federal Register, 2001, p. 7002). A cohort study of a population in Utah concluded that males had a significantly higher risk of prostate cancer mortality related to arsenic in drinking water (Lewis and others, 1999). The first studies relating arsenic ingestion to skin cancer were from Taiwan (Tseng and others, 1968; Tseng, 1977). The most common and best-characterized internal cancers from

epidemiological studies are lung and bladder cancer (Federal Register, 2001, p. 7002). The USEPA's quantitative risk estimates are based on Taiwan arsenic studies (Chen and others, 1988; Wu and others, 1989; Chen and others, 1992). The combined cancer mortality risk for drinking water containing 50 μg/L has been estimated as high as 1 in 100 (National Research Council, 2001; Smith and others, 2002). Other conditions have been reported from specific localities (such as "black foot disease" in Taiwan, caused by diseased blood vessels), and other environmental factors such as malnutrition may contribute to health outcomes (World Health Organization, 2001). Degraded gastrointestinal function and increased diabetes risk also have been documented (Federal Register, 2001, p. 7001). Water-borne arsenic was associated with reduced intellectual function in children (Wasserman and others, 2004). The most important action in mitigating the effects of long-term exposure to arsenic is the prevention of further exposure by providing a safe water supply (World Health Organization, 2001).

HYDROGEOLOGIC SETTING

The Maryland Coastal Plain is underlain by a sequence of sands, gravels, silts, and clays that form a series of aquifers and confining units ranging in age from Cretaceous to Pleistocene (fig. 2). These deposits generally become deeper and thicker to the southeast, forming a wedge-shaped body of sediments that lies atop the surface of various types of bedrock. The total thickness of sediments ranges from zero at the Fall Line to at least 7,700 feet (ft) at the Atlantic coast (Hansen and Edwards, 1986). Sediments composed predominantly of sand and gravel form aquifers that can supply water to wells. Sediments composed predominantly of clay and silt form confining units that restrict the flow of water between aquifers, but supply significant amounts of storage water to the aquifer system.

MAJOR AQUIFERS
OF THE MARYLAND COASTAL PLAIN

For the purpose of this study, the major Coastal Plain aquifers include, from deep to shallow, the Potomac Group aquifers (including the Patuxent and Patapsco aquifers), the Magothy, the Aquia, the Piney Point, the Miocene aquifers (including the Cheswold, Federalsburg, Frederica, Manokin, Ocean City, and Pocomoke aquifers), and the Columbia aquifer (tab. 1). These aquifers are not always synonymous with the stratigraphic units of the same name; for example, on Kent Island (in western Queen Anne's County) the Aquia aquifer includes the Hornerstown Formation, the Aquia Formation, and an unnamed Lower Eocene sand (Drummond,

1988). Except for the Columbia aquifer, the stratigraphic units generally strike in the northeast-southwest direction, and dip gently to the southeast. Hydrogeologic characteristics of Maryland's Coastal Plain aquifers have been documented extensively elsewhere and are summarized in table 1. A discussion of aquifer characteristics for all of Maryland's Coastal Plain aquifers is provided by Hansen (1972).

Potomac Group Aquifers

The Potomac Group aquifers consist of the (Cretaceous) Patuxent and Patapsco Formations, which are a major source of ground water in the upper Chesapeake Bay area of Maryland. The Patuxent and Patapsco Formations are separated by the Arundel Formation (at least from Baltimore southward) which is predominantly clay and silt, and generally acts as a confining unit. The thickness of the Potomac Group exceeds 5,000 ft near Ocean City in eastern Worcester County (Vokes, 1957). In Harford, Cecil, and Kent Counties, the Potomac Group aquifers are undifferentiated because of the difficulty in distinguishing between the individual formations (Otton and Mandle, 1984; Higgins and Conant, 1990). In Southern Maryland and the middle Eastern Shore, the Patapsco Formation is subdivided into the Lower Patapsco and Upper Patapsco aquifers, which are separated by the Middle Patapsco confining unit (Mack and Achmad, 1986; Drummond, 2007). However, for the purpose of this study, no distinction is made between these units.

The Patuxent and Patapsco Formations form a multi-aquifer system in which irregularly shaped sand bodies are separated locally by clay-silt confining units, but are connected at a regional scale to form extensive aquifers (Drummond, 2007). The Potomac Group aquifers outcrop/subcrop in a belt about 10 to 15 miles (mi) wide, adjacent to the crystalline rocks of the Piedmont province. They consist of white to light gray and orange-brown, fine to coarse quartz sands and subordinate gravel, interspersed with multicolored silt and clay beds. Accessory minerals include pyrite and lignite. They comprise a major source of water in Southern Maryland, the upper and middle Eastern Shore, and the central and upper part of the western shore. The estimated withdrawal from the Potomac Group aquifers in Maryland in 2000 was 60 million gallons per day (mgd) (J. Wheeler, U.S. Geological Survey, written commun., 2003).

Magothy Aquifer

The Magothy aquifer comprises sediments of the (Cretaceous) Magothy Formation, which lies unconformably on the Patapsco Formation. It outcrops in a narrow band from Cecil County southwest to Anne Arundel County, but pinches out in the subsurface in Prince George's and Charles Counties. The Magothy aquifer is a significant aquifer in Anne Arundel, Charles, and Prince George's Counties in Southern Maryland, and Kent, Queen Anne's, and Talbot Counties on the Eastern Shore. The Magothy Formation is composed of light gray to white, medium to coarse-grained quartz sand and fine gravel, and commonly contains lignite and pyrite. The estimated ground-water withdrawal from the Magothy aquifer in 2000 was 15 mgd (J. Wheeler, U.S. Geological Survey, written commun., 2003).

Aquia Aquifer

The Aquia aquifer outcrops/subcrops in an irregular band from the Potomac River in western Charles County northeast to exposures along the Sassafras River in eastern Cecil County (Hansen, 1974). On the Eastern Shore, the Aquia subcrops beneath Pleistocene surficial deposits (Hansen, 1972). It is a major aquifer in St. Mary's, Calvert, southern Anne Arundel, Queen Anne's, Talbot, and Kent Counties. It also extends southwest into Virginia and northeast into Delaware. It is Paleocene in age, and of shallow marine origin. It consists of fine- to coarse-grained green to brown sands with interspersed grayish green silts and clays. Fossil shell material is abundant, and includes clams, oysters, and gastropods, as well as locally abundant foraminifera. Figure 3 shows photographs of lithologic components of the Aquia aquifer, including quartz grains (some iron-stained), calcite as both shell fragments and cement, goethite grains, and glauconite grains. Calcite cementation occurs in layers several feet thick, especially in the updip areas. Glauconite is abundant in the Aquia aquifer, and makes up as much as 70 percent of the sand fraction. It occurs as greenish-black, fine to medium sand-sized grains, which with the quartz sand grains impart a "salt-and-pepper" appearance to the sediment. The Aquia aquifer changes from a sandy facies in the northwest to a clayey facies in the southeast, along a northeast-trending line that runs approximately from Point Lookout in southernmost

St. Mary's County to Denton in central Caroline County. The Aquia aquifer acts as a confining unit where it is a clayey facies. Estimated withdrawals from the Aquia aquifer in 2000 were 30 mgd (J. Wheeler, U.S. Geological Survey, written commun., 2003).

Piney Point Aquifer

The Piney Point aquifer is a major water source in Calvert, St. Mary's, Caroline, Talbot, and Dorchester Counties (Williams, 1979; Achmad and Hansen, 1997). It is Eocene in age and of shallow marine origin. The Piney Point aquifer comprises the Piney Point Formation throughout its extent, and the sandy, upper portions of the Nanjemoy Formation in Calvert and St. Mary's Counties (in some reports it is referred to as the "Piney Point-Nanjemoy aquifer," such as Chapelle and Drummond [1983] and Achmad and Hansen [1997]). It also extends southwest into Virginia and northeast into Delaware. The Piney Point aquifer does not outcrop; it is truncated in the subsurface by overlying Miocene sediments. Like the Aquia aquifer, it is an olive-green to greenish-gray, medium- to coarse-grained, glauconitic quartz sand. Shell material and calcite cementation are locally abundant, but are not as extensive as in the Aquia Formation. Southeast of a line approximately parallel to the boundary between Dorchester and Wicomico Counties, water in the Piney Point aquifer exceeds 250 milligrams per liter (mg/L) chloride, which renders it unsuitable as a water supply. An estimated 9 mgd was withdrawn from the Piney Point aquifer in 2000.

Miocene Aquifers

The Miocene aquifers include the Cheswold, Federalsburg, Frederica, Manokin, Ocean City, and Pocomoke aquifers. Each of these individual aquifers is a significant water supply in areas of limited extent for the central and southern parts of the Maryland Eastern Shore. These aquifers were described by Cushing and others (1973), but the extent and degree of separation between the individual aquifers have not been well defined. They are Miocene in age, and shallow marine to estuarine in origin. They are composed of sediments of the Calvert, Choptank, St. Mary's, and Yorktown Formations, although individual aquifers probably do not correlate with individual geologic formations.

Sands of these aquifers consist of light to medium gray quartz sand, separated (at least locally) by medium to dark-gray silty clay. Shell material is generally abundant, in places ranging close to 100 percent of the sediment. Diatomaceous material is abundant in parts of the Miocene aquifers (especially in the deepest strata), but glauconite is sparse or absent. An estimated 18 mgd was withdrawn from the Miocene aquifers in 2000.

Columbia Aquifer

The Columbia aquifer, as used in this report, is an important unconfined aquifer on the Maryland Eastern Shore. It is composed of Pliocene and Pleistocene sediments that blanket and in places truncate older sediments, and is fluvial, littoral, and shallow marine in origin. The Columbia aquifer is composed largely of two stratigraphic units, the Pensauken Formation and the Beaverdam Sand (Bachman, 1984). Sediments are composed predominantly of coarse-grained feldspathic quartz sands and gravels, with interbedded light gray and brown silty clays. The aquifer is highly transmissive in many places, and is used extensively for large irrigation supplies. In the Salisbury area in central Wicomico County, the Pleistocene deposits form a paleochannel more that 250 ft deep that supplies water for the city of Salisbury. The Columbia aquifer produced an estimated 47 mgd in 2000, more than one-third of which was for irrigation.

Plio-Pleistocene surficial deposits comprise the Surficial aquifer on the western shore of Maryland, which is considered separate from the Columbia aquifer. The Surficial aquifer includes sediments of the Talbot Formation, Lowland Deposits and Upland Deposits of Pliocene and Pleistocene age. This aquifer was once used extensively for small domestic and farm supplies, but currently only older wells tap it due to its vulnerability to contamination and drought. No wells in the Surficial aquifer were sampled in this study.

GROUND-WATER FLOW AND LEAKAGE

Water enters the Coastal Plain ground-water system primarily as recharge to the water-table aquifer through precipitation. Minor amounts of water may also enter the system from losing reaches of streams and fresh-water rivers, and as brackish-water intrusion from estuaries. During prepumping

conditions, probably all water entered the aquifer system as recharge, but ground-water withdrawals have reversed flow gradients in many areas, and induced brackish-water intrusion in places (Chapelle, 1985, Drummond, 1988; Achmad and Wilson, 1993; Fleck and Andreasen, 1996). Some water that enters the shallow ground-water system discharges as evapotranspiration, baseflow to streams, submarine discharge to estuaries, or withdrawals to water-table wells. A small fraction of the water that enters the shallow ground-water system flows downward to recharge the confined aquifer system. Carbon-14 age dating of water from the Aquia aquifer in St. Mary's County determined that ground water is between 8,500 and 15,500 years old (Mignery, 1994). This data indicates that water takes thousands of years to travel from the recharge area to the deep confined parts of the aquifer, and that the source of arsenic in these areas could not be anthropogenic contamination.

Water enters the confined aquifers of the Maryland Coastal Plain partially as direct recharge from the Surficial aquifer, but significant amounts of water also enter as leakage through confining units. The Potomac Group aquifers and the Aquia aquifer have significant outcrop areas, which provide direct recharge to the confined portions of the aquifers. The Piney Point aquifer does not outcrop or subcrop in Maryland, and thus receives all of its inflow as leakage. The Magothy aquifer outcrops in northeastern Maryland, but not southwest of Anne Arundel County, and receives inflow from recharge and leakage. Little information is available on the recharge characteristics of the Miocene aquifers, and it is uncertain whether they receive inflow as direct recharge, or entirely as leakage.

Under prepumping conditions, water flowed through confining units as leakage to other aquifers, and as discharge to estuaries, fresh-water streams, and the Atlantic Ocean. Ground-water withdrawals have reversed flow gradients in many areas, and diverted discharge from these other sinks. Lowered hydraulic heads resulting from large ground-water withdrawals may cause changes in water chemistry where induced leakage is chemically different from ambient ground water.

Figures 4 and 5 show simulated prepumping potentiometric surfaces for the Aquia and Piney Point aquifers, respectively. Contours were compiled from ground-water flow models developed for Queen Anne's and Talbot Counties (Drummond, 2001) and Southern Maryland (Drummond, 2007). Prepumping flow lines are also shown in these figures, drawn perpendicular to the potentiometric contours. On the Eastern Shore of Maryland, these flow lines that were derived from flow modeling differ significantly from flow lines derived from chemical distribution. This discrepancy is discussed in a later section of this report.

METHODS OF INVESTIGATION

SOURCES OF DATA

Data used in this study for arsenic and other chemical constituents came from several sources. The initial distribution of arsenic was determined using water-quality samples collected by MGS in this study (Phase 1 sampling). After the area of elevated arsenic was identified, the affected counties began routine testing of all new private wells for arsenic, and these data were obtained by MGS and incorporated into this study. Arsenic data from the MDE database for public-water systems was also used in this study. The hydrogeochemistry of the Aquia and Piney Point aquifers was investigated using data from samples collected by MGS in Phase 2 of this study and from the USGS NWIS database.

MGS-Collected Samples

Well-Numbering System

Wells sampled by MGS personnel were inventoried and entered into the USGS NWIS database. The wells are identified by an alphanumeric system. The first two letters (both uppercase) indicate the county where the well is located. The next two letters (the first uppercase, the second lowercase) correspond to a 5-minute by 5-minute block of a grid superimposed over the county: the first letter corresponds to the row and the second letter corresponds to the column within the grid. Wells within each block are numbered sequentially as they were inventoried. Thus, well

CA Ec 49 refers to the forty-ninth well inventoried in the block located at the intersection of row "E" and column "c" in Calvert County.

Well Selection

MGS personnel sampled 284 wells for arsenic during Phase 1 of this investigation. The wells were selected throughout most of the areas where each of the major Coastal Plain aquifers is used for water supply. The wells were selected to determine the geographic distribution of ground-water arsenic concentrations, rather than to achieve a population-density-weighted selection of wells. USGS, MGS, MDE, and county databases were used to identify potential wells for sampling, with assistance from county personnel. In areas where wells could not be located from these databases, sampling permission was obtained from homeowners whose wells had documented or reported construction characteristics. Well-construction information, arsenic analyses, and field water-quality parameters for MGS-collected samples are given in Appendixes A and B.

After the initial sampling for regional distribution had been conducted, 60 wells that were screened in the Aquia and Piney Point aquifers were resampled for a suite of major ions (referred to as Phase 2 sampling). The purpose of this was to better assess the general geochemical environments of these aquifers. Results of these analyses are shown in Appendix C. Thirty-three of these samples were also analyzed for individual arsenic species (arsenate, arsenite, monomethylarsonate [MMA], and dimethylarsinate [DMA]). Wells were selected to gather data on both low-arsenic and high-arsenic environments.

Sample Collection and Analysis

For both the regional sampling and the subsequent major-ion sampling, all water samples collected by MGS were obtained from spigots or other outlets that were identified by the owners as sources of untreated water. Most domestic wells were field-tested for hardness to confirm the lack of water-softening treatment. Samples from public water-supply wells were collected from spigots drawing water from points located before the treatment systems. Observation wells (without pumps installed) were sampled with mobile submersible pumps.

A YSI 600XL Datasonde[1] was used to measure pH, specific conductance, dissolved oxygen, and water temperature as the well water was purged. The datasonde was calibrated with a two-buffer pH calibration and a one-standard specific conductance calibration. Buffers for the pH calibration were selected to bracket the anticipated pH of the samples; the specific conductance standard that was selected was close to the anticipated specific conductance of the sample. For most samples, the water was run for at least 15 minutes or until measurements of specific conductance, pH, and temperature (recorded at 5-minute intervals) were stable, as determined by the field measurements taken at 5-minute intervals. For some wells, the water was run for a shorter amount of time, either at the request of the well owner or because the water had been run extensively prior to sampling (such as public water-supply wells). Although turbidity was not monitored during purging, samples were not collected until the purge water was clear.

For the regional study, unfiltered, untreated ("raw") water samples were collected and analyzed for arsenic (referred to as total arsenic), since this was considered most representative of well water that was being consumed. Water samples were collected in either 1-liter (L) polyethylene cubitainers (Department of Health and Mental Hygiene [DHMH] analysis) or 250-milliliter (ml) polyethylene bottles (USGS NWQL analysis) and acidified with nitric acid to pH less than 2. Samples were delivered to the Maryland DHMH laboratory for analysis within 1 week.

Samples were analyzed for arsenic at the DHMH by inductively coupled plasma-mass spectroscopy (ICP-MS) by USEPA method 200.8 (U.S. Environmental Protection Agency, 1994). Samples with elevated chloride concentrations (as inferred from specific conductance measurements) were analyzed at the USGS NWQL by graphite furnace-atomic absorption spectrometry (Jones and Garbarino, 1999) to reduce potential chloride interference in the ICP-MS method. Arsenic speciation samples were analyzed at NWQL using the laboratory and field methods of Garbarino and others (2002).

Samples from the 60 resampled wells that were analyzed for major ions were collected in a 5-L

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

amber glass bottle and filtered through a 0.45-micron Gelman[1] capsule filter using a peristaltic pump. Major-ion analyses were conducted at the DHMH laboratory, using the analytical methods listed in table 2. Specific conductance, pH, and alkalinity were measured in the field. After sample collection and processing had been completed, the 5-liter amber glass bottles and the peristaltic pump tubes were cleaned with Liquinox detergent and rinsed with deionized water, rinsed with hydrochloric acid, and re-rinsed with deionized water. Samples analyzed at NWQL were shipped by overnight courier. Major-ion samples were delivered to the DHMH laboratory at the end of each sampling day. Blank, replicate, and reference (known arsenic concentrations) quality-assurance samples were collected, the results of which are described in Appendix D.

MDE Database

Approximately 502 arsenic analyses obtained from public-supply wells were used to map the regional arsenic distribution. These samples were collected by state-certified collectors, including MDE personnel, laboratory personnel, and water-system operators (John Grace, MDE, written commun., 2009). Unfiltered samples were collected from untreated, unfiltered water sources, collected in glass or plastic containers, and acidified with nitric acid to a pH below 2. Analyses were performed at the DHMH laboratory or other state-certified laboratories. Locations of wells and aquifer designations were determined by MDE personnel. Some arsenic concentrations shown on arsenic distribution maps in this report are averages of multiple samples from the same well. Detection levels for these analyses range from 2 to 5 μg/L.

County Health Department Databases

As a result of the preliminary arsenic-distribution maps generated during Phase 1, sampling of ground water for arsenic is required by county health departments for new wells in some areas of Anne Arundel, Calvert, St. Mary's, Caroline, Queen Anne's, Talbot, and Dorchester Counties. Arsenic data were obtained from county health department databases for approximately 3,500 of these wells. In general, these samples were collected by health department personnel from taps inside houses, and analyzed by the DHMH laboratory or other state-certified laboratories. Detection levels for these analyses range from 1 to 5 μg/L.

Location information and aquifer designations for sampled wells were not generally included in the health department databases, so this information was derived through other means. Tax-map, parcel, and lot numbers in these databases were linked to the Maryland Property View (Maryland Department of Planning) database using a GIS Geodatabase (ESRI Arcview versions 9.2 and 9.3). The resulting locations represent property centroids, which are not necessarily the exact well locations on the properties. For small lot sizes, this difference is probably not significant, but for larger lots, it may lead to inexact locations and possible misidentification of the screened aquifer if the location discrepancy resulted in a significant error in land elevation.

The screened aquifer for each sampled well was determined by estimating land-surface elevation, determining screen-interval altitude, then comparing the screen altitude with the altitude of aquifer tops and bottoms at the well location. Land-surface elevation for each domestic well was estimated using LIDAR data (Maryland Department of Natural Resources one arc-second). Screen intervals were determined by linking the well-permit numbers from county databases to an MDE-maintained database containing well-construction characteristics, and extracting values for screen top and bottom depths. Screen depths were converted to altitudes by subtracting them from estimated land-surface elevation. The aquifer screened in each well was determined by comparing the screen altitude to aquifer top and bottom altitudes in the GIS-based aquifer framework developed in previous studies (Drummond, 2001; Drummond, 2007). Because of uncertainties in well location, land-surface elevation, and aquifer frameworks, some wells appeared to be screened (at least partially) in confining units. In these cases, the closest aquifer was assigned to the well.

DISTRIBUTION OF ARSENIC IN GROUND WATER

A total of 284 samples were collected for arsenic analysis in Phase 1 of this study. Of those samples, 30 exceeded the MCL of 10 μg/L, and 105 were above 2 μg/L (the detection limit for most of the samples) (tab. 3). The MCL was exceeded in 24 of 117 (21 percent) wells sampled in the Aquia aquifer, and 5 of 55 (9 percent) wells sampled in the Piney Point aquifer. Only one well in the other aquifers exceeded the MCL. In the MDE database for public-supply wells, 35 of 502 (7 percent) total wells sampled exceeded the MCL. All wells in the MDE database that exceeded the MCL were in the Aquia or Piney Point aquifers, except for one well screened in the Pocomoke aquifer. In the county health department databases, about 400 of 3,500 (11 percent) samples exceeded the MCL for arsenic; all exceedances were in either the Aquia or Piney Point aquifers. These samples were collected from areas and aquifers that were known to have elevated arsenic concentrations and, therefore, the county data do not represent the region as a whole.

POTOMAC GROUP
AND MAGOTHY AQUIFERS

The deepest aquifers in the Maryland Coastal Plain include the Patuxent and Patapsco aquifers, which comprise the Potomac Group; and the Magothy aquifer (tab. 1). All arsenic concentrations in samples from these aquifers were below the MCL (fig. 6). The data indicate that arsenic concentrations are not a widespread problem in these aquifers, although this does not preclude the possibility that there are isolated "hot spots" (localized areas of elevated arsenic concentrations) where arsenic concentrations exceed the MCL.

The Monmouth and Matawan aquifers are used for water supply in limited areas on the upper Eastern Shore, but only three wells screened in these aquifers have been sampled for arsenic, with concentrations ranging from 1 to 4 μg/L. These aquifers are lithologically similar to the Aquia and Piney Point aquifers (they contain glauconite and calcitic shell material), and water from them may contain elevated arsenic concentrations in places. More data are needed to evaluate the arsenic levels throughout the area where the Monmouth and Matawan aquifers are used.

AQUIA AQUIFER

The distribution of arsenic in water from the Aquia aquifer is shown in figure 7. Generalized arsenic-concentration contours are also shown to indicate areas of elevated concentrations. Concentration contours are generalized because there is significant scatter of arsenic concentrations, and many outliers exist outside their respective contours.

Elevated arsenic concentrations in the Aquia aquifer form a band that approximately parallels strike, and includes areas of the Eastern Shore and Southern Maryland. The area of highest arsenic concentrations trends northeast through western Dorchester County, western Talbot County, and central Queen Anne's County. This band appears to continue beneath Chesapeake Bay into southern Calvert County and central St. Mary's County. Arsenic concentrations are generally lower in Southern Maryland than on the Eastern Shore.

A hotspot of high arsenic concentrations was identified on the Mayo Peninsula in Anne Arundel County by the county health department. This area is about 10 mi northwest of the main area of elevated arsenic concentrations shown in figure 7. About 243 arsenic analyses were obtained by the Anne Arundel County Health Department from domestic wells screened in the Aquia aquifer in this area. In these samples, arsenic concentrations range from below detection level (generally 2 μg/L) up to 131 μg/L. The Aquia aquifer is unconfined in this area, and chemical conditions are likely very different from those in the main area of elevated arsenic concentrations. Cross sections constructed using Anne Arundel County data indicate that elevated arsenic concentrations are generally restricted to the depth interval of about 70 to 100 ft below land surface. The reasons for elevated arsenic concentrations in this area and the vertical zonation are unclear. Because the Aquia aquifer is relatively shallow and unconfined in this area, the possibility of surface contamination cannot be ruled out.

The thickness of the Aquia aquifer ranges up to 250 ft in central Queen Anne's County and vertical zonation in arsenic concentrations is possible. Geologic units within the Aquia aquifer were identified for 31 wells sampled in the Kent Island area, in western Queen Anne's County. In this area,

the stratigraphic units comprising the Aquia aquifer are (from top to bottom) the Lower Eocene Sand, the Aquia Formation, and the Hornerstown Sand. Arsenic concentrations for 16 wells screened in the Lower Eocene sand averaged 4.4 μg/L, with a maximum concentration of 7 μg/L. Arsenic concentrations for 10 wells screened in the Aquia Formation averaged 4.2 μg/L, with a maximum concentration of 9 μg/L. Arsenic concentrations for 5 wells screened in the Hornerstown sand averaged 3 μg/L, with a maximum concentration of 6 μg/L. For the purpose of calculating average values, the analyses that were reported as less than the detection limit of 2 μg/L were set at the detection limit. Because of the small sample size and relatively small differences in arsenic concentrations, little can be concluded from these data about vertical zonation in arsenic concentrations.

Differences in arsenic concentrations in the Aquia aquifer are shown on a cross section constructed through the area of elevated arsenic concentrations in southeastern Queen Anne's County and central Talbot County (fig. 8). Most wells are screened in the top part of the Aquia aquifer (presumably to minimize drilling costs) and insufficient data for the lower part of the aquifer are available to establish any vertical trends. In the updip part of the cross section, arsenic concentrations are mostly below 5 μg/L. The area of elevated arsenic concentrations is apparent in the center of the cross section, with maximum concentrations reaching 41 μg/L in eastern Talbot County. Farther downdip, arsenic concentrations decrease to the 5- to 15-μg/L range, then decrease further to below 5 μg/L.

PINEY POINT AQUIFER

Arsenic concentrations in the Piney Point aquifer show a similar distribution pattern as in the Aquia aquifer. Elevated arsenic concentrations form a band in the downdip (southeastern) part of the aquifer that roughly parallels regional strike (fig. 9). The band of elevated arsenic concentrations primarily trends northeast through central Dorchester County, but also appears to extend beneath the Chesapeake Bay into southern St. Mary's County. Farther downdip, in southeastern Dorchester County, arsenic concentrations decrease to below 5 μg/L. A second area of elevated arsenic concentrations is present updip of the main band. This area trends northeast through northern Dorchester County, central Talbot County, and southern Queen Anne's County. Fewer data are available for the Piney Point aquifer in this area, so the delineation of this secondary band is uncertain. This second area is coincident with the band of elevated arsenic in the Aquia aquifer. Because the Piney Point aquifer receives its inflow as leakage from vertically adjacent aquifers (including the Aquia aquifer) through confining units, it is possible that high-arsenic water is migrating from the Aquia aquifer to the Piney Point aquifer in this area. Two elevated arsenic concentrations are also present in Southern Maryland in the updip part of the Piney Point aquifer; whether these points form an extension of the secondary arsenic band on the Eastern Shore is unclear.

MIOCENE AND COLUMBIA AQUIFERS

The aquifers above the Piney Point aquifer include the Miocene aquifers (consisting of the Cheswold, Federalsburg, Frederica, Manokin, Ocean City, and Pocomoke aquifers), the Columbia, and the Surficial aquifers. Only one well screened in these aquifers had an arsenic concentration above the MCL (fig. 10). This well is screened in the Pocomoke aquifer in southern Worcester County, and had an arsenic concentration of 14 μg/L in sampling for this study, and 12 μg/L in MDE sampling. These data indicate that elevated arsenic is not a widespread problem in the shallow aquifers, although there could be additional hotspots that were not detected in the limited sampling. Although large-scale chicken farms have been implicated in environmental arsenic contamination on Maryland's Eastern Shore (Hancock and others, 2001), data from this study do not indicate contamination of shallow aquifers.

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POTENTIAL HYDROCHEMICAL CONTROLS ON ARSENIC

The hydrogeochemistry of arsenic has been studied extensively in many hydrogeologic settings because of health considerations in water supplies (Nordstrom, 2002). However, arsenic chemistry in ground-water environments is complex, and the controls on arsenic sources and mobilization in many ground-water environments are difficult to identify. For instance, in south Asia (Bangladesh and parts of India), where elevated arsenic concentrations in ground-water supplies affect millions of people, the chemical pathways for dissolved arsenic remain unresolved (Dowling and others, 2002). A full discussion of arsenic chemistry in the ground-water environment is beyond the scope of this report; reviews of this subject may be found in Smedley and Kinniburgh (2002) and Welch and Stollenwerk (2002).

With the available data, it was not possible to identify a unique hydrochemical model that fully explains arsenic distribution and mobilization in the Coastal Plain aquifers of Maryland. However, hydrochemical factors that could control arsenic occurrence in the Maryland Coastal Plain are discussed as they relate to patterns in arsenic concentrations in the Aquia and Piney Point aquifers.

Arsenic occurrence in ground-water environments may be controlled by lithologic components in the aquifer material, by mobilization mechanisms, or a combination of both. In lithology-controlled environments, one or more components of the aquifer material, such as shell fragments or phosphate pellets, provide a source of arsenic that is mobilized in ground water. The areal and vertical distribution of the source component within the aquifer determines the distribution of arsenic in the ground water. In mobilization-controlled situations, the distribution of arsenic in ground water is determined by chemical conditions (such as pH or redox potential) that favor mobilization of arsenic from the aquifer materials into ground water. The distribution of arsenic is indirectly controlled by the chemical mechanisms that create the mobilization-favoring conditions. Ground-water arsenic distribution in mobilization-controlled environments can be further complicated in aquifers having variable arsenic concentrations in the aquifer materials.

LITHOLOGIC CONTROLS

Lithologic components that could provide a source for arsenic in the Aquia and Piney Point aquifers include calcitic shell material, calcitic cements, glauconite, phosphate pellets, goethite pellets, and iron oxyhydroxide coatings on other mineral grains. Insufficient data are available on the distribution of these components within the aquifers to determine if they actually control arsenic occurrence in ground water. However, some information suggests that lithology may partially determine arsenic distribution in ground water.

The Aquia Formation exhibits three depositional facies that have distinct hydraulic and lithologic characteristics (Hansen, 1974). Facies 1 is a high-energy offshore sand-bank complex that occupies Calvert, Kent and Queen Anne's Counties, and parts of St. Mary's, Anne Arundel, Dorchester, and Talbot Counties (fig. 7). It is thicker than the other two facies, and has higher percentages of total sand, goethite, glauconite, calcareous material, and more intense iron staining. Facies 2 was deposited in a low-energy inner-shelf environment, landward (northwest) of facies 1, and contains fine, muddy sands. It occupies most of Charles and Prince George's Counties. Facies 3 was deposited in a low-energy outer-shelf environment, seaward (southeast) of facies 1, and occurs in eastern Dorchester County and most of Caroline County. Sand thicknesses in facies 2 and 3 are much less than in facies 1, with lower percentages of total sand, goethite, calcareous material, and iron staining.

The area of elevated arsenic concentrations in the Aquia aquifer occurs within facies 1, and is roughly coincident with the highest percentages of medium to coarse sand within the aquifer. Other lithologic characteristics, including goethite-to-glauconite ratios, intensity of iron-stained quartz grains, and abundance of calcitic material (shell fragments and calcareous cement) also are roughly coincident with the area of elevated arsenic concentrations.

Sedimentary facies in the Piney Point Formation have not been delineated as they have in the Aquia Formation. However, both formations were deposited during marine regressions in littoral to shallow neritic environments (Hansen, 1972), and

the same sedimentary facies likely characterized depositional environments in the Piney Point Formation. Post-depositional downwarping of the Salisbury embayment and Oligo-Miocene erosion caused a truncation of the updip part of the Piney Point Formation, and all or part of facies 2 (as delineated for the Aquia Formation by Hansen [1974]) is missing from this unit. The axis of maximum sand thickness in the Piney Point Formation (which indicates the longitudinal axis of facies 1 in the Aquia Formation) trends from Point Lookout in St. Mary's County, northeastward through central Dorchester County, southern Caroline County, and into Delaware (Hansen, 1972). This axis coincides closely with the main area of elevated arsenic concentrations in the Piney Point aquifer.

The coincidence of specific lithologic components with the areas of elevated arsenic concentrations in the Aquia and Piney Point aquifers indicates that one or more of these components may provide a source of ground-water arsenic in these areas, and may at least partially explain the distribution patterns similar in both aquifers. Lithologic components that may provide a source of arsenic in the Aquia and Piney Point aquifers include clay minerals, calcite, and iron oxyhydroxides.

Clay Minerals

Clay minerals present in sediments may provide adsorption sites for arsenic (Manning and Goldberg, 1996), and the distribution of arsenic-bearing clays may partially control the distribution of arsenic in water in Coastal Plain aquifers. X-ray diffraction analyses of Aquia aquifer sediments from Kent, Queen Anne's and Prince George's Counties indicate the presence of kaolinite, illite, smectite, glauconite, and mixed-layer clays in varying proportions (Hansen, 1977; Hansen, 1992). Clays form as alteration products of other aluminosilicate minerals such as micas and feldspars. Clay minerals are very fine grained, and form as clayey beds interstratified with layers of sand; interstitial clay, which forms a matrix of coarser grained sediments; and (in the case of glauconite) as sand-sized agglomerates.

Glauconite is an authigenic clay mineral that forms greenish-black sand-sized pellets. It is abundant in the Aquia and Piney Point aquifers, but is sparse or absent in the other major aquifers of the Maryland Coastal Plain. Little information is

available on the presence of arsenic in glauconite, but data on similar clays provide some information. Experiments of arsenic adsorption on several types of pure clays indicate that arsenate is strongly adsorbed onto illite, with peak adsorption occurring at pH of 6.5 (Manning and Goldberg, 1996). Adsorption rapidly decreases at pH higher than 6.5, indicating the possibility of arsenate mobilization as pH increases within the range observed in the Aquia and Piney Point aquifers.

Dooley (2001) analyzed arsenic and other metal concentrations in weathered soils and unweathered, "pristine" samples derived from glauconitic Coastal Plain formations in New Jersey. He found that arsenic concentrations in whole-soil samples and glauconite isolates from soils were enriched by factors of approximately 3 and 6, respectively, compared to average U.S. soils. Arsenic concentrations in pristine sediment samples from the same formations in the Ancora core hole (a site in south-central New Jersey) ranged from 7 to 136 parts per million (ppm) with a median concentration of 24 ppm. Arsenic concentrations in glauconite isolates from the soil samples ranged from 18 to 126 ppm with a median concentration of 24 ppm. Median arsenic concentrations from the soil samples were enriched when compared to the pristine samples, indicating that arsenic is generally retained in the solid phase during the weathering process. Sediments in the Dooley (2001) study are Paleocene to Upper Cretaceous in age, and are, therefore, mostly stratigraphically lower than the Aquia and Piney Point aquifers; however, the Hornerstown Formation, which was included in the Dooley (2001) study, is the deepest unit in the Aquia aquifer on the Eastern Shore of Maryland (Drummond, 2001).

Haque and others (2008) analyzed arsenic in glauconite isolates from the Aquia Formation in a core hole (KE Bf 180) in Kent County, Maryland. Total extractable arsenic from depths of 215 ft and 340 ft were 55.5 parts per billion (ppb) and 22.6 ppb, respectively. These values are well below the average crustal abundance of 1,800 ppb (Hering and Kneebone, 2002), and also below the total extractable arsenic concentrations of bulk sediment from those same intervals (151 and 73 ppb, respectively). These data indicate that arsenic is not concentrated in glauconite grains in these samples, and would not provide a supply for arsenic mobilization. This core hole was located in the subcrop area of the Aquia Formation, however, and weathering may have altered the chemical characteristics of the sediments there. Sediment

analyses from farther downdip in the area of high arsenic concentrations may show higher arsenic concentrations on glauconite.

Calcite

Calcite ($CaCO_3$) is a ubiquitous mineral in both the Aquia and Piney Point aquifers. It occurs as original shell material of clams, oysters, gastropods, brachiopods, bryozoans, and echinoids, and as reprecipitated material from these same organisms. Calcite also occurs as foraminiferal tests and calcareous cemented beds. Arsenic may be incorporated into the mineral calcite by substitution of the aqueous oxyanion AsO_3^{3-} (arsenic in reduced form) for the carbonate anion CO_3^{2-} (Cheng and others, 1999). Although no data are available on the arsenic content of calcite material in the Aquia or Piney Point aquifers, the dissolution of arsenic-bearing calcite is a possible mechanism for mobilizing arsenic in these aquifers. Calcite dissolution is an important reaction occurring in these aquifers (Chapelle and Drummond, 1983; Appelo, 1994; Dai and others, 2006; Haque and others, 2008), but this reaction alone could not account for the arsenic distribution patterns observed. Dissolution of calcite takes place throughout the aquifers, so a removal mechanism would also be necessary in the updip and far downdip areas where low concentrations of arsenic occur. Possible removal reactions in the updip and downdip areas could include reprecipitation of arsenic-bearing calcite as calcareous cement, and adsorption of arsenic on metallic oxide grain coatings (such as iron oxyhydroxide) or clays.

Iron Oxyhydroxides

Iron oxyhydroxides are common materials in aquifers of the Maryland Coastal Plain. Along with oxides of aluminum and manganese, iron oxyhydroxides are potentially the most important source and sink for arsenic in aquifer sediments because of their chemistry and widespread occurrence. Iron minerals found in Coastal Plain sediments include hematite, goethite, limonite, and magnetite. They can occur as detrital components, authigenic grains, or coatings on other mineral grains. Iron oxyhydroxides have been cited in numerous hydrogeologic settings as important sources of arsenic, either incorporated into the mineral structure or adsorbed on the mineral surface (Stollenwerk, 2002). Oxyhydroxides of other metals, such as manganese and aluminum, are important factors in arsenic occurrence in some hydrogeologic settings (Stollenwerk, 2002), but are not as common as iron oxyhydroxides in Maryland.

Iron staining of quartz sand grains is common in the Aquia and Piney Point aquifers, particularly in facies 1 of the Aquia aquifer (Hansen, 1974) where high arsenic concentrations are most common. The iron staining found in facies 1 sands originated as antecedent grain coatings of iron oxyhydroxide inherited from original source material, which survived erosion and transport. Iron staining may also have formed by precipitation of iron oxyhydroxide during deposition in the shoaling marine environment. Aquia sands in the outcrop and shallow subsurface also display intense iron staining that was probably caused by post-depositional deep weathering (Hansen, 1974).

Goethite pellets are also common in the Aquia and Piney Point Formations, and reach peak abundance in the middle of facies 1 (Hansen, 1974) where arsenic also reaches peak concentrations. These pellets are generally medium to coarse-grained, irregular to ellipsoidally shaped, and reddish brown with a lustrous surface. They are morphologic composites of weakly crystalline goethite, silty to fine quartz sand, silt-sized glauconite grains, and smaller amounts of illite and mixed-layer clays. Their origin is probably authigenic, and some finer grains may have passed through a glauconitic stage (Hansen, 1974).

Haque and others (2008) analyzed Aquia sediments from four depth intervals in a core hole in Kent County using a sequential extraction technique, in which the sediment sample is subjected to five stages of increasingly aggressive solutes, and the resulting solutions were analyzed for arsenic, iron, manganese, and aluminum. Results indicate the proportions of metals residing in several matrix components. Most of the arsenic in these sediments was found to reside in the non-labile (tightly bound to the sediment matrix and unlikely to desorb) phases associated with poorly-crystallized and well-crystallized metal oxyhydroxides, primarily iron oxyhydroxides (ranging from 17 to 49 percent total extractable arsenic). Arsenic in these phases is not available for desorption reactions, and would only be released to solution if the minerals were dissolved. The fraction with the smallest percentage of arsenic was the physisorbed component (ranging from 0.5 to 1.9 percent total extractable arsenic). Arsenic in this phase is sorbed on the substrate and is available for desorption reactions. Although it is the smallest

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fraction, it is abundant enough to account for arsenic concentrations observed in water throughout the Aquia aquifer. The proportion of arsenic bound to poorly-crystalline, amorphous oxyhydroxides increased with depth relative to well-crystallized material.

MOBILIZATION CONTROLS

Redox Reactions and Speciation

Arsenic occurs in two valence states in natural settings, arsenate [As^{+5} or As(V)] and arsenite [As^{+3} or As(III)]. Although arsenic has a positive charge in both arsenate and arsenite, it forms hydrated oxyanionic complexes in ground-water environments, and does not occur as free cations. The two forms have different chemical properties, so the redox state of the aqueous environment is an important control on arsenic behavior. Arsenate is the predominant form under oxidizing conditions and arsenite is the predominant form under reducing conditions (fig. 11). However, because of reaction kinetics, the measured ratio of the two forms may differ from that predicted by chemical thermodynamics.

Twenty-five water samples from the Aquia aquifer and eight samples from the Piney Point aquifer were analyzed for arsenic species likely to exist under common ground-water conditions. These include the inorganic forms arsenate and arsenite, and the organic methylated species, monomethylarsonic acid $CH_3AsO(OH)_2^0$ (MMA) and dimethylarsinic acid $(CH_3)_2AsO(OH)^0$ (DMA). The methylated forms of arsenic are common products of biosynthesis by bacteria, fungi and algae in arsenic-rich environments, and are more commonly found in surface waters, such as lakes and streams, than ground water (Cullen and Reimer, 1989; Anderson and Bruland, 1991). MMA and DMA may be found in the human body as metabolites of arsenic in cases of acute toxicity. They may also be present in environmental water samples as a result of contamination by pesticides, such as monosodium methylarsonate (Garbarino and others, 2002).

Arsenite was detected in all samples for which it was analyzed, and arsenate was detected for all but two samples (tab. 4). Arsenite was generally the dominant species, with about 80 percent of total arsenic as averaged for the Aquia aquifer and about 70 percent for the Piney Point aquifer. Arsenite ranged from 0.3 to 33.4 μg/L for the Aquia aquifer

and 2.9 to 12.6 μg/L for the Piney Point aquifer. Arsenate ranged from below the detection level of 0.2 to 12.7 μg/L for the Aquia aquifer and 0.8 to 10.0 μg/L for the Piney Point aquifer. Speciation data were determined independently from total arsenic concentrations shown in table 4, so the sum of arsenite plus arsenate often differs slightly from total dissolved values.

In the Aquia aquifer, the ratio of arsenite to arsenate ranges from 0.8 to 43. It appears to increase down-gradient in Southern Maryland, but no trend is apparent on the Eastern Shore (fig. 12). In Southern Maryland, arsenite-to-arsenate ratios below 5 are up-gradient of the area of elevated total arsenic, whereas ratios above 5 occur within the area of elevated arsenic or down-gradient of it. This trend is expected, as chemical conditions generally evolve from a more oxidized state where water enters the Aquia aquifer as oxygenated precipitation in the outcrop area to a more reduced state as progressively more reducing reactions occur. Dissolved oxygen is present in the shallow, unconfined areas of Coastal Plain aquifers, but is quickly consumed as water flows down-gradient. Only one sample from the Aquia aquifer (1.1 mg/L in well SM Ed 17) and one well in the Piney Point aquifer (1.9 mg/L in well DO Cf 39) exceeded 1 mg/L dissolved oxygen (app. A). Leakage from confining units may also cause more reducing conditions downdip if inflow water is more reducing than ambient ground water. In the Piney Point aquifer, arsenite-to-arsenate ratios range from 0.6 to 6.6, and no spatial trend is apparent (fig. 13). Only eight analyses are available for the Piney Point aquifer. Because the Piney Point aquifer does not outcrop, and inflow water enters it exclusively as leakage from adjacent confining units, there is not an oxygenated source of water as there is in the Aquia aquifer, and water in the Piney Point aquifer is not expected to show a strong down-gradient reducing trend.

In the Aquia aquifer, MMA and DMA concentrations ranged from below detection limits (0.1 μg/L for both) to 0.2 and 0.6 μg/L (as arsenic), respectively. The two samples with highest DMA concentrations were from the same wells with highest total arsenic concentrations, although a general trend between the methylated species and total arsenic is not clear. In the Piney Point aquifer, MMA and DMA concentrations ranged from below detection limits to 0.2 μg/L (as arsenic) for both species. No spatial trend is apparent in the methylated species of arsenic in either the Aquia or Piney Point aquifers. The presence of MMA and DMA in ground water indicates that bacterial

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biosynthesis may play a role in the mobilization of arsenic in the Aquia and Piney Point aquifers. However, the low levels of these species indicate that either biosynthesis is a minor factor, or that these organic species are converted to the inorganic forms arsenite and arsenate.

Adsorption/Desorption

Adsorption and desorption reactions are important controls on arsenic mobility in ground-water environments. Aquifer materials that may provide adsorption sites for arsenic include metal oxyhydroxide coatings on mineral grains (especially iron and manganese), clay minerals, and calcareous shell material. Arsenic may also be present in trace amounts coprecipitated in aquifer minerals such as pyrite and goethite. Adsorption occurs when an electrostatically charged mineral surface attracts dissolved ions to the mineral surface (Stollenwerk, 2002). In outer-sphere (or non-specific) adsorption, the charged mineral surface attracts an oppositely charged ion, but remains at a certain distance from the mineral surface. In inner-sphere (or specific) adsorption, the dissolved ion forms a coordinative complex with the mineral surface, and results in stronger bonds than in outer-sphere complexation. Arsenic appears to adsorb to mineral surfaces by forming inner-sphere complexes (Stollenwerk, 2002). This process is sensitive to pH, so changes in ground-water pH may mobilize or demobilize arsenic in solution. Arsenic adsorption is also influenced by concentrations of some other solutes that compete with arsenic for adsorption sites, as discussed in following sections.

pH

The pH of ground water can also influence arsenic mobility. The pH of a solution is controlled by chemical reactions that produce or consume hydrogen ions, and pH in turn influences many interrelated reactions (Hem, 1985). The controlling species are the ones available in greatest abundance or those that react the fastest. The carbonate system is an important control on pH in the Aquia and Piney Point aquifers. In this system, carbon dioxide (initially from the atmosphere and soil processes) dissolves in water to produce carbonic acid (H_2CO_3), which dissociates to form aqueous bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). Calcitic shell material, which is chiefly calcium carbonate

($CaCO_3$), also reacts with acid to form additional bicarbonate and dissolved calcium in the reaction

$$CaCO_3(c) + H^+ = Ca^{2+} + HCO_3^-$$
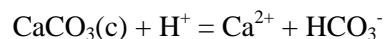
As ground water flows down-gradient, hydrogen ions are consumed, and the pH increases. The oxidation of sulfide minerals, such as pyrite, produces sulfate and hydrogen ions, and may also influence the pH of ground water in Coastal Plain aquifers, but these minerals are sparse or absent in the Aquia and Piney Point aquifers. Sulfide minerals (chiefly pyrite) are common in the non-marine Cretaceous aquifers, such as the Magothy and Potomac Group aquifers.

The pH of ground water, in conjunction with Eh, determines the distribution of aqueous arsenic species (fig. 11). Thermodynamic calculations predict that in common ground-water environments (between pH of 2 and 9) three arsenic species are stable, $H_3AsO_3^0$, $H_2AsO_4^-$, and $HAsO_4^{2-}$. The last two species are the oxidized forms; $H_2AsO_4^-$ is the dominant form below pH 6.9, and $HAsO_4^{2-}$ is dominant above pH 6.9. pH also controls the surface charge of adsorption substrates, and strongly influences the adsorption of metals on iron oxyhydroxides and clays. As pH increases, the surface charge of adsorption surfaces becomes more negative, decreasing the adsorption of negatively charged oxyanions. Arsenate is more strongly adsorbed at low pH values, especially at higher concentrations. Adsorption of neutrally charged arsenite, however, increases with increasing pH, up to a pH of 8 or 9, although the control is not as strong as with arsenate (Stollenwerk, 2002). Thus, under oxidizing conditions, arsenic is mobilized (desorbed) in ground water as the pH increases, but under reducing conditions, arsenic would be demobilized (adsorbed) as pH increases, assuming no other factors were involved.

The pH of water in the Aquia aquifer generally increases downdip (fig. 14). The pH of water near the outcrop area is generally around 7.0, and increases to about 8.0 near the facies change on the Eastern Shore, and up to 8.5 to 9.0 in southern Charles and St. Mary's Counties. The area of elevated arsenic concentrations roughly parallels this trend. However, the high arsenic levels are found in the pH range of 7.5 to 8.0 on the upper Eastern Shore, and in the pH range of 8.0 to 9.0 in Southern Maryland. This trend is consistent with decreasing adsorption with higher pH values for arsenate, but not with arsenite. Both arsenate and arsenite are mobilized in the Aquia aquifer, but arsenite is

generally the dominant species in elevated arsenic water of the Aquia aquifer, and the down-gradient increase in pH does not appear to be the only control on the distribution of arsenic in the Aquia aquifer.

In the Piney Point aquifer a spatial trend in pH is not as clear as in the Aquia aquifer (fig. 15). In Southern Maryland, ground water has lower pH values near the updip truncation line, and the highest pH occurs at the farthest downdip data point. Elsewhere, pH values range between 7.5 and 8.5 with no apparent trend. pH does not appear to influence arsenic mobilization in the Piney Point aquifer.

Reductive Dissolution

Reductive dissolution occurs when a metal oxyhydroxide, such iron hydroxide, dissolves due to increasingly reducing conditions. Ferric iron (oxidized form) in the hydroxide is reduced to ferrous iron, which is more soluble. Arsenic associated with the metal oxyhydroxide, either coprecipitated in the mineral structure or adsorbed on the surface, is mobilized when the substrate is dissolved. Arsenic may not be mobilized during this process if the iron oxide substrate is reprecipitated as mixed-redox oxides, such as magnetite, and the arsenic remains in the adsorbed phase (Tadanier and others, 2005). Reductive dissolution has been proposed as the primary mechanism for mobilization of arsenic in Bangladesh and parts of India (Smedley and Kinniburgh, 2002).

Haque and others (2008) proposed that reductive dissolution mobilizes arsenic in the Aquia aquifer on the Eastern Shore of Maryland, citing the down-gradient decrease in redox potential, and the sharp increase of reduced iron at the same position along the inferred flow path as the increase in arsenic concentrations. In this process, released ferrous iron catalyzes the remaining amorphous ferric oxides into more crystalline iron oxides, such as hematite and magnetite. The more crystalline forms have lower surface area available for adsorption sites, so sorbed arsenic is released along with arsenic that was incorporated in the mineral structure. Farther downgradient, arsenic is readsorbed onto crystalline lattice structures of secondary iron oxyhydroxides, resulting in decreasing arsenic concentrations observed toward the end of the inferred flowpath (fig. 4). However, the flowpath inferred by Haque and others (2008) from ground-water flow modeling does not appear to conform with the distribution of arsenic and other chemical constituents in the Aquia

aquifer (see discussion in subsequent section of this report on chemical evolution of ground water). The flow path Haque and others (2008) used to illustrate arsenic chemistry first trends southeastward into the area of elevated arsenic, but then turns to the west, back into the updip area of low arsenic concentrations, rather than continue southeastward into the downdip area of low arsenic concentrations. Although the chemical flow path assumed by Haque and others (2008) does not seem to agree with chemical evolution patterns in the Aquia aquifer, the basic chemical mechanism may still be valid.

Sulfate Reduction

Elevated arsenic concentrations occur only in wells with sulfate concentrations below the detection level of 10 mg/L in the Aquia and Piney Point aquifers (fig. 16), suggesting that sulfate concentrations influence arsenic mobilization. Microbial communities were shown to control redox processes in the Mahomet aquifer, a glacial drift aquifer in central Illinois (Kirk and others, 2004). In areas of the Mahomet aquifer where sulfate concentrations are relatively high (above 0.25 mg/L), sulfate-reducing bacteria produce sulfide, which precipitates iron- and arsenic-bearing sulfide minerals. This process limits dissolved arsenic concentrations in areas where sulfate concentrations are high enough to support this process. Where sulfate is absent, methanogenic microbes convert bicarbonate to methane, which does not limit arsenic mobility. Plots of sulfate variability from the Mahomet aquifer (Kirk and others, 2004) show that arsenic and methane concentrations are elevated only in areas where sulfate concentrations are relatively low.

Similar patterns are shown in sulfate variations in the Aquia and Piney Point aquifers as in the Mahomet aquifer, and competition with sulfate reduction may limit mobilization of arsenic in these aquifers. In the Aquia aquifer, the highest arsenic concentrations occur in wells where sulfate concentrations are below 10 mg/L (the detection level) (fig. 16). In wells in which sulfate is above 10 mg/L, arsenic concentrations are below 15 μg/L. In the Piney Point aquifer, similar patterns are shown for these constituents, although fewer samples are available, and the patterns are less distinct (fig. 16). Dissolved hydrogen (H_2) and methane (CH_4), key components in the Mahomet aquifer study, were not analyzed in this study, so it is uncertain whether

methanogenesis is occurring in the Aquia or Piney Point aquifers.

Ionic Competition and Enhancement

A given volume of sediment contains a limited number of adsorption sites, and elements with similar sorptive properties will compete for those sites. Solutes may directly compete with arsenic for surface binding sites, or may indirectly affect adsorption by altering the electrostatic charge on the binding surface. If the dissolved concentration of a competing ion increases, it may replace arsenic ions on sorption sites, and thus increase the arsenic concentration in ground water. Conversely, adsorption of other ions may indirectly enhance the adsorption of arsenic by increasing the positive charge on the adsorption surface.

Phosphorus is chemically similar to arsenic, and phosphate (PO_4^-) competes with arsenate for adsorption sites (Manning and Goldberg, 1996). Manning and Goldberg (1996) demonstrated that increasing concentrations of phosphorus up to 6.7 micromoles (μM) (0.21 mg/L) significantly decreased the amount of adsorbed arsenic on three types of clay minerals (illite, montmorillonite, and kaolinite), and developed a model to simulate competitive adsorption between these elements, as well as molybdenum.

Phosphate concentrations for wells sampled in this study were all below the detection level of 0.2 mg/L (as phosphorus) and phosphate concentrations reported by Drummond (2001) for the Aquia and Piney Point aquifers on the Eastern Shore were also all below 0.2 mg/L. However, the data of Manning and Goldberg (1996) suggest that competition with arsenic for adsorption sites on clays can occur at phosphorus concentrations below this detection level, and phosphorus competition could influence the mobilization of arsenic in the Aquia and Piney Point aquifers. Additional sampling for phosphorus with a lower detection level is needed to determine whether there is a relationship with arsenic.

Phosphorus is a major component of many fertilizers, and is a contaminant in shallow aquifers in some agricultural areas. Phosphate contamination is unlikely in the confined parts of the Aquia and Piney Point aquifers where arsenic concentrations are elevated. However, in the hotspot area of Anne Arundel County, the Aquia aquifer is shallow and unconfined (Andreasen, 2002), and an anthropogenic source of phosphate is possible. In this area, ionic competition with phosphorus for

adsorption sites may mobilize arsenic into ground water. Phosphorus is also a component of the mineral apatite, which is present in marine sediments as fossil bone, shark teeth, fish scales, shell and carapace fragments, and mineralized fecal pellets (Kula and Hansen, 1989). These components are common in the Aquia and Piney Point aquifers as well as the Miocene aquifers, but are generally absent in the other major aquifers of the Maryland Coastal Plain. No data are available on the concentrations of arsenic substituting for phosphorus in these materials, or on their areal distribution in the Aquia and Piney Point aquifers.

Calcium and magnesium concentrations may decrease arsenic mobility by enhancing adsorption of arsenic. Wilkie and Herring (1996) found that adsorption of calcium increased the adsorption of arsenate on ferrihydrite (a synthetic iron oxyhydroxide) at pH 9. Calcium and magnesium were both found to enhance adsorption of arsenic on ferrihydrite (Meng and others, 2000). These ions enhance the adsorption of arsenic by increasing the positive charge on the adsorbing substrate, or by negating the competitive effect of silica. Calcium and magnesium concentrations are generally higher in the updip portions of the Aquia and Piney Point aquifers (see following discussion of chemical evolution of ground water), and, therefore, may partially limit arsenic mobilization in these areas. Farther downgradient, where calcium and magnesium decrease because of ion exchange with sodium, arsenic concentrations increase.

Other oxyanions that may compete with arsenic for adsorption sites include molybdenum, selenium, and vanadium (Manning and Goldberg, 1996). Insufficient data are available for the Aquia and Piney Point aquifers to evaluate the possibility of competitive adsorption between these elements and arsenic.

Chemical Evolution of Ground Water in the Aquia and Piney Point Aquifers

Distribution patterns of arsenic in the Aquia and Piney Point aquifers suggest that arsenic occurrence is related, at least in part, to the down-gradient evolution of water chemistry in these aquifers. The banding pattern in the distribution of pH and major ions is similar (although not identical) to that seen in arsenic distribution (figs. 14, 15, and 17 through 20). Because the lithology and other hydrogeologic factors of the two aquifers are similar, it is likely that the same chemical processes operate in both

aquifers. A major difference between the aquifers is that the Aquia aquifer outcrops and receives inflow directly as recharge, whereas the Piney Point aquifer is truncated in the subsurface, and receives all inflow as leakage through adjacent confining units. The Aquia aquifer also receives significant amounts of leakage through adjacent confining units, at least under pumping conditions (Achmad and Hansen, 1997; Drummond, 2007).

The chemical evolution of ground water in the Aquia and Piney Point aquifers in Southern Maryland was described by Chapelle and Drummond (1983). The chemical model for the Aquia aquifer was later refined by Chapelle and Knobel (1983) and Chapelle and Knobel (1985). In this model, water enters the aquifer in the recharge area, with high concentrations of oxygen and carbon dioxide from atmospheric and soil sources. As the water flows into the confined portion of the aquifer, contact with the atmosphere is discontinued, and oxygen is consumed by oxidation of organic matter, producing carbon dioxide. Calcareous shell material is dissolved in this up-gradient area, consuming carbon dioxide and producing dissolved calcium and bicarbonate. As the water continues to flow down-gradient, calcium is removed from solution by exchange for sodium on cation-exchange sites on glauconite grains. The removal of calcium from solution by the exchange reaction allows more shell material to be dissolved, until shell material is depleted in the updip area. Thus calcium is the dominant dissolved cation in the up-gradient area, sodium and bicarbonate concentrations increase down-gradient, and pH also increases down-gradient. Ground-water chemistry in the Aquia and Piney Point aquifers on the Eastern Shore of Maryland shows similar patterns to those in Southern Maryland (Drummond, 1988; Drummond, 2001). Water chemistry in the Aquia aquifer is complicated, however, by brackish-water intrusion near the Chesapeake Bay shoreline in Kent, Queen Anne's, and Talbot Counties.

The chemical evolution of ground water in the Aquia aquifer in Southern Maryland gives rise to a banded pattern of major chemical constituents, in which elongated areas of elevated calcium, magnesium, potassium, and sodium have formed perpendicular to predevelopment flow paths, and roughly parallel to the outcrop area (and thus regional strike) (figs. 17–20). In Southern Maryland the bands of elevated cation distribution are roughly perpendicular to the inferred prepumping flow lines as shown in Chapelle and Drummond (1983). The assumption is that water chemistry evolved over

thousands of years along the prepumping flow paths (fig. 4), creating bands of equal chemical conditions along lines of equal travel time. Although ground-water withdrawals have significantly altered flow directions during the last century (Drummond, 2007), the chemical patterns have probably not shifted significantly.

On the Eastern Shore, however, prepumping flow paths in the Aquia aquifer inferred from flow modeling (Drummond, 2001), shown in figure 4, do not conform with flow paths inferred from chemical distribution. The flow path inferred from flow modeling trends southward from central Kent County (the outcrop/recharge area), but then turns westward toward the discharge area around Kent Island (fig. 4). Contours of pH and calcium and sodium concentrations continue trending to the northeast, implying a southeastward flow direction (figs. 14, 17, and 19). Two possibilities could explain this apparent discrepancy. The hydrochemical patterns could have developed during an older hydrologic regime, in which earlier recharge and/or discharge areas caused a more southeasterly flow direction than that suggested by modeling results. This could have been caused by significantly different drainage patterns within the Chesapeake Bay watershed. Another possible explanation for the discrepancy is that the hydrochemical patterns are controlled more by the distribution of lithologic source materials than by evolution along a flow path. For instance, spatial differences in abundance or type of shell material, glauconite, or organic matter could create areas of differing water chemistry. The patterns of water chemistry roughly parallel regional strike, so depositionally controlled lithologic variations could (at least partially) give rise to observed hydrochemistry.

The possible relation of arsenic distribution with chemical evolution is illustrated using Piper diagrams (figs. 21 and 22). The hydrochemical facies for the Aquia and Piney Point aquifers are similar, with mixed cations, and bicarbonate as the dominant anion. The Aquia aquifer shows some analyses with chloride and sulfate water types caused by brackish-water intrusion. The evolution of water chemistry is shown in the cation water types. Water entering the aquifer has calcium as the dominant cation. As water flows down-gradient, the calcium exchanges for magnesium, then potassium and sodium, creating the arched configuration in the lower parts of the cation triangles for the Aquia and Piney Point aquifers (figs. 21 and 22).

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The lowest arsenic concentrations tend to occur in the up-gradient sections of the aquifers where calcium and magnesium are the dominant cations. Higher arsenic concentrations generally occur farther down-gradient where potassium and sodium are the more dominant cations. However, the highest arsenic concentrations (above 20 μg/L) do not occur at the sodium apex where sodium is nearly the only major cation in solution. This reflects the decrease in arsenic concentrations in the far downdip parts of both aquifers. Elevated chloride concentrations may cause interferences with arsenic analyses, so the analyses further toward the chloride apex for the Aquia aquifer (fig. 21) may appear as false highs in arsenic concentrations.

Leakage

Inflow of water to an aquifer as leakage through confining units could influence water chemistry in ways that have not been addressed in previous studies of chemical evolution of ground water in Coastal Plain aquifers. In areas where leakage is a significant component of inflow to an aquifer, the water chemistry of the inflowing leakage can alter the water chemistry of the aquifer if inflowing water is chemically distinct from ambient water chemistry. For instance, high silica concentrations in parts of the Piney Point aquifer have been attributed to leakage from the overlying Miocene confining units (Cushing and others, 1973). These confining units contain abundant diatomaceous material, which is chiefly non-crystalline silica that dissolves more readily than crystalline quartz grains and most other silicates, and can give rise to high dissolved silica concentrations.

Arsenic distribution can be influenced by leakage if the leakage water has a different arsenic concentration than ambient water, or if other chemical parameters that control arsenic mobility are significantly different from ambient water. For instance, if inflowing leakage has a lower redox potential than ambient water, arsenic may desorb from mineral grains or coatings in the aquifer, and increase dissolved concentrations. This process would theoretically create a vertical zonation in arsenic distribution, in which water in an aquifer adjacent to the confining unit has lower or higher arsenic concentrations than water in the middle part of the aquifer. However, other factors, such as vertical variations in abundance of arsenic-bearing minerals, may also account for the zonation. In order to evaluate the importance of leakage on arsenic distribution, more data are needed on the water chemistry of confining units, and vertical zonation of arsenic in the Aquia and Piney Point aquifers.

Vertical zonation of arsenic concentrations could be an important consideration regarding the ground-water availability of the affected aquifers. Most small-capacity wells are only screened in the top 10 to 20 ft of an aquifer to avoid drilling and material costs when constructing a well. Most of the arsenic data used in this study came from existing small-capacity wells, so there is a bias toward water chemistry in the top portion of most aquifers. If wells in one area are screened in a different part of an aquifer than in another area (for instance, to avoid other water-quality problems in the shallow part of an aquifer, or to tap into a more transmissive, deeper section) arsenic distribution would be distorted. If water in the deeper section of an aquifer has a higher arsenic concentration than the top section, wells may become contaminated if high-arsenic water moves toward the well screen by upconing (a temporary upward movement of deeper water). More data are needed from the deeper parts of the Aquia and Piney Point aquifers to determine if there are vertical differences in arsenic concentrations.

SUMMARY AND CONCLUSIONS

In 2001 the USEPA lowered the MCL for arsenic from 50 to 10 μg/L for public-water systems and newly constructed domestic wells. Several community water systems in Maryland, particularly in Southern Maryland and the Delmarva Peninsula, were known from previous sampling to have ground-water arsenic concentrations that exceed the new standard, especially in the Aquia and Piney Point aquifers. A study was conducted to determine which Coastal Plain aquifers have elevated arsenic concentrations, the extent and range of arsenic in these aquifers, and to identify possible hydrochemical controls on arsenic distribution.

Data were collected for arsenic concentrations and other chemical parameters from four different sources: sampling during this project (284 samples),

the USGS NWIS database (359 samples), county health department databases for residential wells (about 3,500 samples), and the MDE database for public-supply wells (502 samples). The Coastal Plain aquifers evaluated in the study include (from deep to shallow) the Potomac, Magothy, Aquia, Piney Point, Miocene, and Columbia aquifers. Most of these aquifers have extensive outcrop areas that act as recharge zones; the exception is the Piney Point aquifer, which is truncated in the subsurface and does not outcrop. All aquifers receive additional inflow as leakage through confining units.

The Aquia and Piney Point aquifers are the only Coastal Plain aquifers where ground-water exceeds the MCL of 10 μg/L on a widespread basis. For samples collected during this project, there were no exceedances of the MCL in the Potomac, Magothy, or Columbia aquifers, and only one well in the Miocene aquifers (specifically, in the Pocomoke aquifer in southern Worcester County) exceeded the MCL. Arsenic concentrations in the Aquia aquifer ranged from below detection limits (generally 2 μg/L) to 42 μg/L in sampling for this study, and up to 131 μg/L (in Anne Arundel County) in the county health department databases. Arsenic concentrations in the Piney Point aquifer ranged from below detection limits to 24 μg/L in sampling for this study and up to 33 μg/L (in Dorchester County) in the county health department databases. Overall, ground-water arsenic in the Aquia and Piney Point aquifers occurs naturally, as evidenced by the deep, confined nature of the aquifers, the age of the water (as determined by C-14 dating techniques), and the lack of elevated arsenic in the shallow aquifers.

Elevated arsenic concentrations in the Aquia aquifer form a band that approximately parallels strike (northeast/southwest trend), and extends from the Eastern Shore, presumably beneath the Chesapeake Bay (no data are available beneath the Chesapeake Bay), and into Southern Maryland. The highest arsenic concentrations in this main band occur in western Talbot and Dorchester Counties, and central Queen Anne's County. An additional area of high arsenic concentrations was identified on the Mayo Peninsula in Anne Arundel County, about 10 mi northwest of the main area of elevated arsenic. The data are insufficient to evaluate vertical variation of arsenic concentrations in the main band in the Aquia aquifer. However, in the hotspot in Anne Arundel County, elevated arsenic concentrations appear to be restricted to the depth interval of 70 to 100 ft below land surface. The Aquia aquifer is unconfined at this location, and an anthropogenic source cannot be ruled out.

Elevated arsenic concentrations in the Piney Point aquifer form a band similar to the one in the Aquia aquifer, but which is narrower and farther to the southeast. It also extends from the Eastern Shore, presumably beneath the Chesapeake Bay, and into Southern Maryland. The highest concentrations generally occur in central Dorchester County. Additional smaller areas of elevated arsenic concentrations occur north of the main band in Talbot, Queen Anne's, and St. Mary's Counties.

Arsenic distribution in ground water of the Maryland Coastal Plain aquifers may be controlled by distribution of lithologic components in the aquifer material, by mobilization mechanisms, or a combination of both. Lithologic components that could provide a source for arsenic in the Aquia and Piney Point aquifers include calcitic shell material, calcitic cement, glauconite grains, phosphate pellets, goethite pellets, and iron oxyhydroxide coatings on other mineral grains. Insufficient data are available on the distribution of these components within the aquifers to determine the extent to which they impact arsenic occurrence in ground water. The coincidence of the high-energy offshore sand-bank complex (facies 1) of the Aquia aquifer with areas of elevated arsenic concentrations in the Aquia aquifer provides indirect evidence that one or more lithologic components (such as glauconite or goethite) associated with depositional environments may control arsenic distribution. The similarity of the depositional environments of the Aquia and Piney Point aquifers supports this possibility for the Piney Point aquifer as well.

Mobilization controls that may partially determine arsenic distribution in ground water include oxidation-reduction reactions, pH, adsorption/desorption reactions, reductive dissolution, and ionic competition (and enhancement). Redox reactions may control arsenic distribution because arsenic occurs in natural waters in two valence states, a reduced form, arsenite (valence +3) and an oxidized form, arsenate (valence +5). Arsenite is generally the more soluble form in water in the Eh and pH range of Aquia and Piney Point water. Sampling from this study indicates that arsenite is generally the dominant species, with about 80 percent of total arsenic as averaged for the Aquia aquifer and about 70 percent for the Piney Point aquifer. The organic methylated arsenic compounds MMA and DMA were also detected in some samples, although in low concentrations. MMA and DMA concentrations ranged from below detection limits (0.1 μg/L for both) to 0.2 and 0.6 μg/L (as arsenic), respectively, in the Aquia aquifer,

and from below detection limits to 0.2 μg/L (as arsenic) for both species in the Piney Point aquifer.

Ground water in the Aquia and Piney Point aquifers generally increases in pH downgradient in the areas where arsenic is elevated. Arsenate is mobilized with increasing pH conditions, but arsenite is not. Because arsenite is the dominant form of arsenic in water from the Aquia and Piney Point aquifers, pH does not seem to be a major control on arsenic mobilization. Reductive dissolution is a likely mechanism for the mobilization of arsenic, as cited in a previous investigation. In reductive dissolution, an arsenic-bearing substrate, such as iron oxyhydroxide, is solubilized due to increasingly reducing conditions. Arsenic, either as part of the mineral structure or adsorbed on to the substrate surface is mobilized into solution. Sulfate reduction may also play a role in arsenic mobilization. In the Aquia and Piney Point aquifers, the highest arsenic concentrations occur in wells where sulfate concentrations are below 10 mg/L, indicating that sulfate-reducing bacteria may produce sulfide, which can precipitate arsenic-bearing sulfide minerals and therefore limit arsenic mobility. Competition for adsorption sites with other solutes, such as phosphate, may mobilize arsenic in the Aquia and Piney Point aquifers. Phosphate concentrations analyzed in this study were all below the detection level of 0.2 mg/L, but competition can occur below this concentration. Calcium and magnesium can enhance adsorption of arsenic. Arsenic concentrations are generally higher in the downdip portions of the Aquia and Piney Point aquifers where calcium and magnesium concentrations are low, indicating that ionic enhancement of arsenic adsorption may partially control arsenic distribution.

Chemical evolution of ground water may indirectly influence arsenic distribution. Dissolution of calcitic shell material and exchange of calcium for magnesium, potassium, and sodium on cation-exchange sites on glauconite or other clays gives rise to a banded pattern of these constituents that roughly parallels the areas of elevated arsenic concentrations in the Aquia and Piney Point aquifers. Leakage of water from overlying and underlying confining units may also control arsenic distribution, either directly or indirectly. If inflowing leakage is high in arsenic in certain areas, it could develop high arsenic concentrations in the aquifer in those areas. Additionally, if leakage water has chemical characteristics that favor arsenic mobilization (through the mechanisms described previously), it could mobilize arsenic from sources in the solid aquifer matrix. With data currently available, it is not possible to determine the precise hydrochemical mechanism(s) that control arsenic distribution in the Coastal Plain aquifers of Maryland.

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Figure 1. Location of the study area.
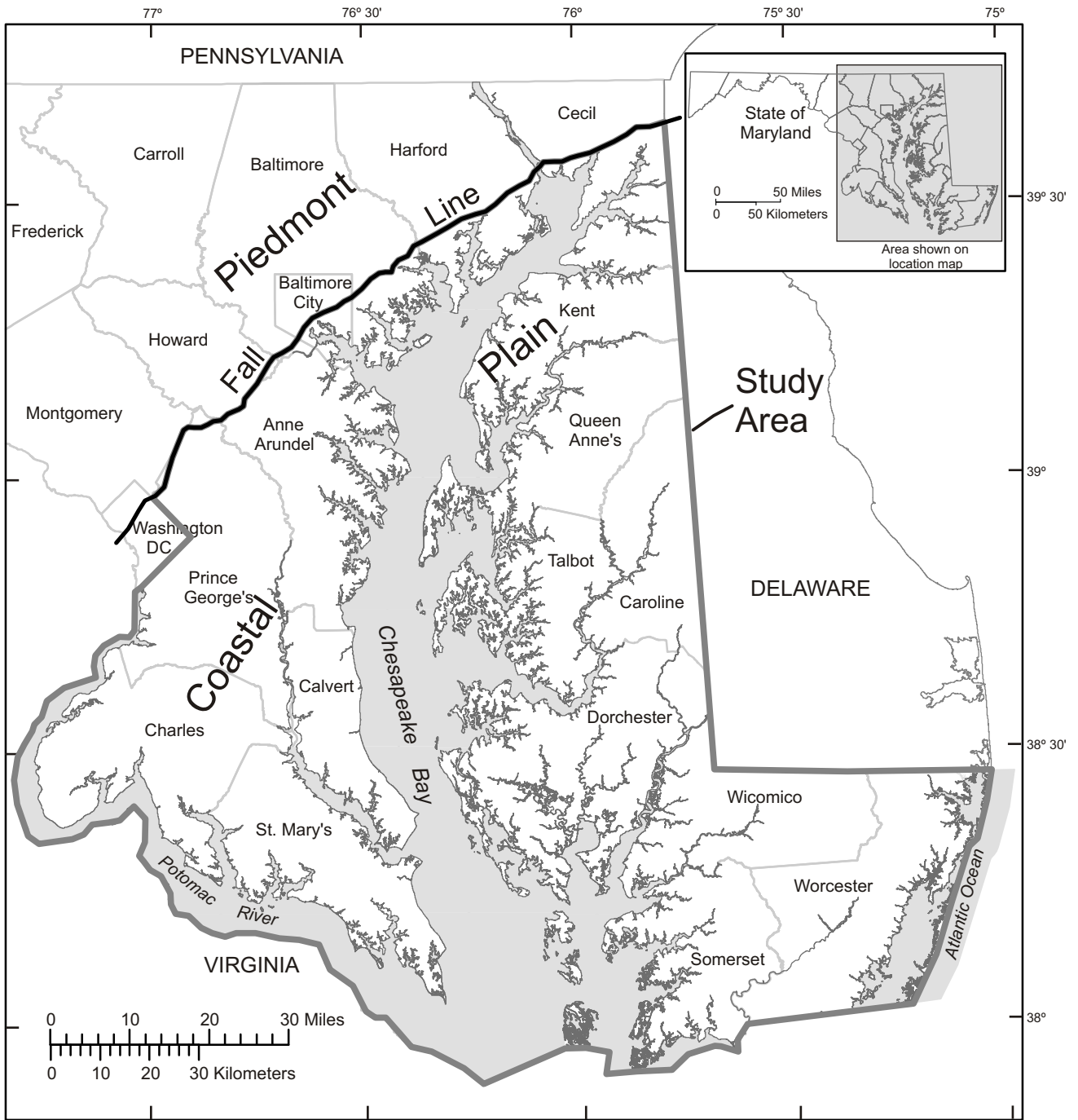
Base map modified from USGS Digital Line Graph 1:250,000

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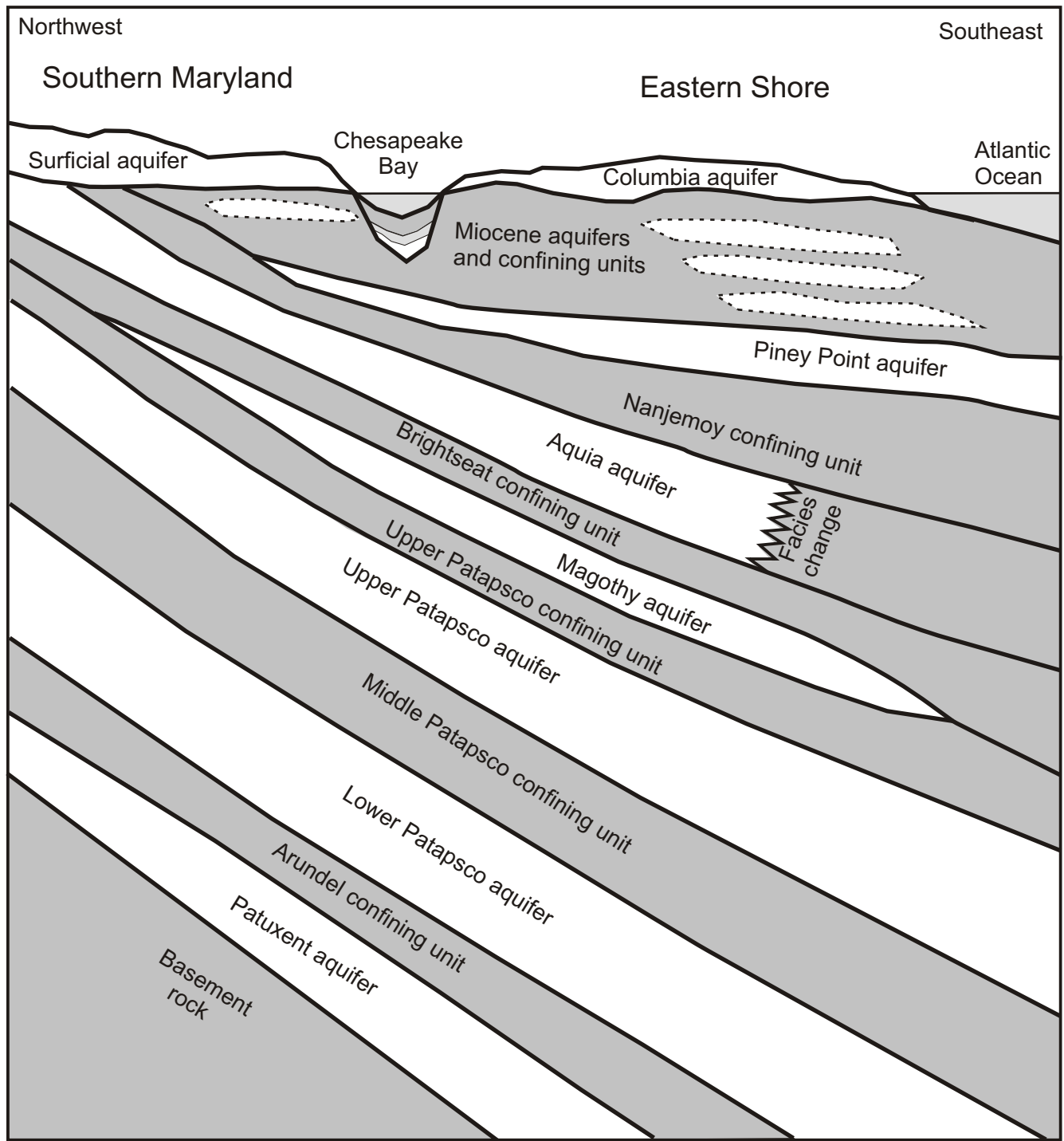
Figure 2. Schematic cross section showing the major hydrogeologic units in the Maryland Coastal Plain.

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Figure 3.   Photomicrographs of Aquia aquifer sediments: A. Washed sand.   B. Quartz grains: iron-stained (left), clear (right).   C. Calcite: cement (left), shell fragments (right). D. Goethite grains.   E. Glauconite grains. Sample from well CA Db 96, 580 to 600 feet.
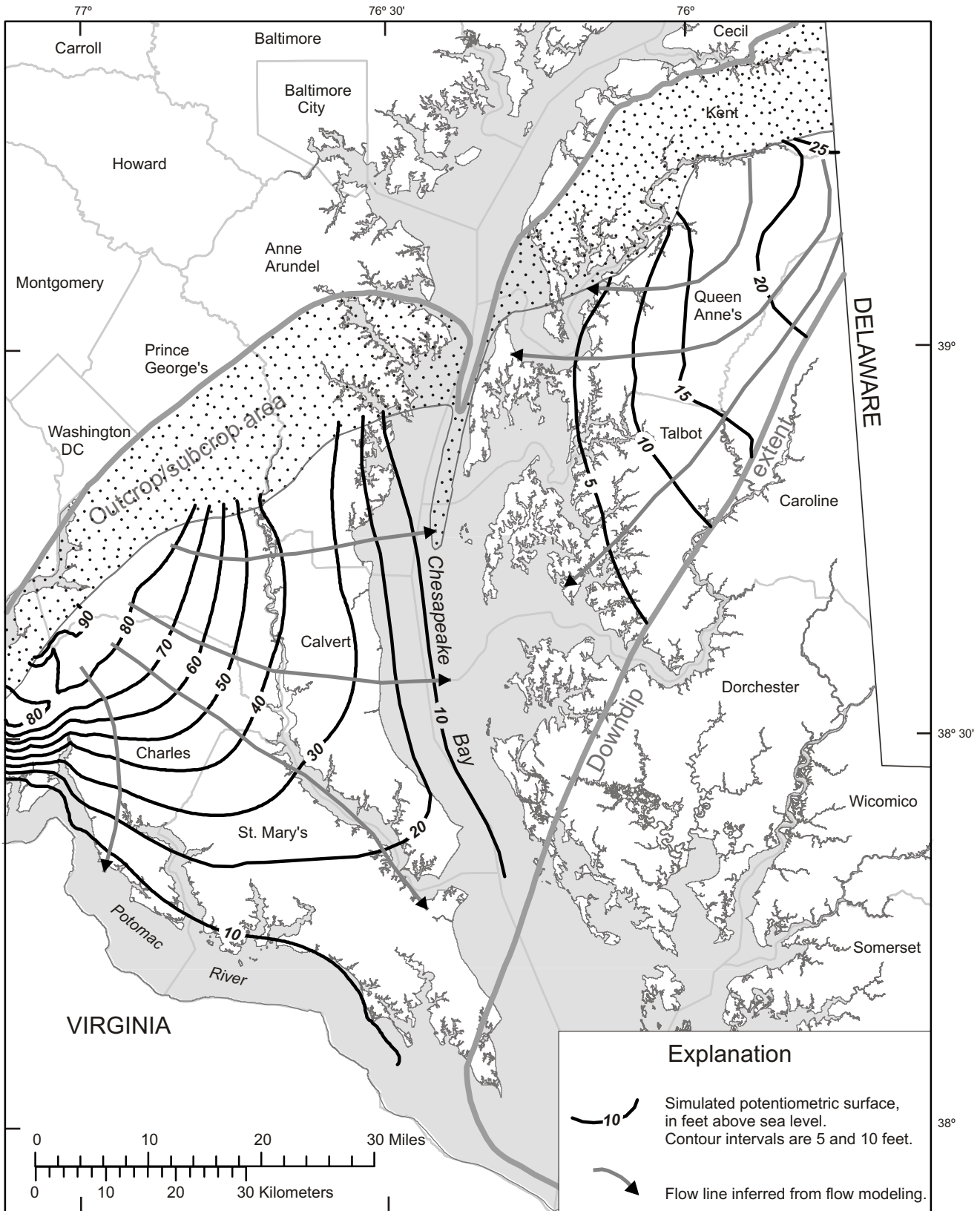
Figure 4. Simulated prepumping potentiometric surface of the Aquia aquifer.
(Simulations from Drummond [2001] for the Eastern Shore, and Drummond [2007] for Southern Maryland.)
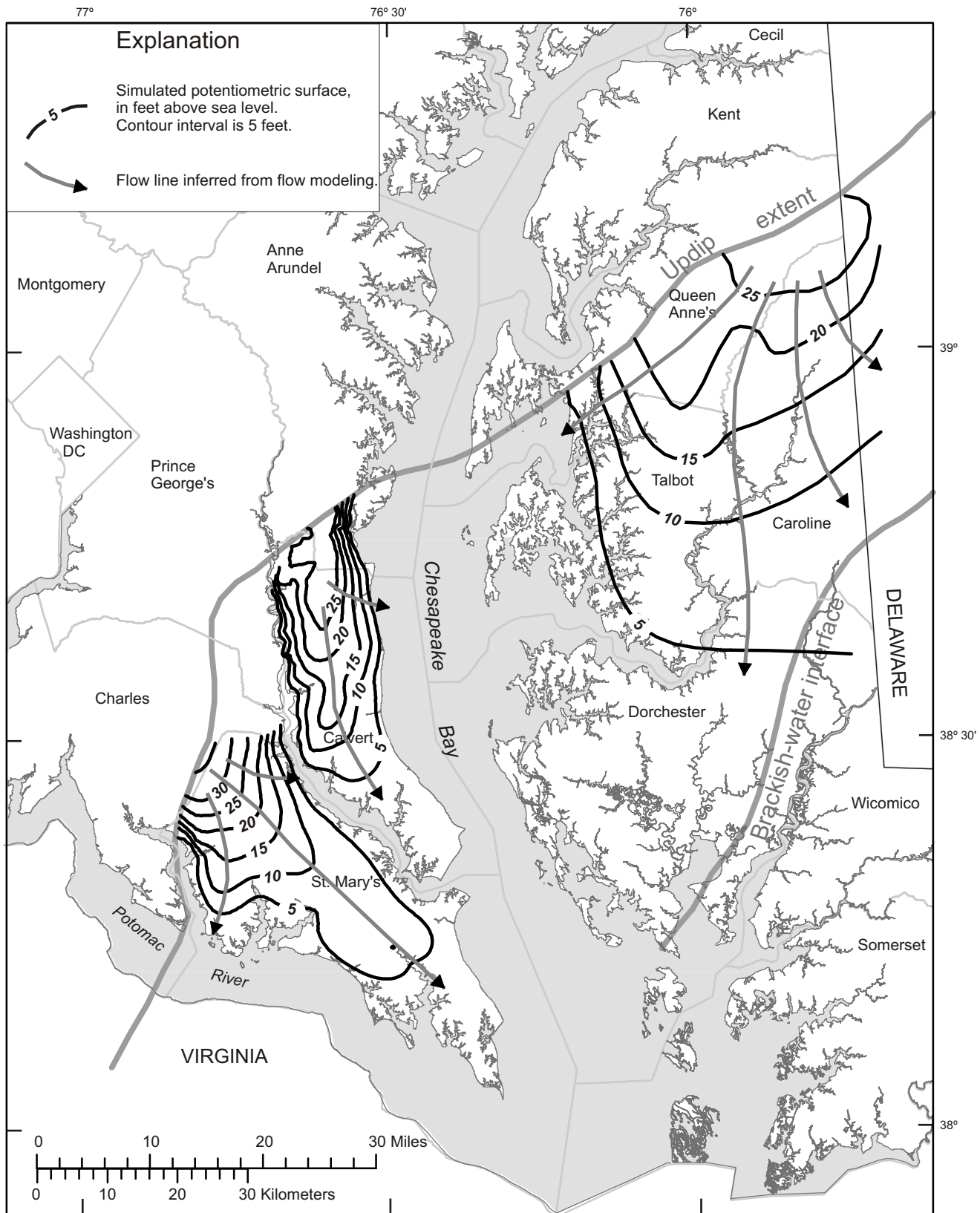
Figure 5. Simulated prepumping potentiometric surface of the Piney Point aquifer.
(Simulations from Drummond [2001] for the Eastern Shore, and Drummond [2007] for Southern Maryland.)
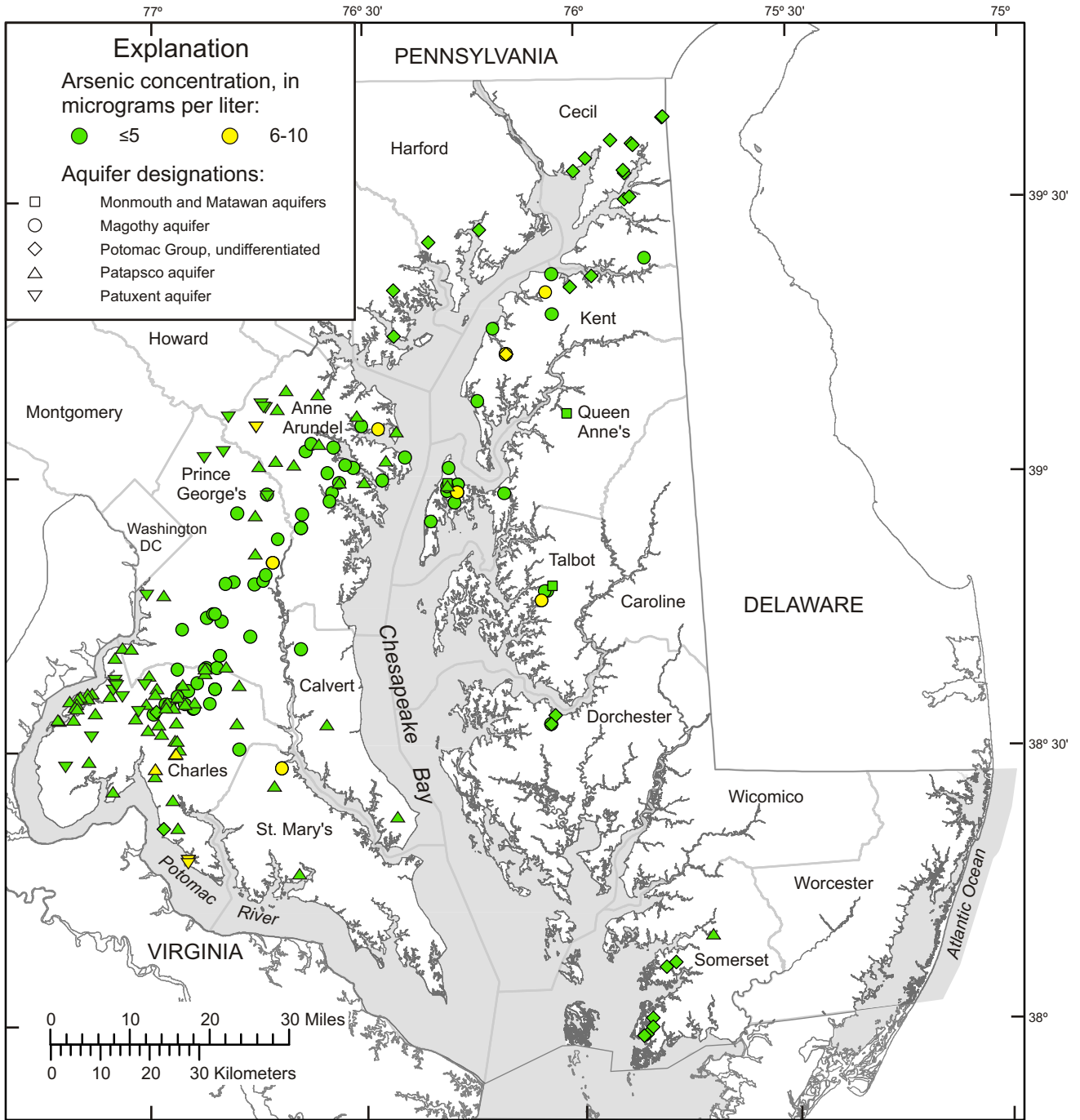
Figure 6. Distribution of arsenic in the Magothy and Potomac Group aquifers.

(Data from this study and the MDE public-supply database.)
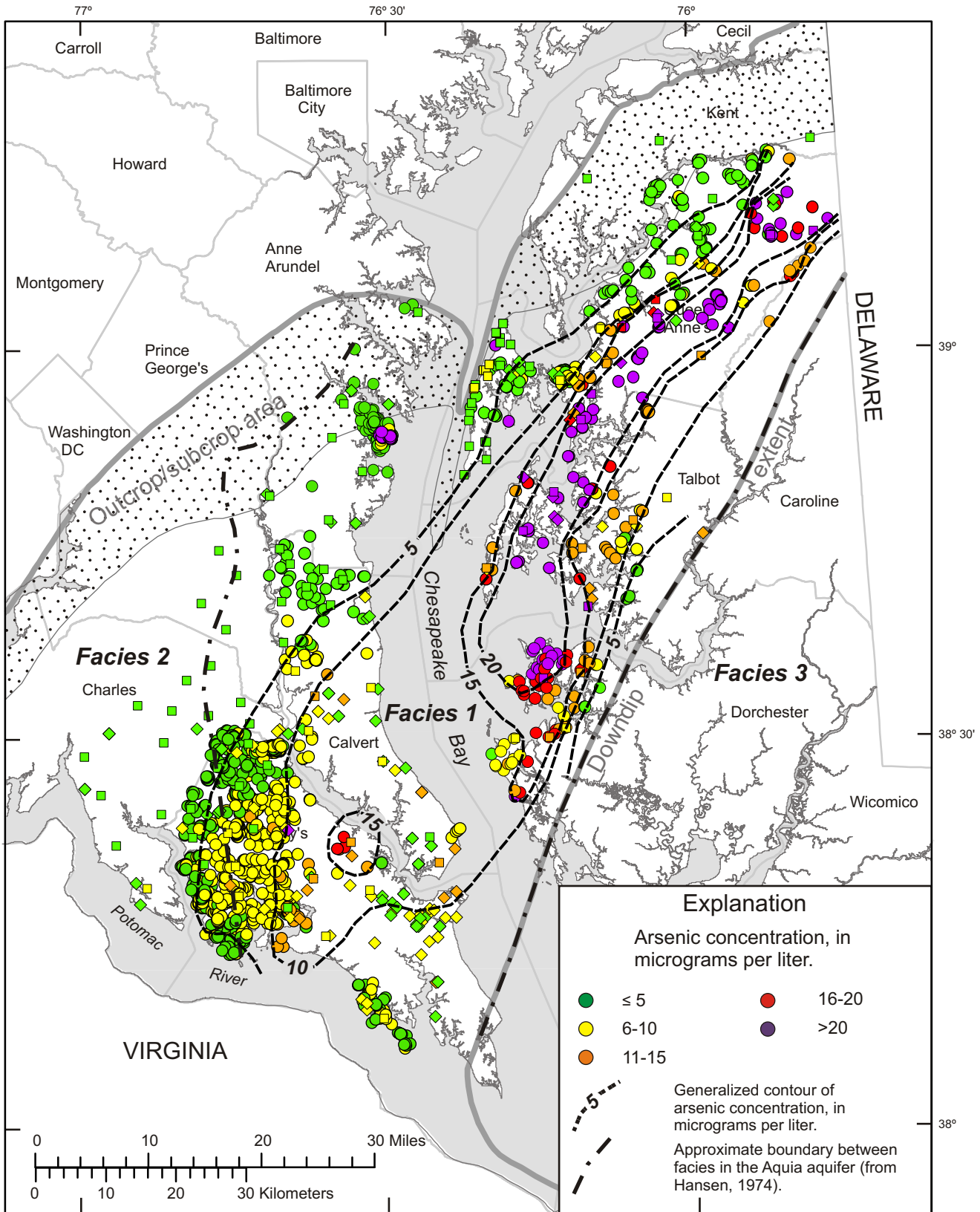
Figure 7. Distribution of arsenic in the Aquia aquifer.
(Circles indicate data from county health departments; squares indicate data from this study; diamonds indicate data from MDE public-supply database)
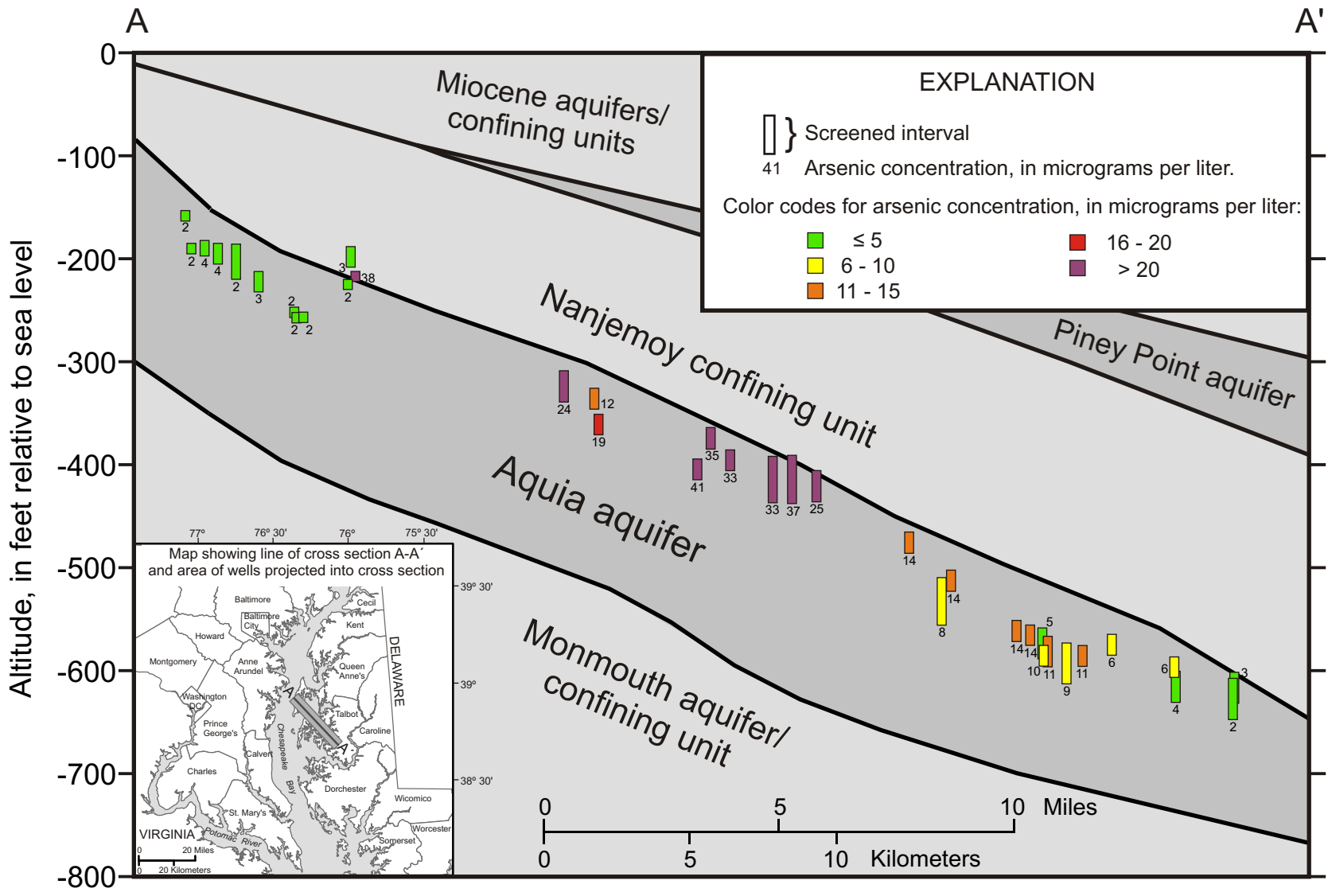
Figure 8. Cross section A-A' showing arsenic concentrations in the Aquia aquifer in Queen Anne's and Talbot Counties.

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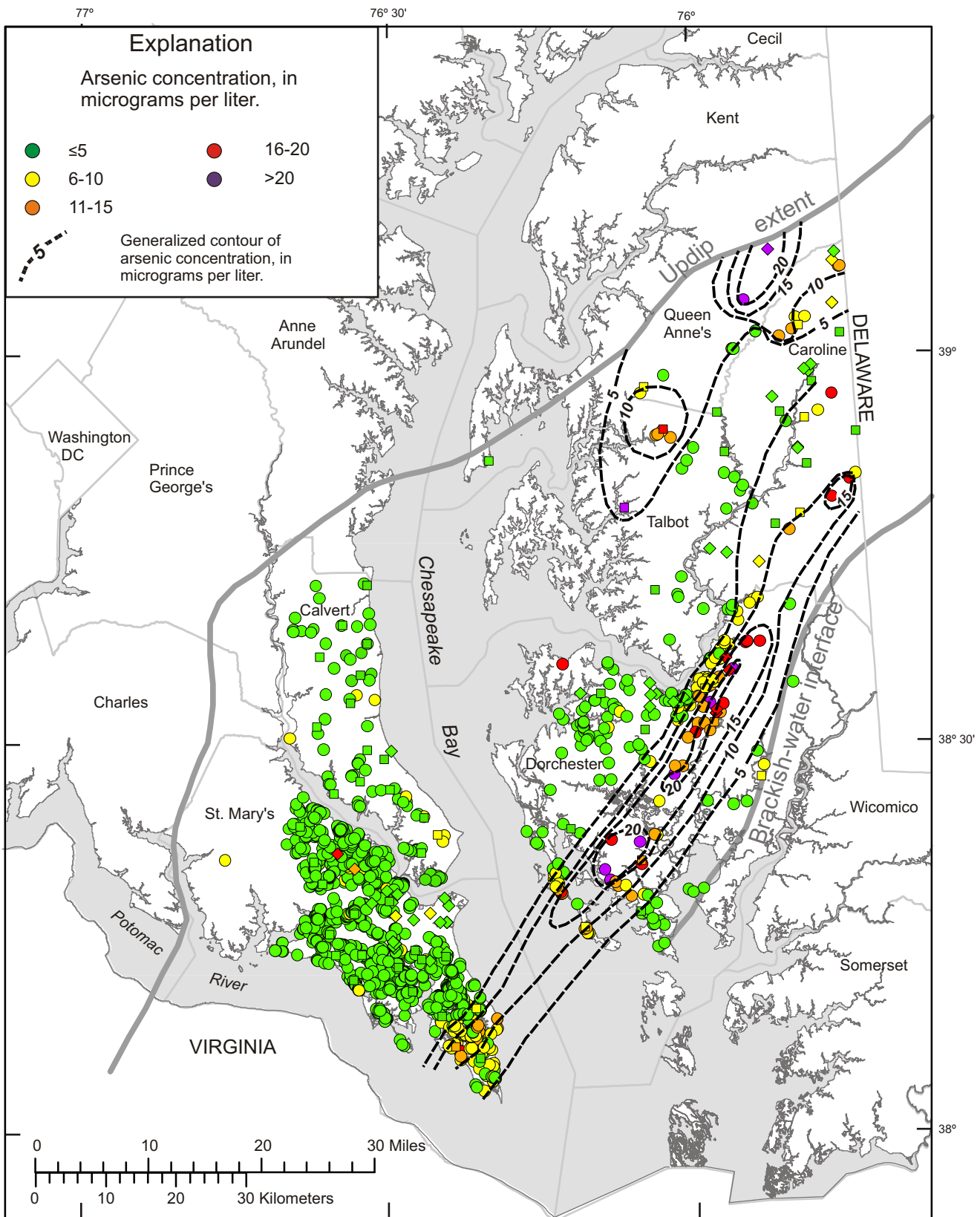
Figure 9. Distribution of arsenic in the Piney Point aquifer.
(Circles from county health departments; squares from this study; diamonds from MDE public-supply database)
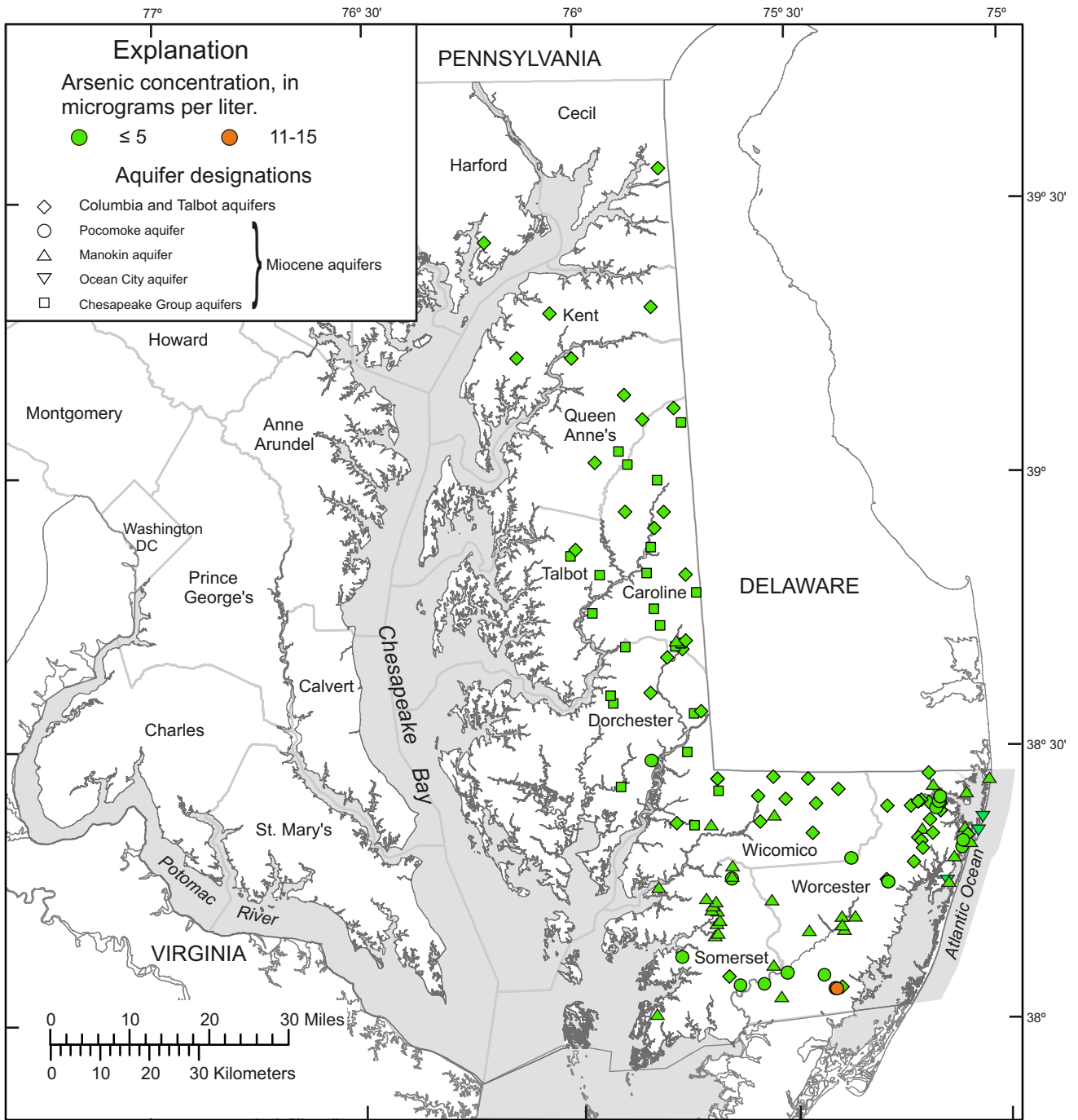
Figure 10. Distribution of arsenic in the Columbia and Miocene aquifers.
(Data from this study and the MDE public-supply database.)
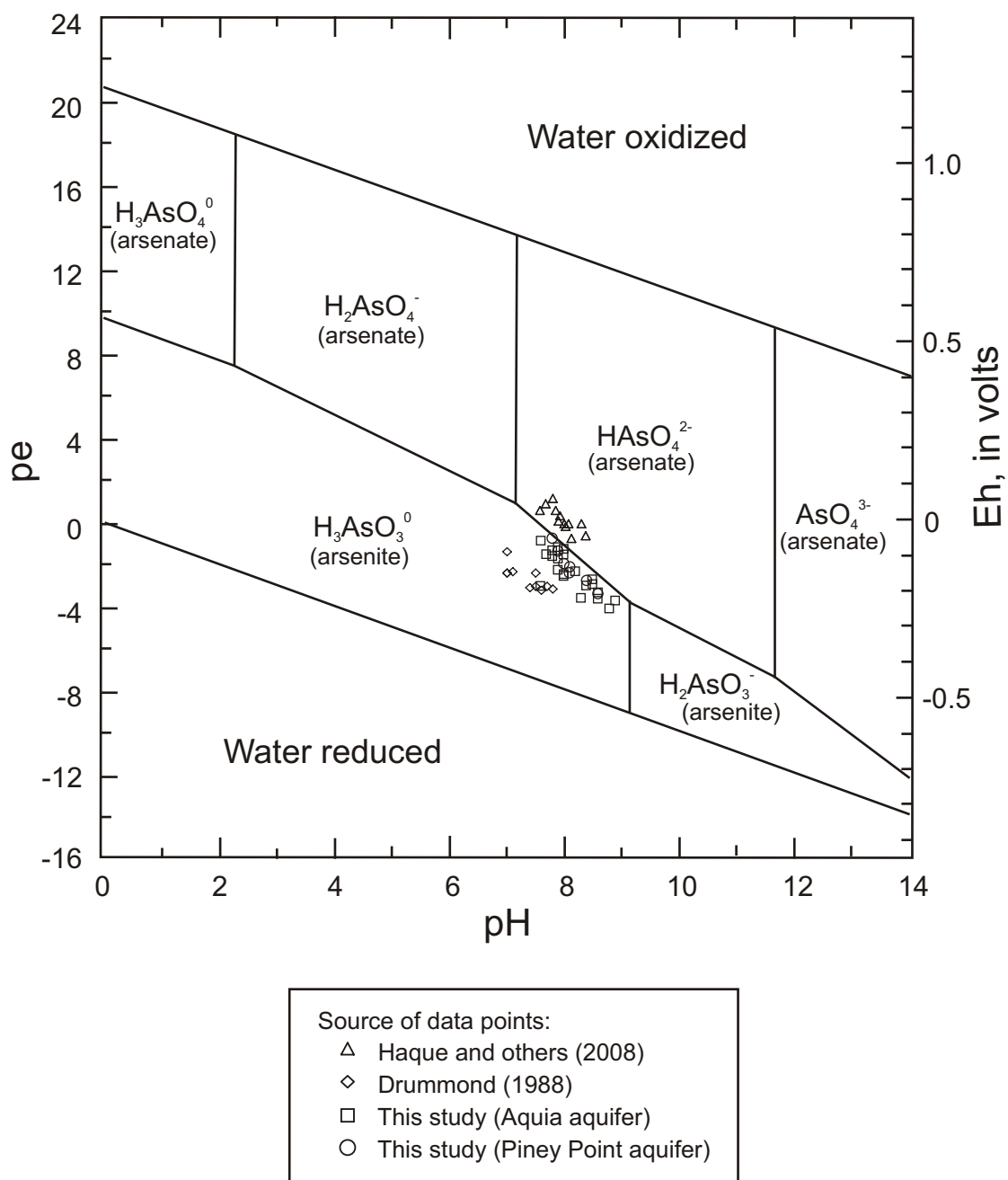
Figure 11. Eh-pH diagram for aqueous arsenic species, with data points.
(pe values for this study were calculated from arsenate/arsenite ratios.
pe values for the other studies were measured using electrodes. Diagram
modified from Nordstrom and Archer, 2002.)
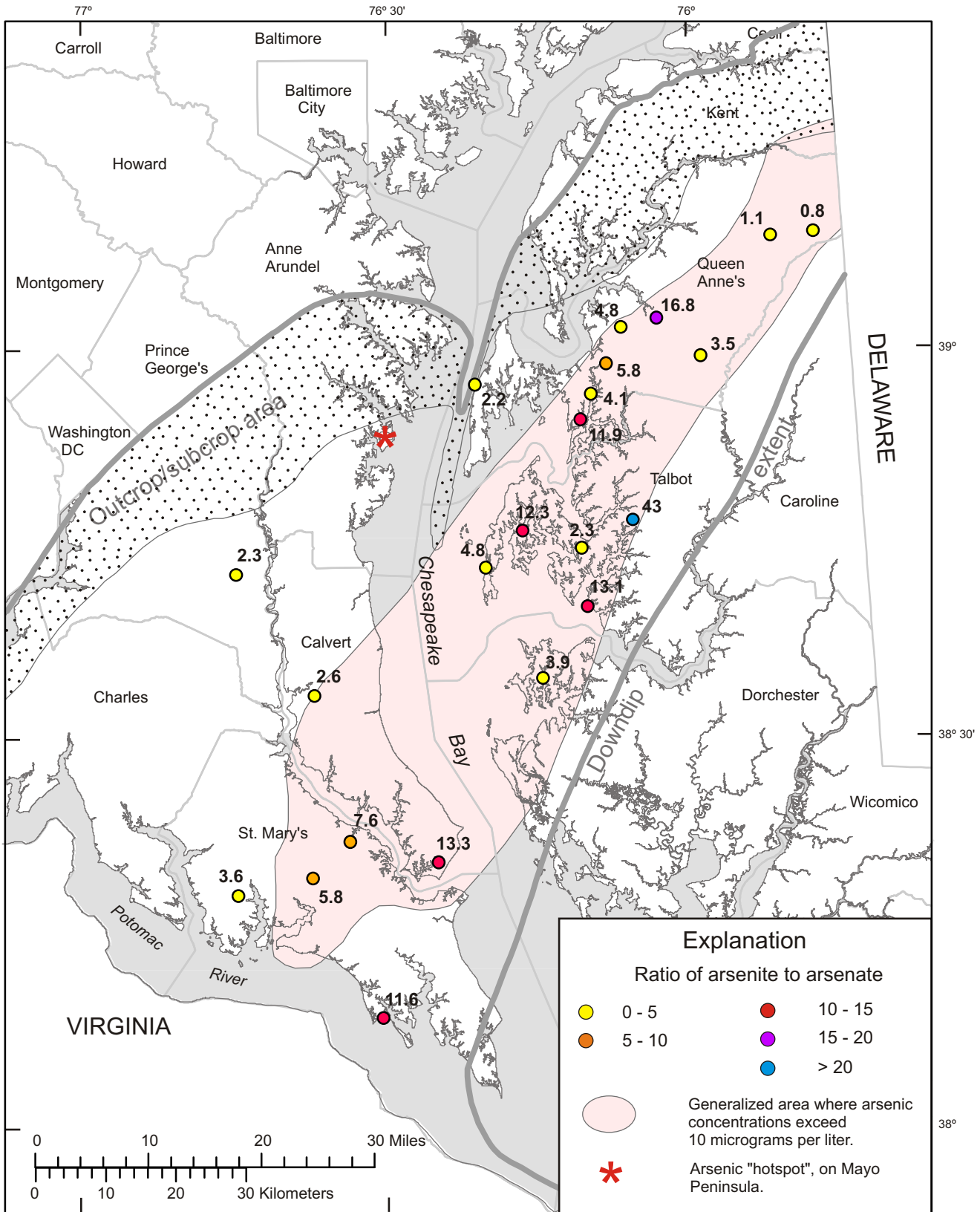
Figure 12. Ratio of arsenite to arsenate in the Aquia aquifer.
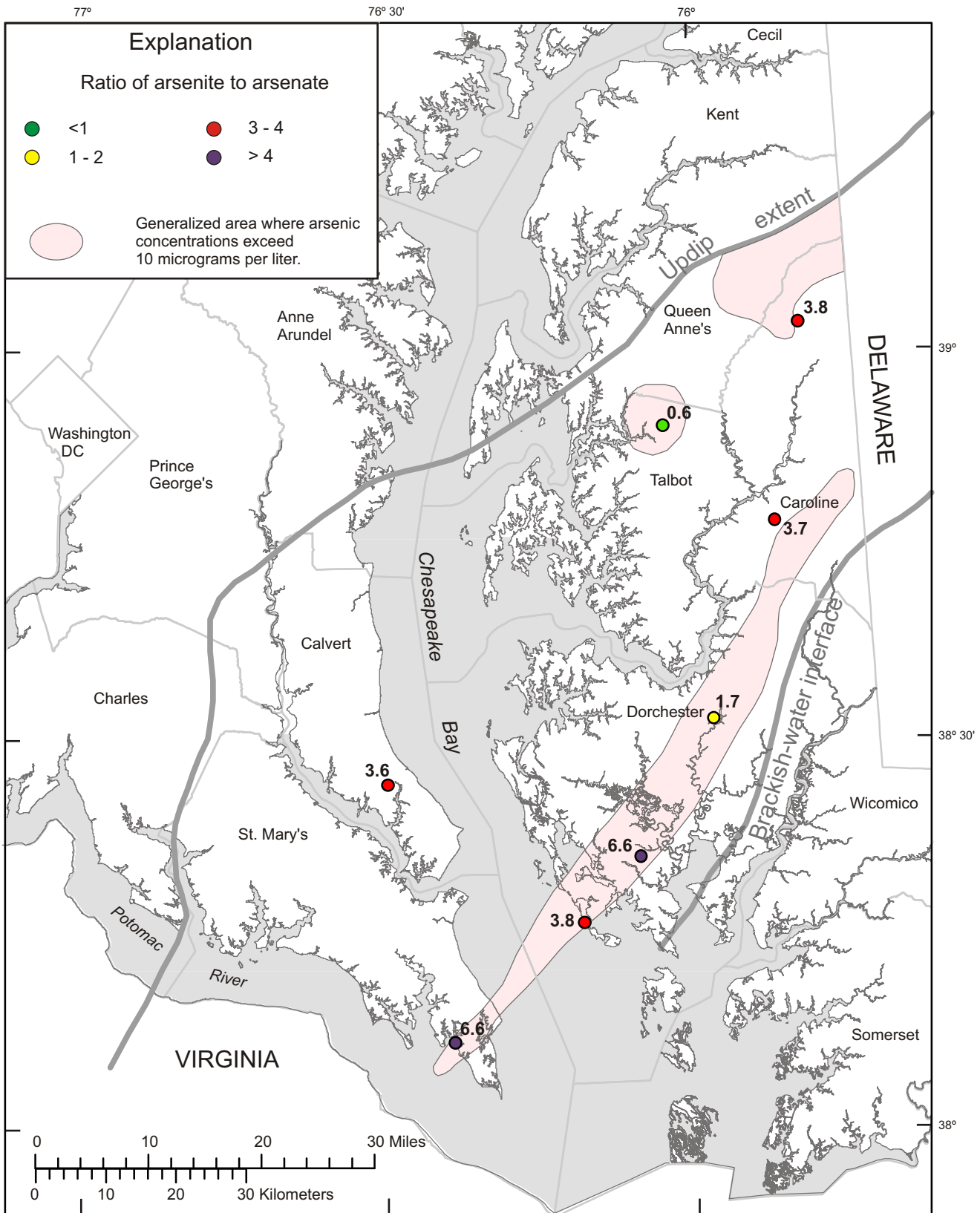
Figure 13. Ratio of arsenite to arsenate in the Piney Point aquifer.
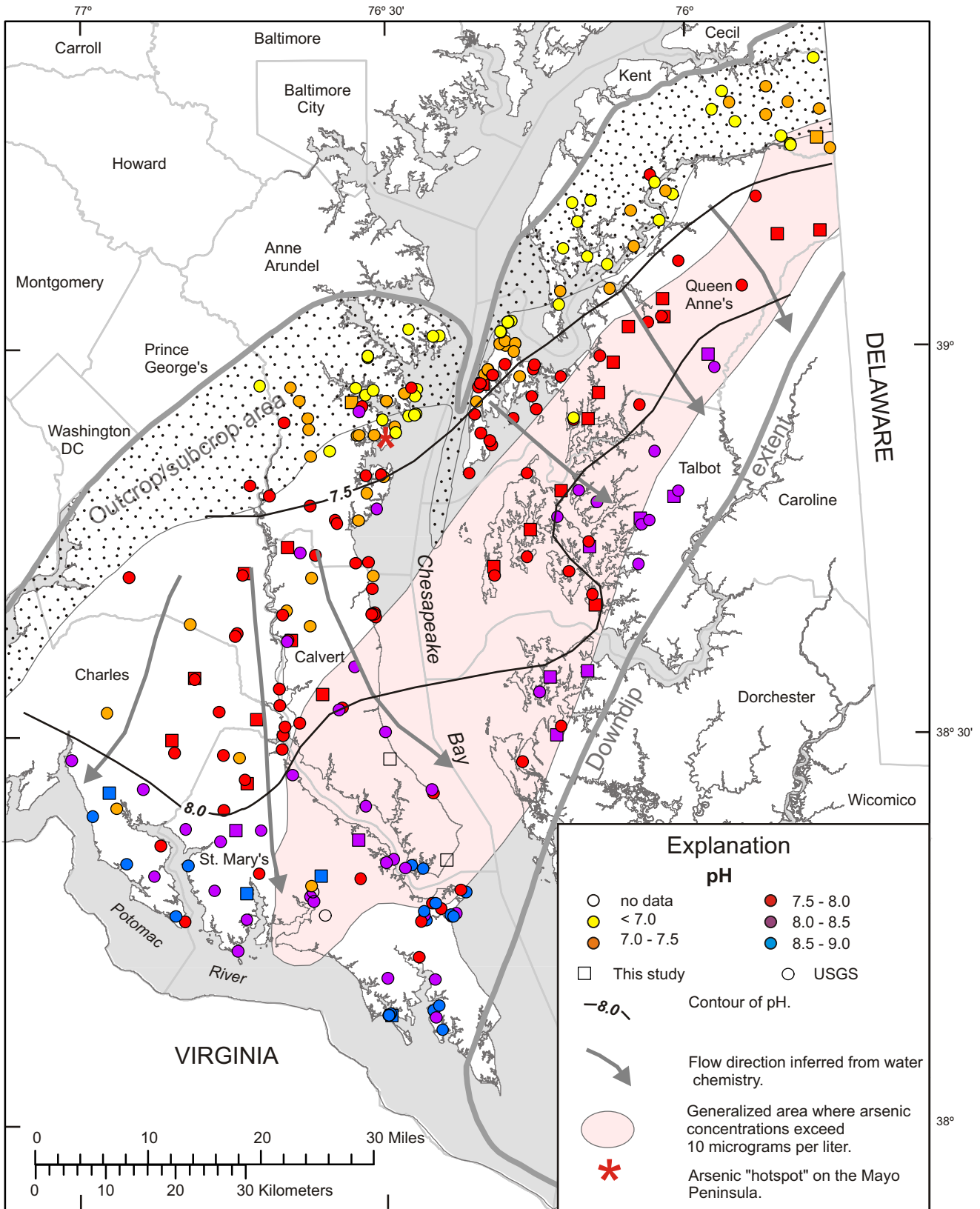
Figure 14. Distribution of pH in the Aquia aquifer.
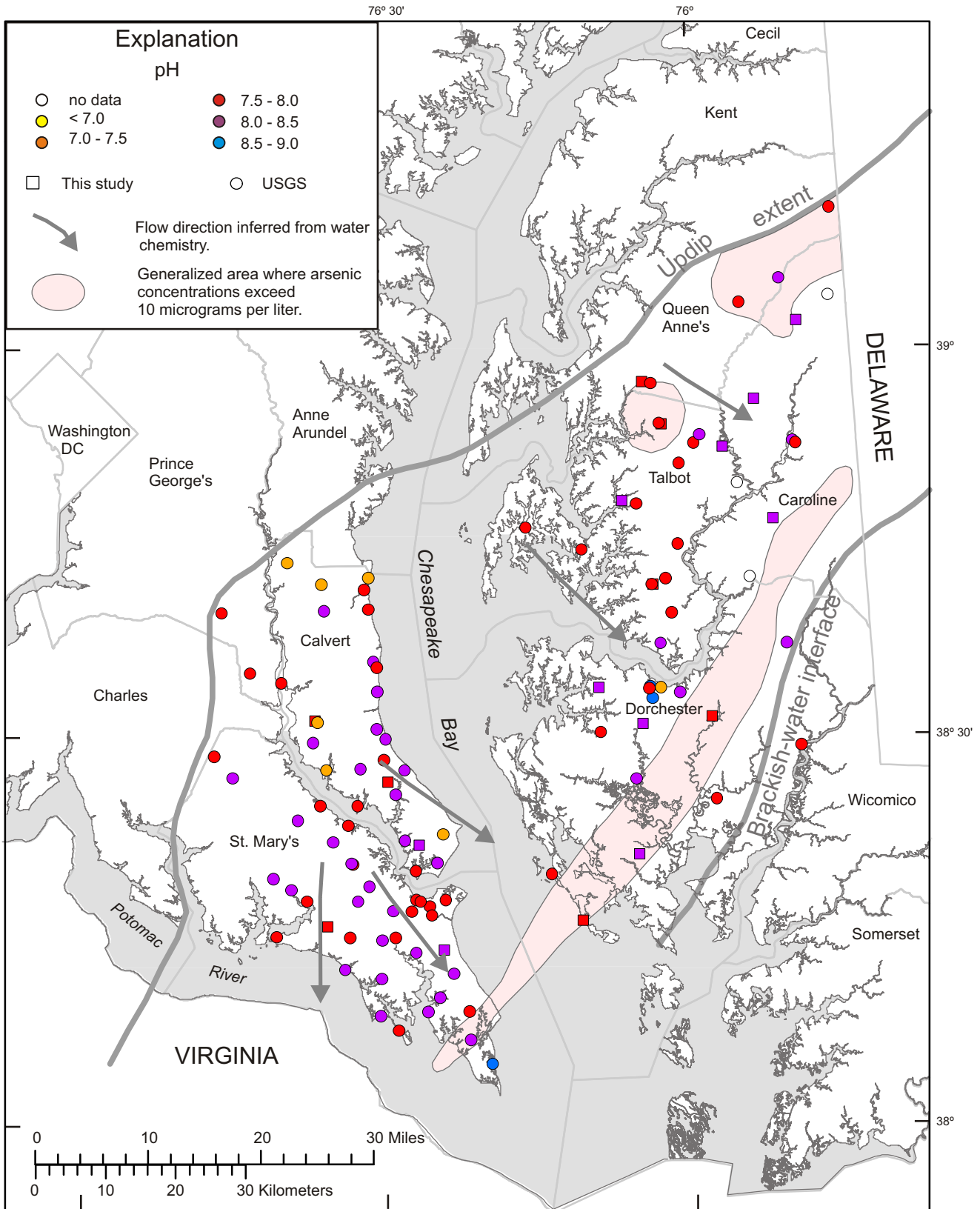
Figure 15. Distribution of pH in the Piney Point aquifer.
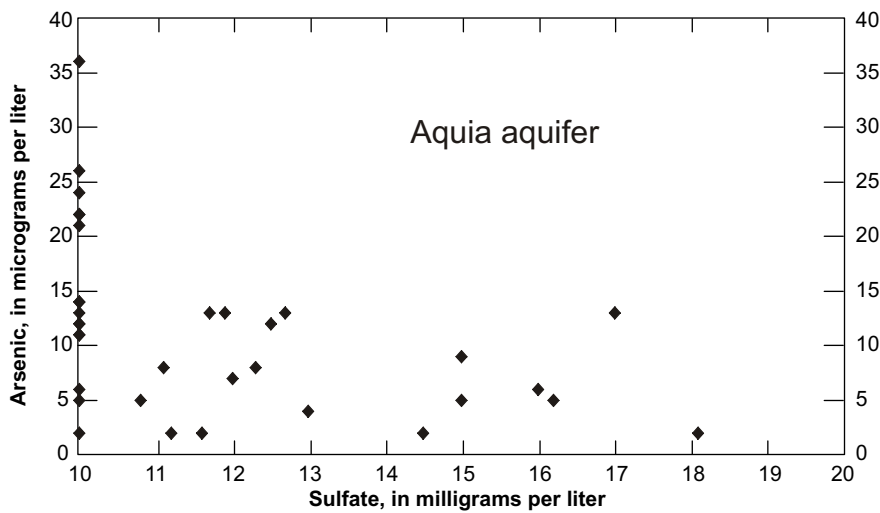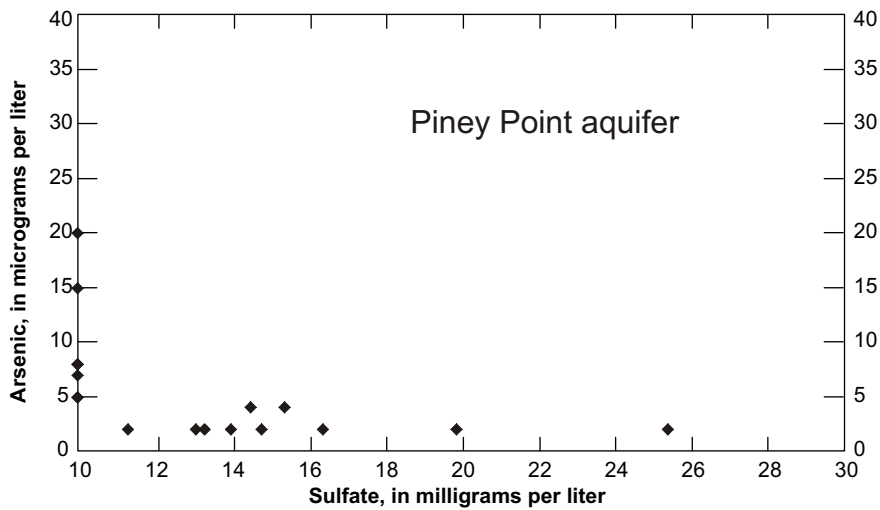
Figure 16. Variation of sulfate content with arsenic in the Aquia and Piney Point aquifers. Samples with more than 20 mg/L chloride were excluded because of possible interference with arsenic analyses.
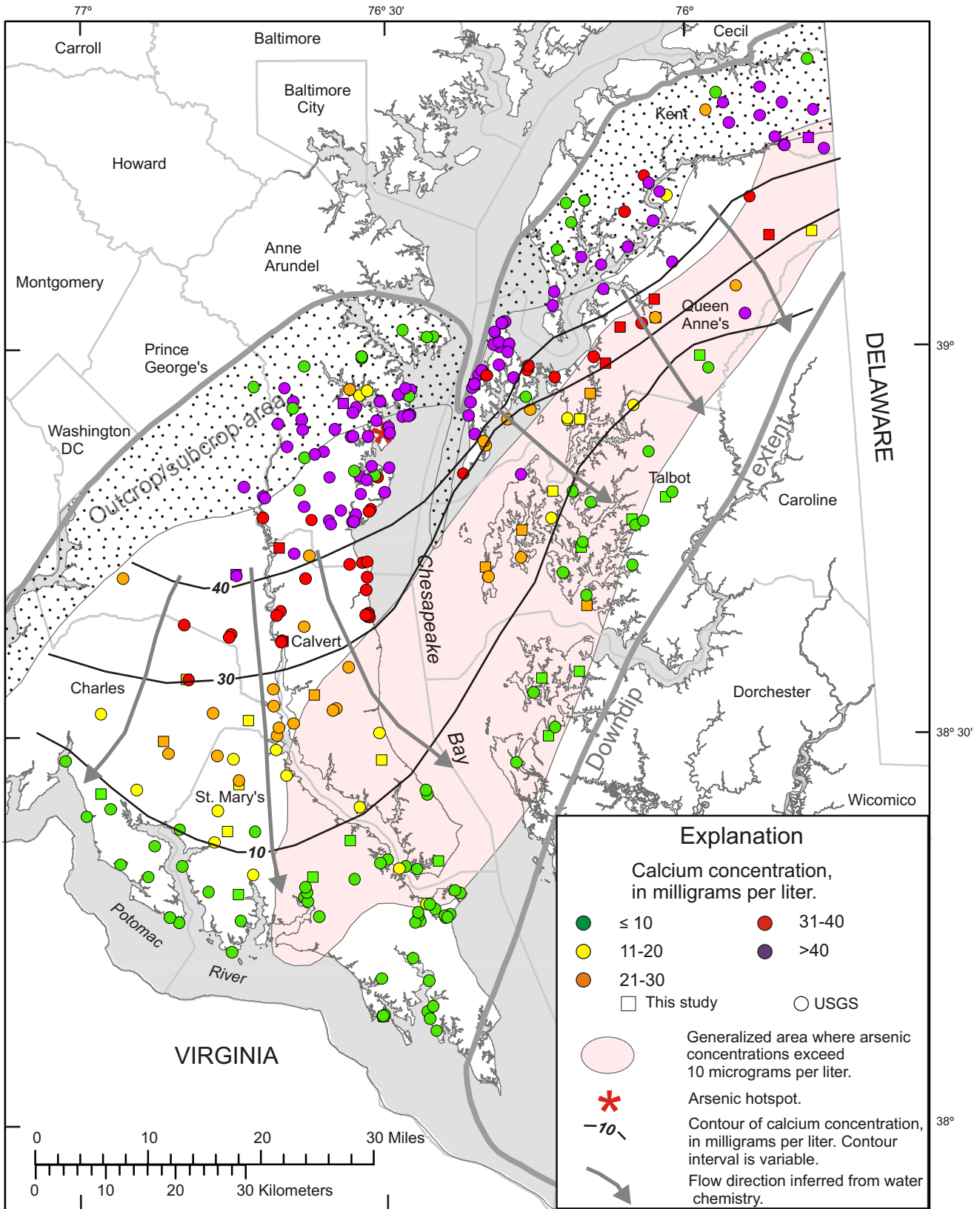
Figure 17. Distribution of calcium in the Aquia aquifer.
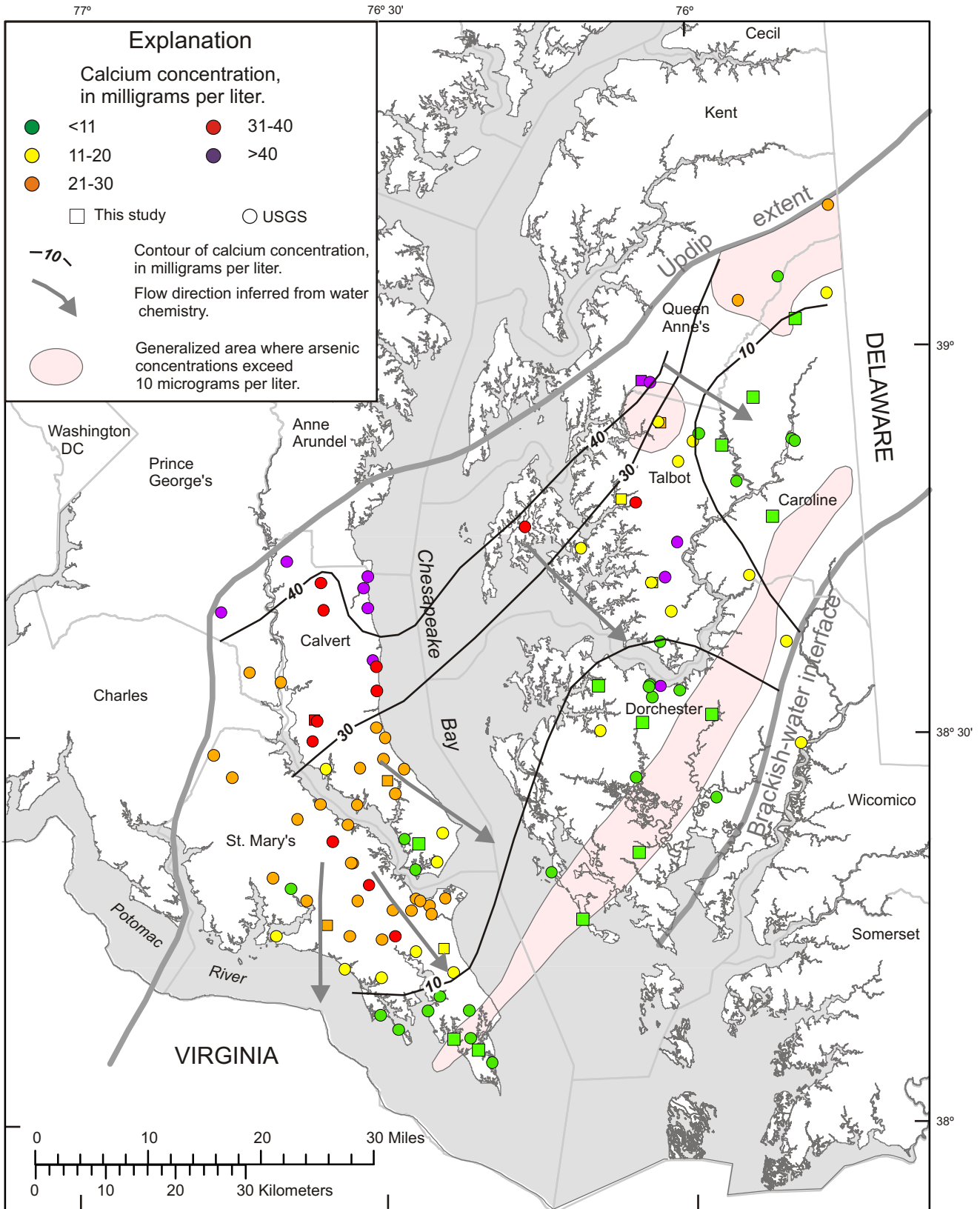
Figure 18. Distribution of calcium in the Piney Point aquifer.

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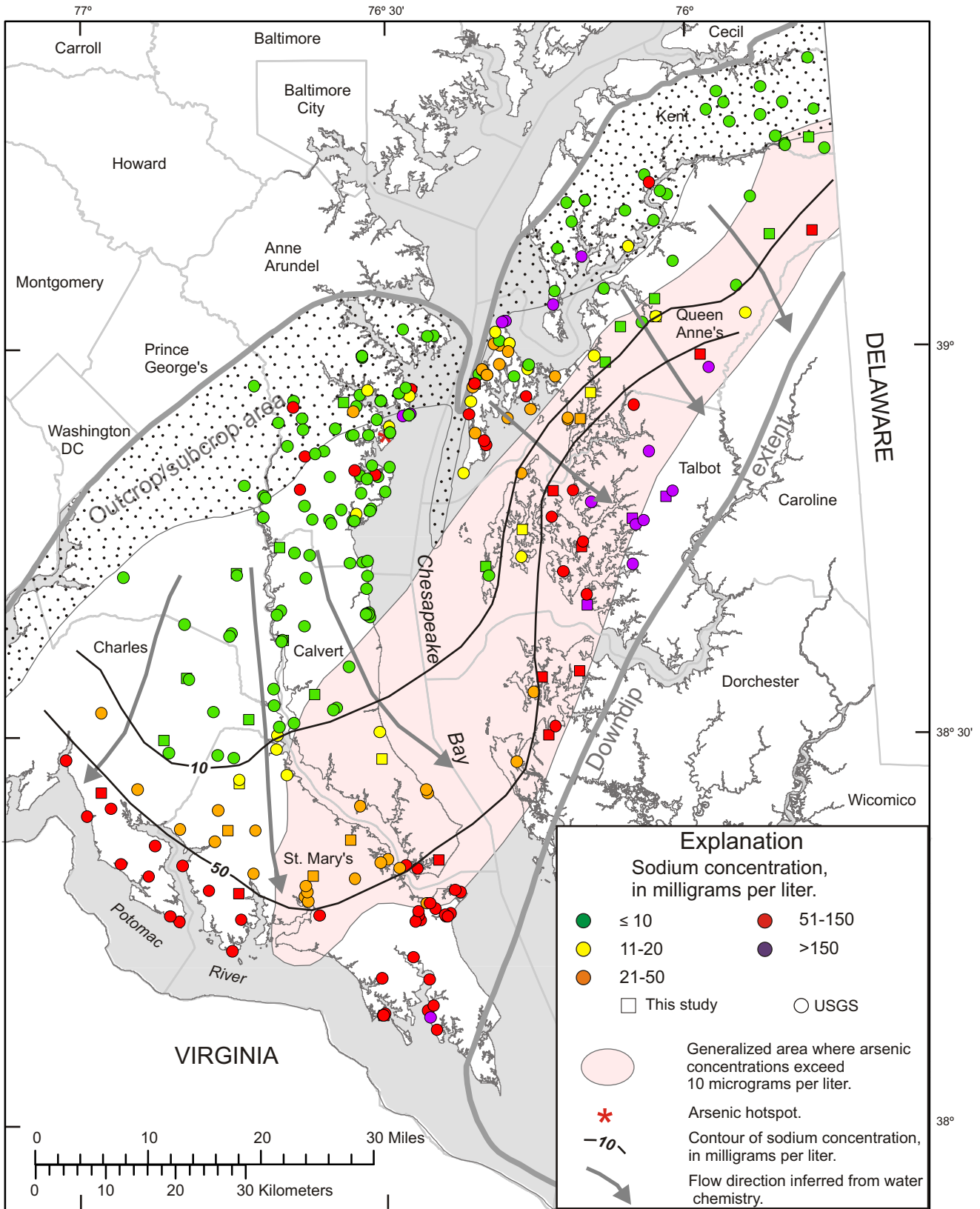
Figure 19. Distribution of sodium in the Aquia aquifer.
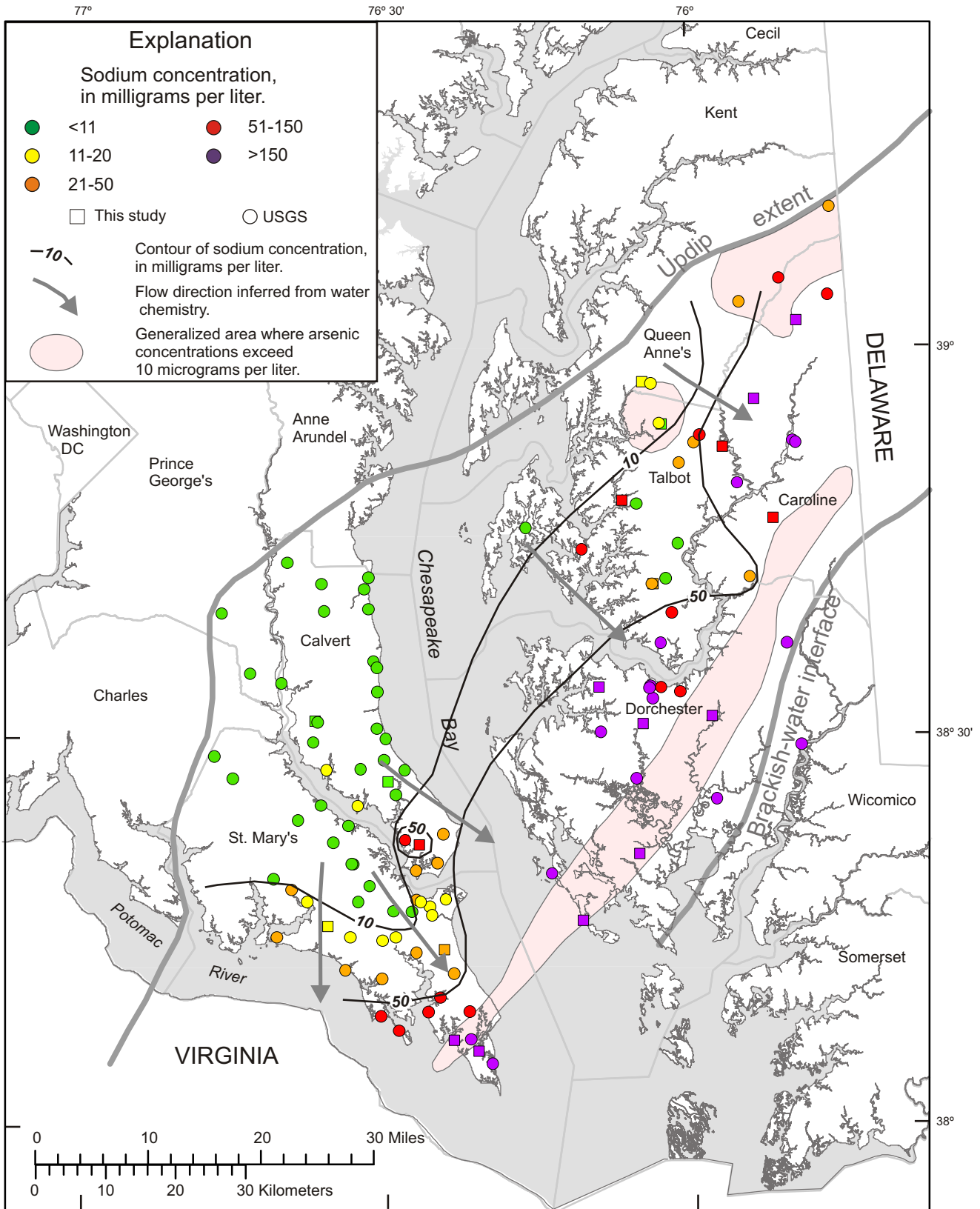
Figure 20. Distribution of sodium in the Piney Point aquifer.
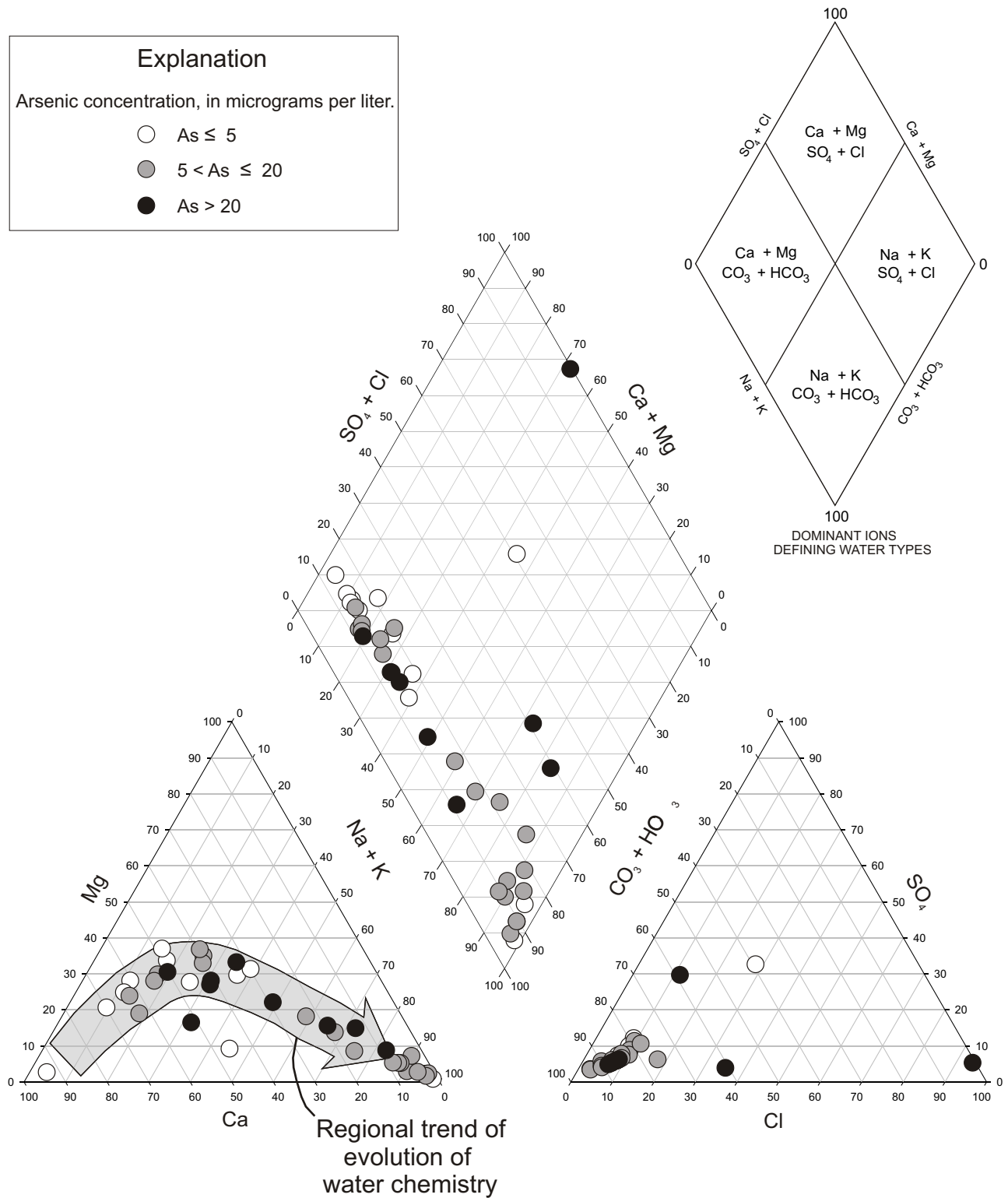
Figure 21. Piper diagram showing hydrochemical facies and arsenic concentrations in the Aquia aquifer.
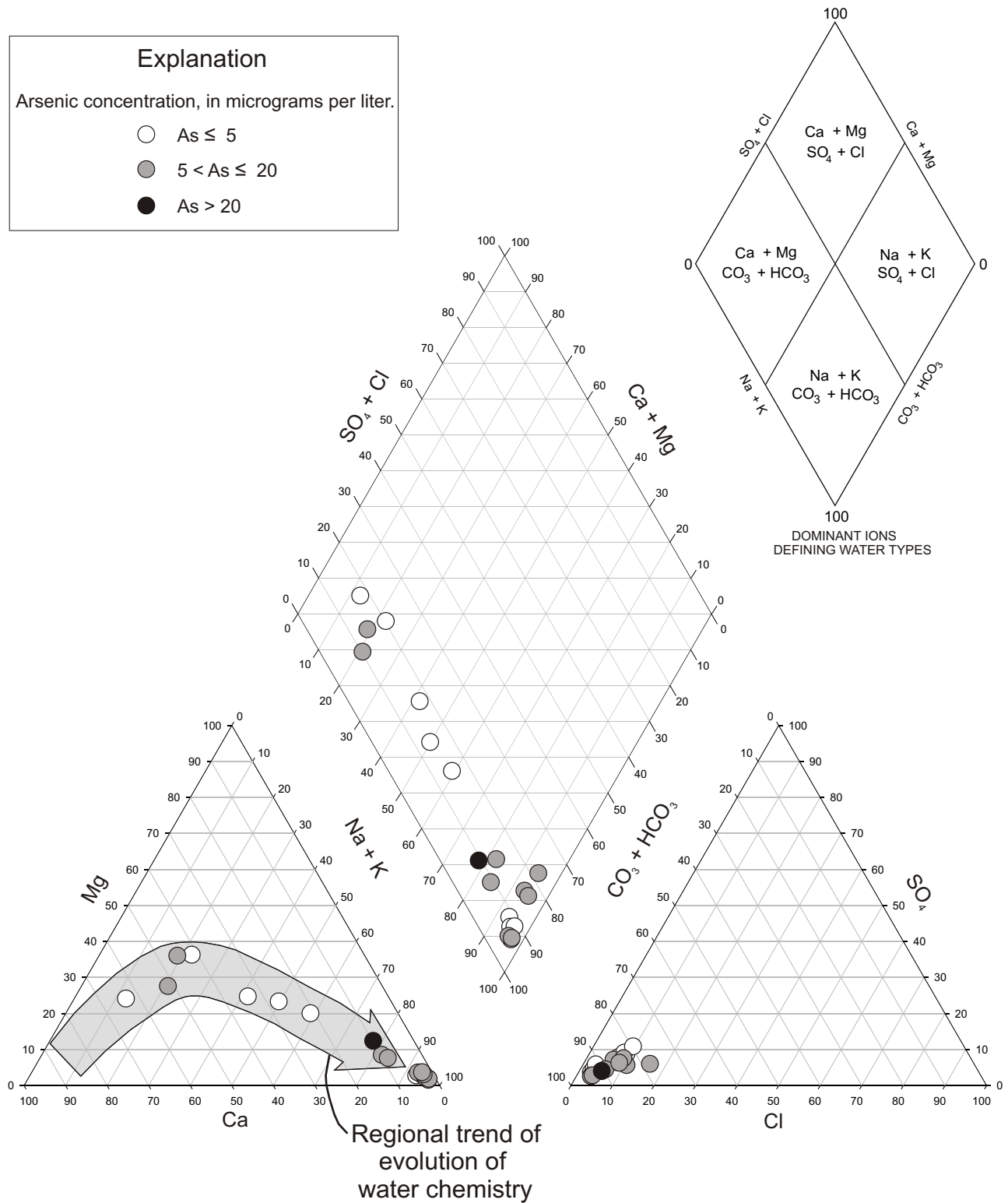
Figure 22. Piper diagram showing hydrochemical facies and arsenic concentrations in the Piney Point aquifer.

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Table 1. Generalized hydrogeology and stratigraphy of the Maryland Coastal Plain

System	Series	Strati-graphic unit	Hydro-geologic unit	Lithology	Water-bearing properties
Quaternary	Pleistocene	Kent Island Formation	Columbia aquifer	Loose, light-colored medium to coarse sand and dark-colored, massive silt clay.	Functions as an unconfined or semi-confined aquifer. Yields moderate amounts of water to shallow wells. Vulnerable to contamination from surface sources.
Tertiary	Pliocene (?) and/or Upper Miocene (?)	Beaverdam Sand	Columbia aquifer	Orange to reddish brown, fine to coarse sand and gravelly sand.	
		Pensauken Formation			
	——— ? ———				
	Miocene	Yorktown Formation	Miocene aquifers/ confining units	Gray quartz sand and dark gray silt and clay with abundant shell material.	Contains multiple aquifers in the southeastern part of the study area, including the Cheswold, Federalsburg, Frederica, Manokin, Ocean City, and Pocomoke aquifers. Elsewhere functions as a leaky confining unit.
		St. Mary's Formation			
		Choptank Formation			
		Calvert Formation			
	Eocene	Piney Point Formation	Piney Point aquifer	Green to gray, fine to coarse glauconitic quartz sand with abundant shell material.	An important confined aquifer in Southern Maryland and middle Eastern Shore.
		Nanjemoy Formation	Nanjemoy confining unit	Green to gray glauconitic sandy silt and clay.	Functions as a leaky confining unit in most of the study area. Sandy strata in the upper part of the Nanjemoy Formation function as part of the Piney Point aquifer in northern Calvert and St. Mary's Counties
		Lower Eocene sand	Aquia aquifer	Green to gray, fine to medium, glauconitic quartz sand with abundant shell material, layers of calcite-cemented sand, goethite grains. and sparse phosphate pellets.	An important confined aquifer in Southern Maryland and the middle Eastern Shore. Vulnerable to brackish-water intrusion on Kent Island and eastern Anne Arundel County.
	Paleocene	Aquia Formation			
		Hornerstown Formation			
Cretaceous	Upper Cretaceous	Monmouth Formation	Monmouth aquifer/ confining unit	Dark gray to dark green glauconitic sandy, silty clay.	Functions as a tight confining unit throughout most of the study area, but is a minor aquifer in Kent County.
		Matawan Group (undivided)	Matawan aquifer/ confining unit	Dark gray to dark green glauconitic sandy, silty clay with lenses of light gray, fine to medium quartz sand.	Functions as a tight confining unit throughout most of the study area, but is a minor aquifer in central Queen Anne's County.
		Magothy Formation	Magothy aquifer/ confining unit	Light gray, fine to coarse quartz sand and gray to black lignitic clay.	Functions as a confined aquifer in parts of the study area; elsewhere as a confining unit. Produces water high in iron in some areas.
	——— ? ———	Potomac Group / Patapsco Formation	Potomac Group aquifers / Upper Patapsco aquifer	Light gray to white fine to very coarse quartz sand, interbedded with dark gray and variegated clay.	A productive confined aquifer throughout much of the study area; produces water high in iron in some areas. Sands are interlayered with clayey confining material.
	Lower Cretaceous		Middle Patapsco confining unit	Dark gray and variegated clay, interbedded with light gray to white, fine quartz sand.	Functions as a tight confining unit; may contain localized water-bearing zones.
			Lower Patapsco aquifer	Fine to medium quartz sand, interbedded with dark gray and variegated silty clay.	A productive confined aquifer throughout much of the study area. Sands are interlayered with clayey confining material.
		Arundel Formation	Arundel confining unit	Gray, red, and variegated silty clay.	Generally functions as a very tight confining unit, but may contain sandy intervals in places.
		Patuxent Formation	Patuxent aquifer	Fine to coarse, silty quartz sand with partially-pyritized lignite.	An important aquifer near the Fall Line. Generally not used farther downdip because of its depth.
Paleozoic	---	Basement Complex	---	Various types of crystalline rock.	Not used for water supply in the study area.

Table 2. **Analytical methods used by the Maryland Department of Health and Mental Hygiene laboratory for this study**

Constituent	EPA method
Arsenic	200.8
Sodium Calcium Iron Magnesium Manganese Potassium	200.7
Ammonia	350.1
Chloride	325.2
Fluoride	340.2
Nitrite Nitrate plus nitrite	353.2
Sulfate	375.2
Total dissolved solids	160.1
Phosphorus (ortho)	365.1
Phosphorus (total)	365.4
Total organic carbon	415.1
Silica	370.1

Table 3. Summary of arsenic concentrations in well water in the major aquifers of the Maryland Coastal Plain

[µg/L, micrograms per liter; <, less than. Table includes samples collected by Maryland Geological Survey. See text for summary discussion of arsenic data from MDE, county, and USGS databases]

Aquifer	Number of samples	Number of samples greater than detection level (2 µg/L)	Number of samples greater than 10 µg/L	Range (µg/L)	Median (µg/L)
Columbia	28	0	0	all <2	<2
Miocene	31	3	1	<2 – 14	<2
Piney Point	55	27	5	<2 – 24	<2
Aquia	117	72	24	<2 – 42	4
Magothy	21	3	0	<2 – 9	<2
Potomac Group	32	0	0	all <2	<2
All aquifers	284	105	30	<2 – 42	<2

Table 4. Arsenic speciation data for the Aquia and Piney Point aquifers

[μg/L, micrograms per liter; E, estimated; <, less than.
Additional water-quality data for these samples is listed in Appendix C]

Well number	Date	Arsenic (μg/L as As)	Arsenite (μg/L as As)	Arsenate (μg/L as As)	Monomethyl-arsonate (μg/L as As)	Dimethyl-arsinate (μg/L as As)
Aquia aquifer:						
CA Db 93	12/2/2002	13	8.7	3.4	<0.1	0.3
CA Fd 87	12/10/2002	13	9.3	0.7	<0.1	0.3
CH Ch 19	11/25/2002	6	3.5	2.1	<0.1	<0.1
DO Cc 54	10/29/2002	18	16.6	4.3	<0.1	0.2
PG Ff 23	11/25/2002	5	3.5	1.5	<0.1	<0.1
QA Cg 68	9/30/2002	24	13.6	11.9	<0.1	0.1
QA Ch 37	9/30/2002	22	10.3	12.7	<0.1	<0.1
QA Dd 33	10/1/2002	12	11.5	2.4	<0.1	<0.1
QA De 30	12/12/2002	26	26.9	1.6	0.2	0.6
QA Ea 77	9/9/2002	3.5E	1.1	<0.2	<0.1	0.1
QA Ea 78	9/9/2002	6	4	1.8	<0.1	0.1
QA Ea 81	8/20/2002	<2	0.3	<0.2	<0.1	0.1
QA Ed 53	11/18/2002	11	9.3	1.6	<0.1	0.2
QA Ed 54	10/1/2002	21	17.2	4.2	<0.1	0.1
QA Ef 34	10/1/2002	14	10.6	3	<0.1	0.1
QA Fc 13	11/19/2002	36	33.4	2.8	0.1	0.5
SM Ce 47	12/3/2002	11	10.6	1.4	0.2	0.3
SM Dc 63	12/3/2002	8	6.2	1.7	<0.1	0.2
SM Dd 70	12/16/2002	12	11.5	2	0.2	0.3
SM Fe 41	12/16/2002	7	9.3	0.8	0.2	0.2
TA Cb 99	11/4/2002	22	20.9	1.7	<0.1	0.2
TA Cd 65	11/19/2002	9	8.6	0.2	<0.1	0.2
TA Da 50	11/4/2002	12	11	2.3	<0.1	0.1
TA Dc 57	11/20/2002	13	8.6	3.8	<0.1	0.2
TA Dc 58	11/20/2002	24	18.4	1.4	<0.1	0.3
Piney Point aquifer:						
CA Ed 53	12/2/2002	4	2.9	0.8	<0.1	0.2
CO Bd 57	12/18/2002	8	6.1	1.6	0.2	0.2
CO Ec 34	11/18/2002	5	3.7	1	<0.1	<0.1
DO Cf 39	10/30/2002	10	7.2	4.3	<0.1	<0.1
DO Ed 17	11/13/2002	14	12.6	1.9	<0.1	0.2
DO Fc 27	10/30/2002	7	6.4	1.7	<0.1	0.1
SM Fg 65	12/4/2002	8	7.3	1.1	0.1	0.2
TA Be 92	11/6/2002	15	5.9	10	<0.1	<0.1

Appendix A. Total arsenic concentrations and other water-quality data for wells sampled in this study

[gpm, gallons per minute; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than; >, greater than; --, no data; E, estimated]

Well number	Aquifer	Date	Flow (gpm)	Specific conductance (µS/cm)	pH	Temperature (°C)	Dissolved oxygen (mg/L)	Arsenic (µg/L)
AA Bb 89	Potomac (Patuxent)	1/17/2002	5	110	4.4	12.7	2	<2
AA Bc 245	Potomac (Patapsco)	4/24/2002	4.5	192	4.2	14.4	5.8	<2
AA Bc 248	Potomac (Patuxent)	1/24/2002	6.7	119	4.2	14.1	<1	<2
AA Be 122	Potomac (Patapsco)	1/24/2002	4.8	61	4.6	13.3	8.2	<2
AA Bf 94	Magothy	1/17/2002	4	81	5.1	14.0	<1	9
AA Cc 141	Potomac (Patapsco)	1/24/2002	5.5	51	3.9	13.5	<1	<2
AA Cd 120	Magothy	1/17/2002	4	--	--	--	--	<2
AA Cd 128	Potomac (Patapsco)	1/9/2002	8.6	36	4.2	13.9	9.6	<2
AA Ce 143	Magothy	1/17/2002	4	218	3.4	12.8	1.8	<2
AA Cf 154	Aquia	2/6/2002	5.5	60	5.6	13.5	<1	<2
AA Cg 27	Magothy	1/28/2002	5	175	5.9	14.6	<1	<2
AA Dd 62	Magothy	1/15/2002	7.1	228	6.8	14.1	<1	<2
AA De 214	Magothy	1/17/2002	5	156	--	14.2	<1	<2
AA De 218	Aquia	1/15/2002	6	293	7.3	14.3	<1	<2
AA Ec 16	Aquia	1/15/2002	6	285	7.6	14.3	<1	<2
AA Ed 66	Aquia	1/15/2002	5.5	334	7.0	14.8	<1	<2
AA Ee 100	Aquia	1/17/2002	4	350	7.7	14.2	<1	<2
AA Fd 61	Aquia	1/15/2002	3.8	300	7.7	15.2	<1	<2
BA Ef 59	Potomac	1/28/2002	4	38	4.7	13.2	4.4	<2
BA Ff 89	Potomac	1/28/2002	4	--	--	14.2	<1	<2
CA Ba 15	Aquia	7/2/2001	6	290	7.7	16.4	<1	<2
CA Ba 16	Aquia	7/2/2001	4	303	7.6	17.3	<1	4
CA Bb 47	Aquia	7/2/2001	6	298	7.7	16.9	<1	<2
CA Bb 50	Aquia	7/2/2001	6	220	7.8	17.3	<1	3
CA Bb 51	Aquia	7/2/2001	4	296	7.7	16.9	<1	4
CA Bb 52	Aquia	7/12/2001	4	257	7.8	18.2	<1	4
CA Bc 38	Piney Point	11/29/2001	3	554	7.7	15.4	<1	<2
CA Bc 52	Aquia	7/2/2001	4	280	7.7	17.7	<1	<2
CA Ca 15	Aquia	7/12/2001	6	288	7.8	17.0	<1	4
CA Cb 42	Aquia	7/12/2001	6	291	7.8	17.1	<1	7

Appendix A. Continued

Well number	Aquifer	Date	Flow (gpm)	Specific conductance (µS/cm)	pH	Temperature (°C)	Dissolved oxygen (mg/L)	Arsenic (µg/L)
CA Cb 43	Aquia	7/26/2001	10	230	7.5	--	--	<2
CA Cc 70	Aquia	7/12/2001	3	331	7.8	16.8	<1	<2
CA Cc 71	Piney Point	7/26/2001	4	--	7.7	16.6	<1	<2
CA Cc 72	Piney Point	7/26/2001	2.5	425	7.5	16.3	<1	<2
CA Db 91	Aquia	7/12/2001	8	244	8.0	20.6	<1	8
CA Db 93	Aquia	7/12/2001	8	272	7.9	17.3	<1	12
CA Db 95	Piney Point	7/12/2001	3	243	7.9	17.9	<1	<2
CA Db 96	Potomac (Upper Patapsco)	2/4/2003	4	240	7.0	18.5	--	0.3
CA Dc 37	Aquia	5/20/2002	E150	298	7.6	17.9	<1	6
CA Dc 54	Piney Point	7/12/2001	4	286	7.8	16.3	<1	4
CA Eb 22	Piney Point	7/3/2001	6	293	7.6	17.3	<1	<2
CA Ec 44	Piney Point	7/3/2001	5	258	7.6	17.1	<1	2
CA Ec 46	Piney Point	7/3/2001	5	263	7.7	16.5	<1	2
CA Ec 48	Piney Point	7/3/2001	6	254	7.6	16.7	<1	3
CA Ec 49	Aquia	5/20/2002	29	278	7.7	18.6	<1	6
CA Ed 53	Piney Point	11/29/2001	5	251	8.0	16.0	<1	3
CA Fd 77	Piney Point	7/3/2001	3	356	8.3	17.0	<1	5
CA Fd 78	Piney Point	7/3/2001	4	300	8.0	20.5	<1	10
CA Fd 79	Piney Point	7/3/2001	6	249	8.0	17.2	<1	<2
CA Fd 85	Potomac (Lower Patapsco)	11/28/2001	82	414	8.6	25.2	--	<0.2
CA Fd 86	Aquia	5/20/2002	300	228	8.5	19.1	<1	4
CA Fd 87	Aquia	5/20/2002	300	268	8.5	18.6	<1	14
CE Ce 60	Potomac	9/7/2001	8	355	4.7	17.1	1.8	<2
CE Ce 83	Potomac	3/12/2002	5	22	4.5	13.2	6.4	<2
CE Cf 81	Columbia	7/9/2001	3	46	5.8	17.3	<1	<2
CE Ee 54	Magothy	3/12/2002	6.7	307	7.5	14.4	<1	<2
CH Bd 54	Potomac (Lower Patapsco)	10/2/2001	6	604	7.5	18.5	<1	<2
CH Be 69	Potomac (Upper Patapsco)	9/27/2001	4	285	7.9	16.9	<1	<2
CH Bg 15	Aquia	9/27/2001	3	300	7.7	17.0	<1	2
CH Bg 17	Potomac (Lower Patapsco)	3/4/2003	60	240	8.0	20.6	<1	<0.3
CH Cc 38	Patuxent	9/27/2001	3	308	7.5	16.8	<1	<2
CH Cf 35	Aquia	9/26/2001	4	281	7.8	17.1	<1	<2
CH Cf 36	Aquia	9/27/2001	3	260	7.9	16.8	<1	<2

Appendix A. Continued

Well number	Aquifer	Date	Flow (gpm)	Specific conductance (µS/cm)	pH	Temperature (°C)	Dissolved oxygen (mg/L)	Arsenic (µg/L)
CH Cf 37	Magothy	9/27/2001	4	302	7.8	17.6	<1	<2
CH Cg 22	Aquia	9/27/2001	4	286	7.9	17.5	<1	<2
CH Cg 23	Aquia	9/27/2001	8	275	7.9	17.1	<1	<2
CH Cg 24	Patapsco	1/29/2002	58	279	7.3	19.8	<1	<2
CH Ch 19	Aquia	7/26/2001	4	255	7.9	18.2	<1	5
CH Ch 20	Aquia	7/26/2001	4	280	7.7	17.9	<1	3
CH Db 14	Patuxent	9/27/2001	4	414	7.2	16.8	<1	<2
CH Dc 22	Potomac (Upper Patapsco)	10/2/2001	4	364	7.4	16.2	<1	<2
CH De 47	Aquia	9/26/2001	4	318	8.7	16.7	<1	<2
CH De 48	Aquia	9/26/2001	4	313	8.8	16.9	<1	<2
CH De 49	Aquia	9/26/2001	4	282	8.4	16.7	<1	<2
CH Df 18	Aquia	9/26/2001	3	249	7.9	17.2	<1	<2
CH Ee 93	Aquia	9/26/2001	4.2	302	8.8	17.9	<1	<2
CH Ef 18	Aquia	9/26/2001	3	254	8.3	16.9	<1	3
CH Ff 63	Aquia	9/26/2001	8	333	9.1	17.7	<1	7
CO Ad 19	Columbia	8/31/2001	2	84	5.1	22.9	4.5	<2
CO Bc 21	Miocene (Cheswold)	2/14/2002	5.5	257	7.9	14.4	<1	<2
CO Bd 57	Piney Point	2/14/2002	5	646	8.3	15.1	<1	7
CO Bd 58	Piney Point	2/14/2002	5	729	8.2	15.5	<1	<2
CO Cc 55	Columbia	8/16/2001	3	169	4.9	15.9	6.3	<2
CO Cc 104	Piney Point	2/14/2002	4.4	566	8.4	14.3	<1	<2
CO Cd 50	Miocene (Cheswold)	2/14/2002	5	288	8.1	14.2	<1	<2
CO Cd 54	Columbia	8/31/2001	4	34	5.0	15.2	3.3	<2
CO Cd 65	Piney Point	2/14/2002	4	766	8.4	15.6	<1	<2
CO Dd 76	Columbia	8/16/2001	3	63	4.7	17.6	5.2	<2
CO Dd 77	Piney Point	2/20/2002	4	492	8.0	16.0	<1	<2
CO Dd 78	Piney Point	2/20/2002	4	783	8.3	15.2	<1	6
CO De 17	Piney Point	2/20/2002	4.6	413	8.0	16.9	<1	5
CO Ec 34	Piney Point	2/20/2002	5	448	8.2	16.0	<1	5
CO Ec 35	Federalsburg	2/20/2002	4.3	333	7.8	14.5	<1	<2
CO Ed 36	Columbia	8/16/2001	5	109	5.2	15.4	8.0	<2
CO Ed 37	Piney Point	2/20/2002	5	443	8.1	15.8	<1	6
CO Ee 21	Federalsburg	2/20/2002	4.3	372	7.9	13.3	<1	<2

Appendix A. Continued

Well number	Aquifer	Date	Flow (gpm)	Specific conductance (µS/cm)	pH	Temperature (°C)	Dissolved oxygen (mg/L)	Arsenic (µg/L)
CO Fd 39	Columbia	8/31/2001	4	129	4.8	15.5	5.8	<2
DO Ag 12	Miocene (Frederica)	3/15/2002	4	244	7.9	14.8	<1	<2
DO Ah 12	Columbia	9/11/2001	2	177	4.2	16.3	2.8	<2
DO Bc 33	Aquia	3/5/2002	4.6	464	8.7	18.7	<1	14
DO Bg 74	Columbia	9/11/2001	120	201	5.0	--	--	<2
DO Cb 9	Aquia	3/5/2002	5	209	8.6	18.5	<1	9
DO Cc 54	Aquia	3/5/2002	6.7	301	8.7	19.0	<1	21
DO Cc 55	Aquia	3/5/2002	15	341	8.5	18.5	<1	15
DO Cc 56	Aquia	3/5/2002	7.1	434	8.5	19.5	<1	8
DO Cd 55	Piney Point	3/5/2002	4	736	8.4	15.3	<1	<2
DO Ce 91	Piney Point	3/6/2002	7.5	798	8.3	17.2	<1	3
DO Cf 39	Piney Point	3/15/2002	8	1,304	8.0	17.8	1.9	13
DO Cf 40	Miocene (Frederica)	3/15/2002	4.5	298	7.7	15.3	<1	<2
DO Cf 41	Piney Point	3/15/2002	4	621	8.2	17.1	<1	9
DO Ci 8	Columbia	9/11/2001	4	64	5.3	17.1	6.3	<2
DO Ci 9	Miocene (Frederica)	3/15/2002	4.6	881	8.2	15.3	<1	<2
DO Dg 28	Federalsburg	3/15/2002	4	1,668	7.8	15.1	<1	<2
DO Dg 29	Piney Point	3/15/2002	6.7	2,339	7.9	18.8	<1	7
DO Ec 22	Piney Point	3/6/2002	6.7	1,044	8.0	17.7	<1	<2
DO Ed 17	Piney Point	3/6/2002	6	1,345	8.1	18.8	<1	15
DO Fc 27	Piney Point	3/6/2002	3.3	974	8.0	17.2	<1	9
DO Fd 17	Piney Point	3/6/2002	6	1,245	8.0	--	<1	<2
HA Dc 120	Potomac	1/31/2002	2	114	4.7	--	9.6	<2
HA De 166	Potomac	1/31/2002	3.5	19	5.1	12.6	7.9	<2
KE Ad 60	Magothy	3/12/2002	5	122	6.1	13.6	<1	6
KE Ad 70	Potomac	3/12/2002	6	129	6.0	14.0	<1	<2
KE Ae 70	Potomac	3/12/2002	4	208	7.1	13.9	<1	<2
KE Bb 14	Magothy	3/12/2002	5	85	5.4	13.2	<1	<2
KE Bd 81	Columbia	7/9/2001	3	161	5.1	14.6	10	<2
KE Bd 87	Magothy	6/27/2002	--	122	--	--	--	<2
KE Bd 129	Aquia	6/27/2002	5	216	6.9	14.3	<1	<2
KE Bg 63	Columbia	7/9/2001	3	135	5.1	14.8	10	<2
KE Bg 106	Aquia	4/12/2002	6	278	7.5	13.8	<1	<2

Appendix A. Continued

Well number	Aquifer	Date	Flow (gpm)	Specific conductance (µS/cm)	pH	Temperature (°C)	Dissolved oxygen (mg/L)	Arsenic (µg/L)
KE Cb 41	Aquia	6/27/2002	4	79	--	--	--	<2
KE Cc 39	Columbia	8/8/2001	4	168	4.8	15.0	9.5	<2
PG Bd 44	Potomac (Patuxent)	11/14/2001	4.8	24	4.9	14.4	9.6	<2
PG Bd 45	Potomac (Patuxent)	1/28/2002	7.5	39	5.0	13.4	8.7	<2
PG Be 36	Patapsco	1/24/2002	5	44	4.1	13.1	5.8	<2
PG Ce 43	Potomac (Patapsco)	11/14/2001	5	162	6.4	14.3	<1	<2
PG Ce 47	Potomac (Patapsco)	11/14/2001	4	174	4.7	13.8	<1	<2
PG De 34	Magothy	10/17/2001	4	335	7.5	15.1	<1	<2
PG Df 44	Magothy	11/14/2001	3.5	271	7.2	14.4	<1	<2
PG Ec 49	Potomac (Patapsco)	1/24/2002	4	220	7.1	15.2	<1	<2
PG Ee 55	Magothy	10/17/2001	6	371	7.7	15.2	<1	<2
PG Ee 56	Magothy	10/17/2001	4	329	7.7	15.6	<1	<2
PG Fb 56	Potomac (Patapsco)	2/6/2002	5	220	7.7	15.6	--	<2
PG Fc 38	Magothy	10/17/2001	5	291	7.9	15.5	<1	<2
PG Fd 71	Magothy	10/17/2001	4.5	259	7.8	16.1	<1	<2
PG Fe 38	Aquia	10/17/2001	6	280	7.8	16.0	<1	<2
PG Fe 39	Aquia	11/14/2001	6	293	7.8	17.0	<1	<2
PG Ff 23	Aquia	10/17/2001	5	306	7.8	15.9	<1	4
PG Ge 21	Aquia	10/17/2001	6	271	7.9	17.0	<1	<2
QA Be 36	Columbia	8/8/2001	5	96	5.0	14.8	9.4	<2
QA Bf 45	Aquia	11/27/2001	8	289	7.6	14.0	<1	<2
QA Ce 38	Magothy (Monmouth)	11/27/2001	4	275	8.0	15.0	<1	4
QA Cf 76	Aquia	11/27/2001	8	324	7.7	14.5	<1	<2
QA Cg 66	Columbia	8/9/2001	4	57	5.6	15.2	7.5	<2
QA Cg 67	Columbia	8/8/2001	4	118	4.8	14.8	3.6	<2
QA Cg 68	Aquia	11/27/2001	6	322	7.9	15.4	<1	30
QA Ch 37	Aquia	4/12/2002	5	348	8.0	15.8	<1	23
QA Db 14	Aquia (Aquia)	3/26/2003	--	439	7.2	14.4	--	<2
QA Db 23	Aquia (Aquia)	3/24/2003	2.4	427	7.3	14.7	--	<2
QA Db 27	Aquia (Aquia)	8/22/2003	2	1,300	6.5	15.0	--	12[1]
QA Db 30	Aquia (Hornerstown)	8/20/2003	5.7	18,000	6.2	16.7	--	6[1]
QA Db 32	Aquia (Aquia)	8/20/2003	4	8,150	6.5	16.2	--	2[1]
QA Db 34	Aquia (Aquia)	8/20/2003	60	499	7.2	15.7	--	E1[1]

Appendix A. Continued

Well number	Aquifer	Date	Flow (gpm)	Specific conductance (µS/cm)	pH	Temperature (°C)	Dissolved oxygen (mg/L)	Arsenic (µg/L)
QA Db 35	Aquia (Hornerstown)	8/22/2003	4	15,400	6.7	17.2	--	<4[1]
QA Db 37	Aquia (Hornerstown)	8/20/2003	5.2	540	7.4	17.1	--	E1[1]
QA Db 46	Magothy	11/16/2001	4.5	273	6.5	16.0	<1	<2
QA Dd 33	Aquia	11/16/2001	6	324	7.9	15.3	<1	17
QA Dd 34	Aquia	11/16/2001	6	347	7.8	15.0	<1	7
QA De 30	Aquia	9/10/2001	490	302	7.8	16.1	<1	26
QA De 45	Aquia	11/27/2001	7.1	296	7.9	15.2	<1	17
QA Df 61	Columbia	8/9/2001	8	202	5.1	16.0	--	<2
QA Dg 44	Miocene (Cheswold)	8/9/2001	4	369	6.9	16.3	<1	<2
QA Ea 39	Aquia (Lower Eocene)	3/19/2003	5	424	7.5	14.8	--	7
QA Ea 42	Aquia (Lower Eocene)	3/26/2003	2	368	7.5	15.0	--	7
QA Ea 45	Aquia (Lower Eocene)	3/27/2003	2.4	347	6.8	14.7	--	<2
QA Ea 48	Aquia (Lower Eocene)	8/27/2003	6	1,570	7.2	16.1	--	9[1]
QA Ea 59	Aquia (Lower Eocene)	3/19/2003	4	569	7.9	15.3	--	4
QA Ea 60	Aquia (Lower Eocene)	4/2/2003	6	1,780	7.5	15.4	--	11[1]
QA Ea 77	Aquia (Aquia)	9/9/2002	--	19,200	7.2	15.8	--	3.5E[1]
QA Ea 78	Aquia (Lower Eocene)	8/13/2001	--	321	7.7	16.3	--	7[1]
QA Ea 79	Aquia (Hornerstown)	8/21/2003	5	358	9.0	17.2	--	E2[1]
QA Ea 80	Aquia (Lower Eocene)	8/21/2003	24	352	7.8	15.3	--	6[1]
QA Ea 81	Aquia (Hornerstown)	8/13/2001	--	574	7.9	16.1	--	<2
QA Ea 82	Aquia (Lower Eocene)	3/28/2003	1.6	1,140	7.6	14.4	--	6
QA Ea 87	Magothy	6/27/2002	8	242	6.1	18.8	<1	<2
QA Eb 144	Aquia (Aquia)	8/27/2003	5	420	7.7	16.2	--	3[1]
QA Eb 155	Aquia (Aquia)	8/21/2003	7	327	7.8	17.2	--	E1[1]
QA Eb 156	Aquia (Aquia)	8/22/2003	6.3	22,000	6.9	16.8	--	6[1]
QA Eb 157	Aquia (Lower Eocene)	8/22/2003	20	338	7.4	15.0	--	6[1]
QA Ec 107	Aquia	11/27/2001	5.7	404	7.8	15.1	<1	6
QA Ed 53	Aquia	11/16/2001	4	280	7.8	15.2	<1	13
QA Ed 54	Aquia	11/16/2001	4	287	7.9	15.5	--	25
QA Ee 33	Piney Point	12/19/2001	6	368	7.8	14.6	<1	7
QA Ef 33	Piney Point	11/27/2001	5	473	8.4	16.1	<1	<2
QA Ef 34	Aquia	11/27/2001	5	425	8.3	16.5	<1	13
QA Fa 54	Aquia (Lower Eocene)	3/19/2003	4	348	7.7	15.6	--	3

Appendix A. Continued

Well number	Aquifer	Date	Flow (gpm)	Specific conductance (µS/cm)	pH	Temperature (°C)	Dissolved oxygen (mg/L)	Arsenic (µg/L)
QA Fa 58	Aquia (Lower Eocene)	3/24/2003	5.5	453	7.9	15.5	--	5
QA Fa 60	Aquia (Lower Eocene)	3/24/2003	1	413	8.3	17.7	--	<2
QA Fa 63	Aquia (Lower Eocene)	3/28/2003	1.9	452	7.1	15.2	--	<2
QA Fa 66	Aquia (Lower Eocene)	3/27/2003	3.8	505	7.7	13.7	--	3
QA Fa 72	Aquia (Lower Eocene)	3/28/2003	4	479	7.9	15.2	--	3
QA Fa 75	Aquia (Lower Eocene)	3/27/2003	--	510	7.9	15.2	--	4
QA Fc 13	Aquia	11/16/2001	5	300	8.0	15.9	<1	42
SM Bb 31	Aquia	10/2/2001	6	281	7.9	18.8	<1	4
SM Bb 32	Aquia	10/2/2001	4	256	8.2	17.4	<1	4
SM Bc 37	Aquia	10/2/2001	2.4	250	8.2	15.6	<1	<2
SM Bc 38	Aquia	10/3/2001	3	254	8.0	18.2	<1	5
SM Bc 39	Potomac (Lower Patapsco)	3/28/2002	67	297	8.4	26.0	--	<0.2
SM Bc 40	Aquia	6/25/2002	137	267	--	18.5	<1	4
SM Cb 31	Aquia	10/3/2001	3	246	8.6	17.1	<1	5
SM Cb 32	Aquia	10/3/2001	4	243	8.6	16.5	<1	4
SM Cb 33	Aquia	10/3/2001	4	249	8.2	17.7	<1	7
SM Cb 34	Aquia	10/3/2001	6	237	8.8	18.4	<1	9
SM Cc 14	Aquia	10/2/2001	6	263	8.1	16.6	<1	<2
SM Cd 36	Piney Point	11/19/2001	6	369	7.9	15.6	<1	<2
SM Cd 46	Piney Point	10/3/2001	4	221	7.9	16.3	<1	<2
SM Ce 47	Aquia	11/20/2001	5	236	8.4	16.0	<1	11
SM Dc 63	Aquia	10/3/2001	4	236	8.8	17.5	<1	8
SM Dd 70	Aquia	8/24/2001	70	197	8.3	18.0	<1	11
SM Dd 72	Potomac (Lower Patapsco)	5/15/2001	70	420	8.3	22.5	--	<0.2
SM Dd 75	Piney Point	10/3/2001	6	323	7.9	16.2	<1	<2
SM Dd 76	Aquia	10/2/2001	4	295	7.9	16.7	--	<2
SM Dd 77	Piney Point	11/19/2001	6.7	299	8.1	16.5	<1	3
SM De 50	Aquia	5/23/2002	70	221	8.6	18.4	<1	9
SM De 57	Piney Point	11/19/2001	6	293	7.9	16.2	<1	<2
SM De 58	Piney Point	11/19/2001	4.8	289	8.0	16.5	<1	4
SM Ed 17	Aquia	5/23/2002	100	284	8.6	19.4	1.1	9
SM Ed 19	Piney Point	11/19/2001	5	308	8.1	17.0	<1	<2
SM Ee 52	Piney Point	11/19/2001	6	315	8.2	17.2	<1	<2

Appendix A. Continued

Well number	Aquifer	Date	Flow (gpm)	Specific conductance (µS/cm)	pH	Temperature (°C)	Dissolved oxygen (mg/L)	Arsenic (µg/L)
SM Ee 53	Piney Point	11/19/2001	5	304	8.1	17.1	<1	<2
SM Ef 86	Piney Point	5/23/2002	100	297	7.8	17.3	<1	<2
SM Ef 91	Piney Point	11/19/2001	3	301	8.2	15.7	<1	<2
SM Ef 92	Piney Point	11/20/2001	4	293	8.1	15.7	<1	<2
SM Ef 93	Piney Point	11/20/2001	5	347	8.3	17.5	<1	<2
SM Eg 34	Piney Point	11/20/2001	6	331	8.1	17.4	<1	<2
SM Fe 41	Aquia	5/23/2002	--	488	8.4	19.9	<1	7
SM Fg 63	Piney Point	11/20/2001	4	580	8.6	16.8	<1	6
SM Fg 64	Piney Point	11/20/2001	5	702	8.6	17.2	<1	5
SM Fg 65	Piney Point	11/20/2001	6	648	8.6	15.6	<1	11
SM Fg 66	Piney Point	11/20/2001	4	454	8.5	15.7	<1	2
SO Af 26	Miocene (Pocomoke)	9/12/2001	3	73	6.1	17.1	<1	2
SO Bd 47	Miocene (Manokin)	5/15/2002	5	472	7.2	16.1	<1	<2
SO Be 113	Miocene (Manokin)	5/15/2002	5	891	7.9	15.9	<1	<2
SO Cd 55	Miocene (Pocomoke)	9/12/2001	4	444	6.3	16.8	<1	<2
SO Cg 7	Miocene (Manokin)	5/15/2002	5	1,731	7.9	16.0	<1	<2
SO Dd 74	Miocene (Manokin)	5/15/2002	7	1,311	7.5	16.6	<1	<2
SO Df 29	Miocene (Pocomoke)	5/15/2002	3	289	6.7	16.1	<1	<2
TA Be 91	Columbia	8/31/2001	6	139	5.0	15.2	7.0	<2
TA Be 92	Piney Point	12/19/2001	6	262	7.8	15.6	<1	18
TA Be 93	Miocene (Cheswold)	4/12/2002	5	367	7.6	15.5	<1	<2
TA Bf 98	Piney Point	4/12/2002	3.5	503	8.3	14.9	<1	<2
TA Cb 99	Aquia	12/19/2001	6	284	7.9	16.2	<1	25
TA Cc 52	Aquia	3/25/2002	6	712	8.0	16.1	--	41
TA Cd 64	Piney Point	12/19/2001	5.5	439	8.2	17.0	<1	24
TA Cd 65	Aquia	3/25/2002	6.3	793	8.4	19.2	--	11
TA Ce 70	Magothy	6/19/2002	750	166	7.3	26.3	<1	<2
TA Ce 79	Aquia	12/19/2001	7.1	792	8.6	19.5	<1	6
TA Cf 25	Miocene (Cheswold)	4/12/2002	7.1	358	7.7	15.4	<1	<2
TA Da 50	Aquia	12/19/2001	6	276	7.8	16.6	<1	15
TA Dc 57	Aquia	3/25/2002	11	552	8.5	18.2	--	14
TA Dc 58	Aquia	3/25/2002	7.5	803	7.9	18.3	--	24
TA De 24	Piney Point	3/25/2002	5	301	8.0	16.7	--	<2

Appendix A. Continued

Well number	Aquifer	Date	Flow (gpm)	Specific conductance (µS/cm)	pH	Temperature (°C)	Dissolved oxygen (mg/L)	Arsenic (µg/L)
WI Bc 67	Miocene (Frederica)	6/20/2002	5	2,461	7.7	16.6	--	2
WI Bg 19	Columbia (Pensauken)	6/20/2002	5	68	--	16.0	--	<2
WI Bh 15	Columbia	10/30/2001	4.6	88	6.1	14.9	<1	<2
WI Cd 96	Miocene (Manokin)	5/15/2002	6	75	5.4	15.4	<1	<2
WI Cf 226	Columbia	9/12/2001	4	76	5.4	14.7	<1	<2
WI Cf 227	Miocene (Manokin)	6/20/2002	6	125	6.0	16.1	<1	<2
WI Cg 59	Columbia	9/12/2001	3	49	6.1	16.1	1.8	<2
WI Dh 16	Miocene (Pocomoke)	6/19/2002	6	111	5.7	15.5	<1	<2
WO Be 34	Columbia	10/30/2001	4	82	6.0	15.5	<1	<2
WO Bf 89	Columbia	10/29/2001	6	197	5.3	14.7	10	<2
WO Bf 90	Columbia	10/29/2001	3	85	5.9	15.5	<1	<2
WO Bf 91	Miocene (Manokin)	7/25/2002	8	413	7.7	15.2	<1	<2
WO Bg 62	Miocene (Manokin)	7/25/2002	--	415	6.6	18.5	<1	<2
WO Ce 32	Columbia	5/13/2002	5	115	6.0	15.5	<1	<2
WO Cf 60	Columbia	10/30/2001	8	195	5.7	14.1	9.6	<2
WO Cg 88	Miocene (Pocomoke)	7/25/2002	--	282	6.7	23.6	<1	<2
WO Db 5	Miocene (Manokin)	5/13/2002	4	415	7.8	16.2	<1	<2
WO Dd 62	Miocene (Manokin)	5/13/2002	8	441	7.6	16.4	<1	<2
WO Dg 26	Miocene (Ocean City)	6/19/2002	40	436	--	18.1	--	<2
WO Ec 43	Miocene (Manokin)	5/13/2002	4	712	8.0	16.4	<1	<2
WO Fc 59	Miocene (Pocomoke)	5/13/2002	6	477	7.4	17.0	<1	<2
WO Fc 60	Miocene (Pocomoke)	6/19/2002	4	440	--	16.9	--	14
WO Fd 34	Columbia	10/29/2001	3	348	5.2	16.2	8.3	<2

[1] Arsenic analysis by graphite furnace–atomic absorption spectrometry at USGS National Water-Quality Laboratory.

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

[deg, degree; min, minute; sec, second; ft amsl, feet above mean sea level; ft bls, feet below land surface]

Well number	Latitude (deg-min-sec)	Longitude (deg-min-sec)	Well permit number	Elevation (ft amsl)	Top of screen (ft bls)	Bottom of screen (ft bls)
AA Bb 89	39-06-45	76-49-24	AA-73-6975	240	117	122
AA Bc 245	39-09-22	76-41-13	AA-94-1453	160	138	145
AA Bc 248	39-08-12	76-44-43	AA-73-9063	280	346	351
AA Be 122	39-06-30	76-31-20	AA-94-1941	75	115	120
AA Bf 94	39-05-13	76-28-16	AA-73-8930	10	60	65
AA Cc 141	39-01-36	76-42-45	AA-94-1663	70	180	187
AA Cd 120	39-02-45	76-38-28	AA-88-8571	100	125	130
AA Cd 128	39-03-27	76-36-37	AA-94-6030	110	370	380
AA Ce 143	39-03-11	76-34-33	AA-92-0664	100	103	110
AA Cf 154	39-02-57	76-26-53	AA-88-9735	20	70	77
AA Cg 27	39-02-04	76-24-31	AA-88-2552	20	240	250
AA Dd 62	38-55-53	76-39-00	AA-81-5604	140	301	308
AA De 214	38-58-15	76-34-45	AA-94-2010	80	203	210
AA De 218	38-55-54	76-34-14	AA-93-0566	25	80	87
AA Ec 16	38-48-50	76-41-35	AA-94-4969	50	148	168
AA Ed 66	38-53-17	76-35-26	AA-92-1357	110	219	226
AA Ee 100	38-50-42	76-32-27	AA-94-3205	5	--	120[1]
AA Fd 61	38-46-58	76-35-48	AA-73-8329	110	220	240
BA Ef 59	39-20-24	76-26-06	BA-94-2207	45	85	92
BA Ff 89	39-15-20	76-26-00	BA-73-7186	15	175	180
CA Ba 15	38-44-45	76-40-37	CA-94-2719	70	260	275
CA Ba 16	38-40-26	76-40-42	CA-88-3267	40	360	370
CA Bb 47	38-43-35	76-39-34	CA-92-1044	120	320	350
CA Bb 50	38-43-10	76-36-17	CA-73-0381	90	328	333
CA Bb 51	38-41-48	76-37-59	CA-88-4172	100	390	410
CA Bb 52	38-40-25	76-35-37	CA-73-3395	150	440	450
CA Bc 38	38-42-17	76-32-05	CA-73-1232	15	109[2]	205[2]
CA Bc 52	38-42-20	76-34-25	CA-88-0679	140	410	420
CA Ca 15	38-37-33	76-40-16	CA-94-2137	40	394	424
CA Cb 42	38-35-20	76-39-07	CA-88-3519	100	480	495
CA Cb 43	38-36-52	76-36-50	CA-81-1407	160	395	405
CA Cc 70	38-39-18	76-34-34	CA-81-2663	100	305	315
CA Cc 71	38-37-46	76-32-06	CA-94-0550	150	273	280
CA Cc 72	38-35-22	76-32-47	CA-94-0065	140	283	290
CA Db 91	38-30-43	76-37-51	CA-88-2198	50	447	462
CA Db 93	38-33-23	76-37-12	CA-94-1194	100	470	480
CA Db 95	38-31-22	76-37-07	CA-81-2274	150	300	310
CA Db 96	38-32-44	76-35-42	CA-94-4191	140	930	960
CA Dc 37	38-34-03	76-31-41	CA-73-1780	110	555	595
CA Dc 54	38-33-11	76-33-45	CA-92-0631	140	280	295
CA Eb 22	38-26-20	76-35-29	CA-43-4069	25	208	223
CA Ec 44	38-27-15	76-32-54	CA-92-0416	120	325	345
CA Ec 46	38-28-52	76-30-30	CA-73-0295	120	237[2]	361[2]
CA Ec 48	38-29-42	76-32-12	CA-81-0284	150	437	442
CA Ec 49	38-28-22	76-30-37	CA-94-2436	130	581	601
CA Ed 53	38-26-38	76-29-59	CA-81-1391	110	370	380
CA Fd 77	38-21-45	76-26-58	CA-88-0346	50	370	380
CA Fd 78	38-23-08	76-25-21	CA-73-4259	120	413	433

Appendix B. Continued

Well number	Latitude (deg-min-sec)	Longitude (deg-min-sec)	Well permit number	Elevation (ft amsl)	Top of screen (ft bls)	Bottom of screen (ft bls)
CA Fd 79	38-24-20	76-26-36	CA-73-4408	100	240[2]	445[2]
CA Fd 85	38-22-36	76-25-54	CA-94-3305	106	1,535	1,633
CA Fd 86	38-22-31	76-26-00	CA-88-3340	110	604	684
CA Fd 87	38-20-32	76-25-07	CA-94-0409	80	560	640
CE Ce 60	39-30-11	75-53-21	CE-73-3929	70	107	112
CE Ce 83	39-33-02	75-53-13	CE-81-3426	80	83	88
CE Cf 81	39-33-41	75-48-21	CE-73-1915	80	35	36
CE Ee 54	39-23-41	75-50-37	CE-88-1305	80	315	325
CH Bd 54	38-35-02	77-00-51	CH-94-1569	180	819	839
CH Be 69	38-35-11	76-57-55	CH-81-2539	200	419	434
CH Bg 15	38-35-46	76-47-24	CH-94-0377	190	410	430
CH Bg 17	38-37-06	76-47-54	CH-94-5325	199	1,299	1,343
CH Cc 38	38-31-43	77-08-33	CH-88-1346	150	620	640
CH Cf 35	38-32-17	76-51-15	CH-93-0284	180	450	470
CH Cf 36	38-32-42	76-54-37	CH-81-0554	190	410	420
CH Cf 37	38-34-36	76-54-14	CH-81-2268	190	430	445
CH Cg 22	38-31-55	76-47-39	CH-94-2394	180	520	540
CH Cg 23	38-34-38	76-49-49	CH-88-0527	180	410	430
CH Cg 24	38-32-54	76-48-14	CH-94-4194	182	795	835
CH Ch 19	38-31-27	76-43-42	CH-94-3169	130	400	420
CH Ch 20	38-32-56	76-44-30	CH-94-3009	160	502	517
CH Db 14	38-28-25	77-12-05	CH-88-0097	80	480	500
CH Dc 22	38-28-43	77-08-51	CH-81-1524	130	260	270
CH De 47	38-28-45	76-59-49	CH-81-0658	140	340	360
CH De 48	38-25-47	76-58-11	CH-94-3019	130	386	406
CH De 49	38-29-37	76-55-53	CH-94-3218	50	365	375
CH Df 18	38-29-51	76-52-03	CH-94-1422	180	460	480
CH Ee 93	38-21-53	76-56-42	CH-92-0066	120	378	399
CH Ef 18	38-24-19	76-52-17	CH-94-1097	100	380	390
CH Ff 63	38-18-36	76-53-41	CH-93-0027	10	300	310
CO Ad 19	39-07-20	75-46-35	--	70	--	20[1]
CO Bc 21	39-01-10	75-53-08	CO-94-0540	50	110	125
CO Bd 57	39-02-04	75-49-23	CO-81-1724	60	285	300
CO Bd 58	39-01-28	75-45-17	CO-94-1448	50	340	360
CO Cc 55	38-55-58	75-53-36	CO-73-0409	60	59	61
CO Cc 104	38-55-25	75-51-18	CO-94-0910	60	360	380
CO Cd 50	38-59-23	75-49-01	CO-81-1377	40	180	200
CO Cd 54	38-55-57	75-48-12	CO-73-0695	50	35	45
CO Cd 65	38-57-44	75-48-08	CO-94-0773	40	365	395
CO Dd 76	38-54-14	75-49-30	CO-88-0679	30	20	26
CO Dd 77	38-51-24	75-48-42	CO-81-1641	40	360	380
CO Dd 78	38-54-57	75-48-53	CO-94-1672	25	393	423
CO De 17	38-53-54	75-43-50	CO-94-0330	60	430	450
CO Ec 34	38-46-48	75-51-52	CO-94-0818	50	420	440
CO Ec 35	38-49-14	75-50-40	CO-94-0933	50	195	215
CO Ed 36	38-49-03	75-45-13	CO-70-0081	55	40	50
CO Ed 37	38-47-37	75-49-25	CO-94-0204	50	200	440
CO Ee 21	38-47-02	75-43-44	CO-81-1738	40	230	250
CO Fd 39	38-41-02	75-45-33	CO-81-1247	30	40	45
DO Ag 12	38-41-10	75-53-43	DO-88-1419	25	135	155

Well number	Latitude (deg-min-sec)	Longitude (deg-min-sec)	Well permit number	Elevation (ft amsl)	Top of screen (ft bls)	Bottom of screen (ft bls)
DO Ah 12	38-40-02	75-47-57	DO-88-1052	30	53	58
DO Bc 33	38-35-05	76-11-07	DO-92-0791	5	560	580
DO Bg 74	38-36-08	75-50-18	DO-88-0413	35	45	75
DO Cb 9	38-30-04	76-17-33	DO-88-0131	10	540	560
DO Cc 54	38-34-37	76-14-50	DO-94-0024	5	505	525
DO Cc 55	38-30-09	76-14-13	DO-94-0026	5	524	544
DO Cc 56	38-30-46	76-12-37	DO-88-0648	5	555	565
DO Cd 55	38-33-50	76-09-10	DO-94-0065	10	382	402
DO Ce 91	38-31-01	76-04-53	DO-88-1531	5	440	460
DO Cf 39	38-31-33	75-58-05	DO-81-1249	15	461	481
DO Cf 40	38-34-59	75-55-33	DO-88-1525	35	148	158
DO Cf 41	38-34-08	75-58-57	DO-92-0622	20	440	460
DO Ci 8	38-34-03	75-43-17	DO-92-0663	20	80	90
DO Ci 9	38-33-47	75-44-16	DO-88-1492	15	194	206
DO Dg 28	38-25-50	75-54-35	DO-88-0356	10	265	285
DO Dg 29	38-27-22	75-53-30	DO-88-0427	10	605	630
DO Ec 22	38-23-26	76-12-16	DO-88-0652	5	360	380
DO Ed 17	38-20-58	76-05-20	DO-92-0780	5	460	480
DO Fc 27	38-15-51	76-10-56	DO-88-1702	10	420	440
DO Fd 17	38-17-02	76-05-25	DO-00-6321	5	465	504
HA Dc 120	39-25-37	76-21-07	HA-81-0045	130	87	107
HA De 166	39-26-58	76-13-55	HA-81-2322	17	131	140
KE Ad 60	39-20-02	76-04-35	KE-81-0330	80	120	140
KE Ad 70	39-20-39	76-01-12	KE-71-0074	75	184	195
KE Ae 70	39-21-46	75-58-06	KE-92-0018	65	228	238
KE Bb 14	39-16-06	76-12-02	KE-81-0077	25	62	72
KE Bd 81	39-17-50	76-03-54	KE-73-0674	75	37	42
KE Bd 87	39-17-37	76-03-42	KE-02-9953	70	247	257
KE Bd 129	39-16-00	76-02-50	KE-66-0125	50	80	115
KE Bg 63	39-18-28	75-49-38	KE-81-0776	70	50	60
KE Bg 106	39-16-06	75-47-54	KE-94-0465	60	90	100
KE Cb 41	39-13-08	76-10-03	KE-73-1009	90	86	96
KE Cc 39	39-12-57	76-08-39	KE-81-1146	75	50	60
PG Bd 44	39-03-03	76-50-05	PG-81-0842	200	258	265
PG Bd 45	39-02-21	76-52-44	PG-94-0134	160	222	253
PG Be 36	39-01-03	76-45-02	PG-94-1013	90	233	238
PG Ce 43	38-55-39	76-45-37	PG-88-2804	150	201	206
PG Ce 47	38-56-03	76-48-07	PG-81-0002	140	130	137
PG De 34	38-51-29	76-45-37	PG-92-0940	110	216	224
PG Df 44	38-53-10	76-42-22	PG-81-0832	120	270	280
PG Ec 49	38-46-58	76-58-23	PG-94-0747	170	410	425
PG Ee 55	38-48-30	76-48-37	PG-81-1942	160	303	313
PG Ee 56	38-48-17	76-45-43	PG-94-0409	180	350	360
PG Fb 56	38-41-11	77-04-11	PG-81-0470	155	398	413
PG Fc 38	38-43-18	76-55-48	PG-88-3320	210	325	340
PG Fd 71	38-44 38	76-52-20	PG-81-1884	220	410	425
PG Fe 38	38-44-38	76-46-35	PG-81-1249	200	315	330
PG Fe 39	38-40-34	76-48-21	PG-94-1424	225	435	455
PG Ff 23	38-42-43	76-44-53	PG-92-0616	140	340	360
PG Ge 21	38-38-32	76-45-54	PG-81-0721	200	410	425

Well number	Latitude (deg-min-sec)	Longitude (deg-min-sec)	Well permit number	Elevation (ft amsl)	Top of screen (ft bls)	Bottom of screen (ft bls)
QA Be 36	39-12-55	76-00-56	QA-81-0601	30	70	80
QA Bf 45	39-11-38	75-57-38	QA-88-1277	60	150	160
QA Ce 38	39-06-47	76-01-47	QA-94-0348	60	363	393
QA Cf 76	39-08-38	75-59-07	QA-88-1926	40	170	180
QA Cg 66	39-06-08	75-51-00	QA-73-2655	70	44	54
QA Cg 67	39-08-50	75-53-32	QA-73-3248	70	27	33
QA Cg 68	39-08-39	75-51-56	QA-94-1322	70	270	290
QA Ch 37	39-08-56	75-47-42	QA-88-1883	80	325	340
QA Db 14	39-00-55	76-18-45	QA-73-2453	15	145	165
QA Db 23	39-00-33	76-18-45	QA-73-2961	18	165	185
QA Db 27	39-01-16	76-19-08	QA-66-0101	15	110	145
QA Db 30	39-02-01	76-18-27	QA-81-0473	18	210	220
QA Db 32	39-02-01	76-18-27	QA-81-0473	18	106	116
QA Db 34	39-00-23	76-17-43	QA-81-0471	7	170	180
QA Db 35	39-01-19	76-19-10	QA-81-0472	7	190	200
QA Db 37	39-00-23	76-17-43	QA-81-0471	7	240	250
QA Db 46	39-00-53	76-18-21	QA-88-1818	15	390	410
QA Dd 33	39-01-38	76-06-48	QA-88-2088	60	270	280
QA Dd 34	39-01-33	76-08-50	QA-73-3626	25	180	200
QA De 30	39-02-21	76-03-14	QA-67-W-30	55	272[2]	448[2]
QA De 45	39-03-46	76-03-22	QA-81-3082	60	220	240
QA Df 61	39-01-28	75-57-45	QA-81-1549	60	--	45[1]
QA Dg 44	39-02-35	75-54-22	QA-94-0512	70	90	110
QA Ea 39	38-58-25	76-20-29	QA-73-3240	15	80	95
QA Ea 42	38-58-25	76-20-25	QA-73-2611	18	100	120
QA Ea 45	38-55-54	76-21-38	QA-73-2731	15	200	210
QA Ea 48	38-58-25	76-20-12	QA-73-0747	5	129	160
QA Ea 59	38-55-05	76-21-50	QA-73-2746	10	195	215
QA Ea 60	38-57-01	76-21-25	QA-73-1361	7	165	185
QA Ea 77	38-57-18	76-21-15	QA-81-0474	11	195	205
QA Ea 78	38-57-18	76-21-15	QA-81-0474	12	125	135
QA Ea 79	38-57-57	76-20-01	QA-81-0469	8	288	298
QA Ea 80	38-57-57	76-20-01	QA-81-0469	8	120	130
QA Ea 81	38-57-18	76-21-15	QA-81-0474	12	300	310
QA Ea 82	38-57-05	76-21-20	QA-81-2169	10	155	170
QA Ea 87	38-55-02	76-20-54	QA-81-1950	5	595	615
QA Eb 144	38-58-47	76-18-48	QA-73-1817	15	220	240
QA Eb 155	38-58-43	76-15-53	QA-81-0470	4	235	245
QA Eb 156	38-58-52	76-19-52	QA-81-0475	12	210	220
QA Eb 157	38-58-52	76-19-52	QA-81-0475	12	110	120
QA Ec 107	38-57-37	76-12-52	QA-92-0451	5	--	240[1]
QA Ed 53	38-58-53	76-08-18	QA-73-1551	50	273	280
QA Ed 54	38-56-33	76-09-47	QA-81-2298	10	320	330
QA Ee 33	38-57-24	76-04-41	QA-73-2985	60	195	215
QA Ef 33	38-55-24	75-57-30	QA-88-1638	40	269	279
QA Ef 34	38-59-25	75-58-57	QA-73-2008	70	420	440
QA Fa 54	38-50-24	76-22-25	QA-73-1131	10	240	260
QA Fa 58	38-51-33	76-20-12	QA-81-0002	7	260	280
QA Fa 60	38-52-54	76-20-19	QA-73-2330	10	230	240
QA Fa 63	38-54-34	76-21-56	QA-73-0220	15	200	235

Well number	Latitude (deg-min-sec)	Longitude (deg-min-sec)	Well permit number	Elevation (ft amsl)	Top of screen (ft bls)	Bottom of screen (ft bls)
QA Fa 66	38-52-36	76-21-52	QA-73-2988	13	250	270
QA Fa 72	38-52-54	76-20-13	QA-81-0241	12	200	220
QA Fa 75	38-51-55	76-20-04	QA-73-3334	10	180	200
QA Fc 13	38-54-33	76-10-51	QA-73-2200	10	330	350
SM Bb 31	38-27-53	76-46-47	SM-93-0123	160	526	540
SM Bb 32	38-24-44	76-49-25	SM-88-2512	150	469	490
SM Bc 37	38-29-44	76-43-46	SM-73-2063	80	385	405
SM Bc 38	38-26-30	76-44-38	SM-94-1880	160	470	485
SM Bc 39	38-26-05	76-43-02	SM-94-3921	162	1,492	1,512
SM Bc 40	38-28-05	76-41-55	SM-88-1131	140	515	555
SM Cb 31	38-20-27	76-48-08	SM-81-3686	80	376	390
SM Cb 32	38-22-30	76-49-13	SM-73-4092	120	465	480
SM Cb 33	38-22-53	76-45-47	SM-88-2118	100	465	485
SM Cb 34	38-20-18	76-45-03	SM-92-0066	120	470	490
SM Cc 14	38-23-18	76-43-16	SM-73-1795	120	437	457
SM Cd 36	38-21-03	76-37-27	SM-94-0715	120	345	355
SM Cd 46	38-23-48	76-38-48	SM-93-0415	140	311	325
SM Ce 47	38-22-08	76-33-43	SM-94-2522	70	540	555
SM Dc 63	38-18-00	76-44-45	SM-88-0435	45	350	370
SM Dd 70	38-19-21	76-37-26	SM-92-0701	125	450[3]	545[3]
SM Dd 72	38-16-26	76-39-35	SM-94-3616	110	1,300	1,330
SM Dd 75	38-19-23	76-36-39	SM-88-0755	130	350	365
SM Dd 76	38-17-07	76-39-58	SM-73-0683	120	460	480
SM Dd 77	38-15-29	76-35-57	SM-94-2721	100	330	340
SM De 50	38-18-27	76-31-54	SM-81-0060	130	560	585
SM De 57	38-17-54	76-30-02	SM-81-1702	110	340	354
SM De 58	38-17-03	76-33-31	SM-81-1025	110	362	376
SM Ed 17	38-14-55	76-36-14	SM-81-2634	85	510	570
SM Ed 19	38-13-53	76-35-22	SM-81-1991	100	345	355
SM Ee 52	38-11-52	76-33-35	SM-88-2563	15	235	250
SM Ee 53	38-13-53	76-32-48	SM-81-3747	90	365	375
SM Ef 86	38-13-27	76-26-56	SM-88-0280	85	355	375
SM Ef 91	38-12-49	76-29-12	SM-73-0916	85	314	360
SM Ef 92	38-14-09	76-27-35	SM-88-0578	80	360	375
SM Ef 93	38-10-57	76-27-49	SM-81-1517	100	374	395
SM Eg 34	38-13-39	76-24-32	SM-88-1891	110	412	426
SM Fe 41	38-08-33	76-30-33	SM-81-3684	8	400	420
SM Fg 63	38-09-38	76-21-38	SM-94-3292	30	400	420
SM Fg 64	38-05-48	76-21-13	SM-81-3126	15	365	375
SM Fg 65	38-06-40	76-23-39	SM-94-1816	10	350	364
SM Fg 66	38-09-01	76-24-57	SM-81-2543	25	325	335
SO Af 26	38-15-35	75-39-17	SO-94-0243	30	65	75
SO Bd 47	38-14-40	75-49-30	SO-94-0545	10	115	125
SO Be 113	38-10-35	75-41-28	SO-92-0238	15	180	200
SO Cd 55	38-07-03	75-46-17	SO-81-1903	5	55	65
SO Cg 7	38-05-53	75-33-43	SO-81-1228	10	240	270
SO Dd 74	38-00-38	75-49-54	SO-94-0798	5	130	155
SO Df 29	38-03-52	75-38-16	SO-68-0011	15	88	100
TA Be 91	38-51-54	76-00-38	TA-81-0414	70	26	31
TA Be 92	38-54-08	76-02-47	TA-88-0311	60	260	280

Well number	Latitude (deg-min-sec)	Longitude (deg-min-sec)	Well permit number	Elevation (ft amsl)	Top of screen (ft bls)	Bottom of screen (ft bls)
TA Be 93	38-51-12	76-01-17	TA-88-1593	70	220	235
TA Bf 98	38-52-21	75-56-48	TA-88-1516	40	300	340
TA Cb 99	38-46-02	76-16-39	TA-73-1324	5	349	379
TA Cc 52	38-49-01	76-13-36	TA-94-0083	10	400	420
TA Cd 64	38-48-15	76-06-47	TA-73-1606	10	320	360
TA Cd 65	38-46-49	76-05-48	TA-88-1378	15	585	595
TA Ce 70	38-47-17	76-04-43	TA-81-1967	25	1,143	1,184
TA Ce 79	38-48-30	76-02-27	TA-94-1485	60	663	682
TA Cf 25	38-49-03	75-57-13	TA-94-0057	40	245	260
TA Da 50	38-43-12	76-20-17	TA-94-1347	5	360	380
TA Dc 57	38-44-40	76-10-49	TA-88-1058	5	508	528
TA Dc 58	38-40-10	76-10-20	TA-94-1473	5	555	575
TA De 24	38-41-47	76-03-45	TA-88-1281	50	363	403
WI Bc 67	38-29-33	75-45-15	WI-81-0955	15	270	290
WI Bg 19	38-26-30	75-28-33	WI-81-4464	65	135	140
WI Bh 15	38-25-19	75-24-19	WI-92-0513	50	80	90
WI Cd 96	38-21-21	75-42-03	WI-94-2987	20	156	166
WI Cf 226	38-24-18	75-31-42	WI-94-4039	50	63	73
WI Cf 227	38-22-25	75-33-17	WI-88-1288	45	130	140
WI Cg 59	38-20-33	75-27-58	WI-88-1212	40	70	75
WI Dh 16	38-17-36	75-22-35	WI-94-3906	25	100	110
WO Be 34	38-23-22	75-17-30	WI-94-0834	30	74	80
WO Bf 89	38-23-42	75-11-45	WO-73-2074	20	46	56
WO Bf 90	38-21-48	75-11-38	WO-81-1086	25	70	80
WO Bf 91	38-20-36	75-12-38	WO-93-0127	35	267	287
WO Bg 62	38-24-30	75-06-22	WO-94-1612	5	320	340
WO Ce 32	38-15-18	75-17-47	WO-94-1239	30	65	70
WO Cf 60	38-17-13	75-13-58	WO-94-2244	35	90	100
WO Cg 88	38-18-42	75-07-09	WO-93-0647	10	197	217
WO Db 5	38-13-02	75-33-47	WO-81-0218	40	220	240
WO Dd 62	38-11-10	75-24-08	WO-94-2239	15	290	310
WO Dg 26	38-14-54	75-09-21	WO-93-0322	10	260	315
WO Ec 43	38-09-34	75-28-38	WO-81-0318	30	295	320
WO Fc 59	38-04-52	75-26-35	WO-88-0868	20	135	160
WO Fc 60	38-03-23	75-25-04	WO-94-0090	30	210	230
WO Fd 34	38-03-38	75-24-13	--	15	--	17[1]

[1] Bottom of well (open interval unavailable)
[2] Open hole
[3] Multiple screens

Appendix C. Water-quality analyses from the Aquia and Piney Point aquifers

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter;
--, not reported; <, less than. All analyses for total phosphorus and orthophosphorus were below the detection level of 0.2 mg/L, as P]

Well number	Date	pH	Temperature (°C)	Specific conductance (µS/cm)	Total dissolved solids (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sulfate (mg/L)	Alkalinity (mg/L as CaCO$_3$)
Aquia aquifer											
AA De 218	8/7/2002	7.1	13.6	298	189	1.08	3.21	58.8	1.04	<10	148
CA Ba 15	12/10/2002	7.8	15.0	286	188	4.24	7.18	38.9	11.0	11.6	151
CA Ca 15	9/23/2002	7.7	17.0	302	180	4.10	11.7	31.6	14.7	13.0	157
CA Db 93	12/2/2002	7.9	16.7	273	166	6.78	15.1	22.5	12.8	12.7	142
CA Ec 49	12/10/2002	7.9	18.4	278	163	17.2	14.9	17.4	11.1	<10	140
CA Fd 87	12/10/2002	8.8	18.5	266	158	60	5.31	2.33	<1	<10	133
CH Cg 23	11/25/2002	7.8	16.4	266	164	4.73	11.1	27.4	11.5	18.1	122
CH Ch 19	11/25/2002	8.0	17.4	--	146	6.37	14.3	19.8	10.7	16.0	116
CH De 48	12/17/2002	8.8	16.3	296	211	77.1	5.31	1.76	<1	11.2	158
CH Df 18	12/17/2002	8.0	16.1	248	169	9.69	12.9	26.8	9.76	14.5	118
DO Bc 33	10/29/2002	8.5	19.1	477	300	115	7.33	2.74	1.10	11.7	244
DO Cc 54	10/29/2002	8.5	18.6	310	190	58.1	10.2	5.60	2.11	<10	127
DO Cc 55	10/30/2002	8.4	19.0	--	220	73.6	9.20	5.35	2.50	11.9	176
KE Bg 106	12/18/2002	7.5	13.0	285	209	5.25	3.13	45.6	8.19	<10	146
PG Ff 23	11/25/2002	7.8	15.7	300	182	3.80	7.92	40.4	9.63	10.8	155
QA Cg 68	9/30/2002	7.9	17.9	320	200	8.59	12.1	35.8	13.2	<10	174
QA Ch 37	9/30/2002	8.0	16.2	346	220	51.1	12.4	15.0	7.42	<10	188
QA Dd 33	10/1/2002	7.8	15.8	320	194	6.05	13.2	37.1	12.7	<10	174
QA De 30	12/12/2002	8.0	15.5	306	180	15.7	11.9	26.5	10.4	<10	148
QA De 45	9/30/2002	7.8	15.9	292	180	4.97	12.5	34.0	10.6	<10	153
QA Ea 77	9/9/2002	7.1	16.6	18,350	12,056	1,300	37.0	1,860	362	492	62
QA Ea 78	9/9/2002	7.6	16.5	335	190	11.6	3.89	41.8	7.69	<10	167
QA Ea 81	8/20/2002	7.6	18.1	579	326	47.1	5.00	44.8	5.46	83.4	104
QA Ed 53	11/18/2002	7.7	15.0	284	190	4.00	9.11	38.2	8.84	<10	144
QA Ed 54	10/1/2002	7.9	16.6	282	180	13.7	13.7	25.2	10.5	<10	150
QA Ef 34	10/1/2002	8.2	16.9	421	274	91.2	8.49	7.06	3.08	<10	232
QA Fc 13	11/19/2002	8.0	15.7	--	174	29.5	12.2	19.1	8.80	<10	152
SM Bc 38	12/2/2002	8.0	14.4	264	158	13.3	15.5	18.2	9.68	15.0	126
SM Cb 33	12/16/2002	8.2	15.8	246	168	30.3	16.0	13.6	6.52	11.1	125
SM Ce 47	12/3/2002	8.4	15.4	220	150	32.5	13.8	9.59	4.37	<10	113
SM Dc 63	12/3/2002	8.9	16.0	222	154	54.2	6.45	3.63	<1	12.3	117
SM Dd 70	12/16/2002	8.6	17.1	207	149	35.1	8.85	7.62	2.43	12.5	96
SM Fe 41	12/16/2002	8.6	19.7	484	317	122	7.89	2.70	1.27	12.0	248
TA Cb 99	11/4/2002	7.9	16.1	297	171	17.6	16.0	22.1	13.8	<10	141
TA Cc 52	11/6/2002	7.9	16.5	710	412	137	15.3	13.1	8.20	13.7	221
TA Cd 65	11/19/2002	8.3	18.6	772	490	190	9.34	2.89	2.55	15.0	427
TA Ce 79	11/18/2002	8.5	19.5	792	534	214	7.66	2.45	<1	16.2	444
TA Da 50	11/4/2002	7.8	16.5	287	176	9.74	14.9	24.7	12.2	<10	143
TA Dc 57	11/20/2002	8.5	17.5	--	341	126	10.8	4.15	2.65	17.0	277
TA Dc 58	11/20/2002	8.0	--	657	598	154	18.3	25.5	18.0	155.2	320

Chloride (mg/L)	Fluoride (mg/L)	Silica (mg/L as SiO$_2$)	Manganese (mg/L)	Iron (mg/L)	N0$_2$+NO$_3$ (mg/L as N)	Nitrite (mg/L as N)	Ammonia (mg/L as N)	Total organic carbon (mg/L)	Arsenic (µg/L as As)	Well number
<10	<0.1	13.8	<0.05	0.65	<0.2	<0.002	<0.2	<0.5	<2	AA De 218
<10	0.20	7.49	<0.05	0.14	<0.2	<0.002	0.2	0.67	<2	CA Ba 15
<10	0.18	8.0	<0.05	0.26	<0.2	<0.002	0.3	0.63	4	CA Ca 15
<10	0.18	6.62	<0.05	<0.1	<0.2	<0.002	0.3	0.70	13	CA Db 93
<10	0.23	4.51	<0.05	<0.1	<0.2	0.002	0.3	0.62	5	CA Ec 49
<10	0.35	5.89	<0.05	<0.1	<0.2	0.003	0.3	0.52	13	CA Fd 87
<10	0.20	6.72	<0.05	<0.1	<0.2	0.002	0.4	0.55	<2	CH Cg 23
<10	0.19	5.78	<0.05	<0.1	<0.2	0.002	0.3	0.5	6	CH Ch 19
<10	0.35	5.50	<0.05	<0.1	<0.2	<0.002	<0.2	0.63	<2	CH De 48
<10	0.22	6.49	<0.05	<0.1	<0.2	<0.002	<0.2	<0.5	2	CH Df 18
<10	1.25	5.80	<0.05	<0.1	<0.2	<0.002	0.2	0.58	13	DO Bc 33
21	0.35	6.22	<0.05	<0.1	<0.2	<0.002	0.2	<0.5	18	DO Cc 54
<10	0.62	6.10	<0.05	<0.1	<0.2	<0.002	0.2	0.56	13	DO Cc 55
<10	0.29	17.0	0.09	1.01	<0.2	0.002	0.4	1.06	<2	KE Bg 106
<10	0.22	6.89	<0.05	0.18	<0.2	<0.002	0.3	0.95	5	PG Ff 23
<10	0.54	7.25	<0.05	0.14	<0.2	0.002	0.5	0.61	24	QA Cg 68
<10	1.14	5.80	<0.05	<0.1	<0.2	<0.002	0.7	0.64	22	QA Ch 37
<10	0.29	7.75	<0.05	0.19	<0.2	<0.002	0.6	0.59	12	QA Dd 33
<10	0.47	8.69	<0.05	0.14	<0.2	0.002	0.7	0.70	26	QA De 30
<10	0.26	8.25	<0.05	0.14	<0.2	<0.002	0.6	0.51	14	QA De 45
6,390	<0.1	9.5	0.61	15.0	<0.2	0.021	1.4	1.2	21	QA Ea 77
<10	<0.1	14.0	<0.05	1.26	<0.2	0.002	1.0	0.93	6	QA Ea 78
53	0.19	9.25	<0.05	0.57	<0.2	<0.002	<0.2	0.56	<2	QA Ea 81
<10	0.30	14.15	<0.05	<0.1	<0.2	0.003	0.2	0.86	11	QA Ed 53
<10	0.72	7.12	<0.05	0.12	<0.2	<0.002	0.6	<0.5	21	QA Ed 54
<10	2.52	6.00	<0.05	<0.1	<0.2	<0.002	0.6	0.65	14	QA Ef 34
<10	1.28	6.75	<0.05	0.11	<0.2	0.003	0.4	0.77	36	QA Fc 13
<10	0.21	6.52	<0.05	<0.1	<0.2	0.008	0.3	<0.5	5	SM Bc 38
<10	0.16	6.70	<0.05	<0.1	<0.2	<0.002	<0.2	<0.5	8	SM Cb 33
<10	0.17	4.28	<0.05	<0.1	<0.2	0.005	0.3	<0.5	11	SM Ce 47
<10	0.19	4.95	<0.05	<0.1	<0.2	0.005	0.2	<0.5	8	SM Dc 63
<10	0.20	5.82	<0.05	<0.1	<0.2	<0.002	0.2	<0.5	12	SM Dd 70
<10	0.83	6.20	<0.05	<0.1	<0.2	<0.002	0.2	<0.5	7	SM Fe 41
<10	0.25	6.80	<0.05	<0.1	<0.2	0.094	0.2	0.87	22	TA Cb 99
91	0.42	7.75	<0.05	<0.1	<0.2	0.010	0.3	0.68	36	TA Cc 52
<10	3.76	7.00	<0.05	<0.1	<0.2	0.002	0.2	0.68	9	TA Cd 65
<10	3.66	7.25	<0.05	<0.1	<0.2	0.004	0.3	0.94	5	TA Ce 79
<10	0.23	7.20	<0.05	0.16	<0.2	0.007	0.2	0.76	12	TA Da 50
10	0.94	7.45	<0.05	<0.1	<0.2	0.003	0.3	0.54	13	TA Dc 57
44	1.20	14.0	<0.05	<0.1	<0.2	0.003	0.4	1.00	24	TA Dc 58

Appendix C. Water-quality analyses from the Aquia and Piney Point aquifers - Continued

Well number	Date	pH	Temp- erature (°C)	Specific conduc- tance (µS/cm)	Total dissolved solids (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Sulfate (mg/L)	Alkalinity (mg/L as CaCO$_3$)
Piney Point aquifer											
CA Db 95	9/24/2002	7.8	17.9	247	188	2.40	8.48	32.9	7.60	13.3	129
CA Ed 53	12/2/2002	8.0	15.5	246	172	4.13	14.7	20.9	11.1	15.4	118
CA Fd 77	9/23/2002	8.3	16.8	--	222	65.4	10.6	7.44	3.95	14.5	180
CO Bd 57	12/18/2002	8.4	15.3	634	444	171	7.31	3.86	2.21	<10	371
CO Cd 65	12/18/2002	8.4	15.8	744	526	204	7.02	3.52	2.23	16.4	431
CO Ec 34	11/18/2002	8.1	16.7	439	292	94.7	9.14	9.09	4.85	<10	235
DO Cd 55	10/29/2002	8.2	15.7	752	493	185	8.90	4.72	3.02	19.9	405
DO Ce 91	11/20/2002	8.5	17.0	--	496	187	8.34	3.97	2.41	25.4	410
DO Cf 39	10/30/2002	7.9	17.9	--	832	314	12.9	6.92	5.66	53.1	608
DO Ed 17	11/13/2002	8.1	18.4	--	736	288	13.7	6.75	6.23	37.6	506
DO Fc 27	10/30/2002	8.0	18.4	--	613	228	11.0	7.60	4.88	29.9	456
QA Ee 33	11/19/2002	7.8	14.6	389	258	11.4	14.5	43.1	14.0	<10	207
SM Dd 77	12/3/2002	8.0	16.4	--	196	18.0	22.4	22.2	9.86	14.8	139
SM Eg 34	12/4/2002	8.1	17.7	330	222	38.8	14.6	14.8	8.56	14.0	156
SM Fg 64	12/4/2002	8.6	--	--	424	176	7.96	3.26	1.57	<10	362
SM Fg 65	12/4/2002	8.6	16.6	663	392	152	7.48	2.47	1.61	<10	340
TA Be 92	11/6/2002	7.8	15.3	277	197	7.15	13.0	26.6	12.9	<10	140
TA Bf 98	11/13/2002	8.4	15.3	505	360	123	7.52	5.13	2.04	13.1	279
TA Cd 64	11/4/2002	8.1	16.7	457	290	86.4	16	10.6	8.09	<10	232
TA De 24	11/6/2002	7.9	17.4	298	230	33.3	9.48	18.5	9.69	11.3	155

Appendix C. Continued

Chloride (mg/L)	Fluoride (mg/L)	Silica (mg/L as SiO$_2$)	Manganese (mg/L)	Iron (mg/L)	N0$_2$+NO$_3$ (mg/L as N)	Nitrite (mg/L as N)	Ammonia (mg/L as N)	Total organic carbon (mg/L)	Arsenic (µg/L as As)	Well number
<10	0.24	27.2	<0.05	<0.1	<0.2	<0.002	0.2	<0.5	<2	CA Db 95
<10	0.29	18.28	<0.05	<0.1	<0.2	<0.002	0.3	0.53	4	CA Ed 53
<10	0.57	8.6	<0.05	<0.1	<0.2	<0.002	0.3	0.64	4	CA Fd 77
<10	2.30	12.28	<0.05	<0.1	<0.2	<0.002	0.4	1.30	8	CO Bd 57
<10	1.38	16.22	<0.05	<0.1	<0.2	<0.002	0.2	1.69	2	CO Cd 65
<10	0.72	11	<0.05	<0.1	<0.2	0.006	0.3	0.76	5	CO Ec 34
<10	1.21	14.18	<0.05	<0.1	<0.2	<0.002	0.2	1.00	<2	DO Cd 55
<10	1.34	9.58	<0.05	<0.1	<0.2	0.003	0.2	0.94	2	DO Ce 91
46	1.36	8.3	<0.05	<0.1	<0.2	<0.002	0.3	1.40	10	DO Cf 39
74	1.36	6.75	<0.05	<0.1	<0.2	0.007	0.3	1.15	14	DO Ed 17
41	1.34	10.25	<0.05	<0.1	<0.2	<0.002	0.3	1.09	7	DO Fc 27
<10	0.26	26.75	<0.05	0.18	<0.2	0.003	0.5	0.84	7	QA Ee 33
<10	0.28	13.05	<0.05	<0.1	<0.2	0.005	0.4	<0.5	2	SM Dd 77
<10	0.55	20.75	<0.05	<0.1	<0.2	<0.002	0.4	0.72	<2	SM Eg 34
<10	1.59	7.26	<0.05	<0.1	<0.2	<0.002	0.4	0.83	5	SM Fg 64
<10	1.51	6.69	<0.05	<0.1	<0.2	<0.002	0.3	0.71	8	SM Fg 65
<10	0.31	21.75	<0.05	<0.1	<0.2	0.009	0.3	0.66	15	TA Be 92
<10	1.25	24.95	<0.05	<0.1	<0.2	0.002	0.3	0.84	<2	TA Bf 98
<10	0.62	9.13	<0.05	<0.1	<0.2	0.023	0.5	0.61	20	TA Cd 64
<10	0.32	28.4	<0.05	<0.1	<0.2	0.005	<0.2	0.52	<2	TA De 24

Appendix D. Quality-assurance samples

Several types of quality-assurance samples were collected as a check on data quality. This section provides a summary of results of these samples. All quality-assurance data are on file at the Maryland Geological Survey.

Fourteen blank samples were collected and analyzed for total arsenic to evaluate potential contamination during sample collection, transport, and laboratory analysis. All analyses were reported as <2 µg/L (the reporting level for the DHMH laboratory). Sixteen replicate samples were analyzed for total arsenic (including replicate reference samples) at concentrations ranging from <2 to 92 µg/L. For 13 of the 16 samples, the arsenic concentration for the replicate sample was identical to the arsenic concentration reported for the associated environmental sample; the remaining 3 replicate samples differed by only 1 µg/L from the concentration of the environmental sample. Reference samples of known total arsenic concentration were submitted to both the Maryland DHMH laboratory and the U.S. Geological Survey NWQL for analysis. Differences between known and reference concentrations were less than 1 µg/L for concentrations below 10 µg/L, and less than 6 µg/L for the reference concentrations at 92 µg/L (the maximum reference sample submitted).

Fifteen samples were analyzed twice for total arsenic (once during the initial regional study, and again 8 to 12 months later when major-ion samples were collected). In all cases, the arsenic concentration in the second sample was less than the arsenic concentration in the first sample. Differences between values ranged from 1 to 6 µg/L, with the larger differences occurring in the higher arsenic concentrations. It is unlikely that the differences represent an actual change in arsenic concentration in the aquifer, because the aquifers involved are confined, and differences are seen in all pairs of samples. Possible causes of the differences include use of different field collection practices (different lots of nitric acid used to preserve samples; different lots of sampling containers) or differences in laboratory analytical conditions (changes in equipment or personnel). The discrepancy makes minimal difference to the conclusions of this study regarding arsenic distribution in the major Coastal Plain aquifers of Maryland. The higher of the two values was used to map arsenic distribution, and thus represents a conservative approach to the interpretation (e.g., protective of public health).

Five major-ion blank samples were analyzed. Two samples had low-level (<0.02 mg/L) detections of nitrite, and one sample had a total organic carbon concentration of 0.86 mg/L, slightly above the reporting level of 0.5 mg/L. All other individual species concentrations were less than reporting levels. Five major-ion replicate samples were analyzed, with differences almost always within a few tenths of milligrams per liter. Calcium, sodium, and other constituents having concentrations greater than 20 mg/L showed less than a 5-percent difference between environmental and replicate samples. Charge balance errors calculated for major-ion samples ranged from -4.4 to +7.5 percent, averaging 0.96 percent.

Martin O'Malley
Governor

Anthony G. Brown
Lt. Governor
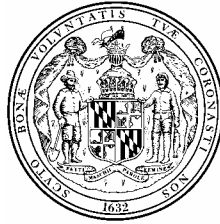
John R. Griffin
Secretary

Joseph P. Gill
Deputy Secretary

A message to Maryland's citizens

The Maryland Department of Natural Resources (DNR) seeks to balance the preservation and enhancement of the living and physical resources of the state with prudent extraction and utilization policies that benefit the citizens of Maryland. This publication provides information that will increase your understanding of how DNR strives to reach that goal through the earth science assessments conducted by the Maryland Geological Survey.

Martin O'Malley
Governor